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Earthquake Damage and Loss Assessment – Predicting the Unpredictable

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This thesis comprises research work that has been conducted between the years 2007 and 2012. The work is reported in separate papers, of which the following only peer-reviewed (refereed) papers are selected for corroborating this thesis' topic.

Paper P1 Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2): 199–210 [DOI: 10.1080/13632460802014055].

Paper P2 Lang, D.H., and Gutiérrez Corea, F.V. (2010). *RISe:* Illustrating geo-referenced data of seismic risk and loss assessment studies using Google Earth, *Earthquake Spectra*, Technical Note, **26**(1): 295–307 [DOI: 10.1193/1.3283906].

Paper P3 Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269, [DOI: 10.1016/j.cageo.2009.07.006].

Paper P4 Lang, D.H., Molina-Palacios, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88, [DOI: 10.1007/s10950-011-9250-y].

Paper P5 Lang, D.H., Singh, Y. and Prasad, J.S.R. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28**(2): 595–619 [DOI: 10.1193/1.4000004].

Paper P6 Khose, V.N., Singh, Y., and Lang, D.H. (2012). A comparative study of selected seismic design codes for RC frame buildings, *Earthquake Spectra* **28**(3): 1047–1070, August 2012, [DOI: 10.1193/1.4000057].

Paper P7 Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

Paper P8 Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research, Karachi (Pakistan),* Thematic Issue on Earthquakes, 73–86, October 2012.

Paper P9 Singh, Y., Lang, D.H., Prasad, JSR, and Deoliya, R. (2013). An analytical study on the seismic vulnerability of masonry buildings in India, *Journal of Earthquake Engineering* **17**: 399–422. DOI:10.1080/13632469.2012.746210.

Paper P10 Lang, D.H., Schwarz, J. and Gülkan, P. (2011). Site-structure resonance as a proxy for structural damage, *Earthquake Spectra* **27**(4): 1105–1125, [DOI: 10.1193/1.3651403]. *(partly connected to PhD in 2004)*

Preamble

The thesis in hand represents a summary of my work on earthquake damage and loss assessment during the past couple of years when being with NORSAR. The thesis consists of two parts: a summary and a number of separate research publications.

The summary's purpose was not only to recapitulate the main contents of the different research papers, but more to provide a thorough overview of the topic of damage and loss assessment in terms of a monograph that may also be of interest to various readers on its own. When writing the monograph, I tried to exercise due care with respect to paying tribute to the work done by other researchers through providing proper citation and references.

During the past years I was fortunate to meet and get to know a lot of great people, many of whom I was allowed to work closer with and became good friends. It is probably not possible to give adequate consideration to all the individuals that have influenced me and my work in these years. Many ideas were collaboratively developed during this time and are an integral source for the present thesis.

I want to further address my deepest gratefulness to Marjorie Greene for providing wonderful language edits to most of my products including this thesis, to Yogendra Singh, Amit Kumar, Sergio Molina, Conrad Lindholm, Louise W. Bjerrum and Emrah Erduran for reviewing this thesis and/or for always being there for me when I felt an urgent need for discussion.

I also would like to use this opportunity to thank the different agencies and institutions that funded many of the projects I was able to be involved in the past years. This applies especially to the Royal Norwegian Embassy to India (New Delhi), the Norwegian Ministry of Foreign Affairs and the Research Council of Norway as well as the International Centre for Geohazards (ICG).

To my wife and my daughter Toni

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Introduction

Predicting the likely consequences of an earthquake to a nation, a city or an individual facility is generally covered by the scientific field of earthquake risk assessment. Earthquake risk assessment is a comparably young discipline, which basically began with the seminal works on earthquake hazard by Luis Esteva (Esteva, 1967, Esteva, 1968) and Allin Cornell (Cornell, 1968). An elementary definition of this discipline was given by the EERI Committee on Seismic Risk in 1984, according to which *"seismic risk is the probability that social and economic consequences of earthquakes will equal or exceed specified values at a site, at various sites or in an area during a specified exposure time"* (EERI, 1984).

In the present thesis, the use of the term 'seismic risk' is mostly substituted by its more neutral notation 'earthquake damage and loss assessment'. This due to the fact that the definition of the term risk is always connected to the probabilities of occurrence of earthquakes over a defined time period (e.g., McGuire, 2004). Since most of these studies are, however, conducted for deterministic (sometimes 'worst-case') scenarios neglecting the recurrence period of the respective event, the general term 'damage and loss assessment' is more suitable.

Earthquake damage and loss assessment, or short 'earthquake loss estimation' (ELE) represents a true inter-disciplinary research field since it requires the expertise and knowledge of a number of research areas such as:

- seismology, or more precise seismic hazard assessment (SHA),
- geology and tectonics,
- geotechnical and structural (earthquake) engineering,
- urban land-use planning
- sociology, or more precise disaster sociology,
- insurance/re-insurance industry,
- disaster management and emergency relief, as well as
- Geographical Information Systems (GIS).

Earthquake loss estimation studies establish a central component in the causal chain from the basic research disciplines to prevention and mitigation actions against the causes of the natural hazard earthquakes (**Figure 1**, Bungum and Lang, 2010). The main purpose of earthquake loss assessment studies is to generate reliable estimates of expected physical damage as well as the economic and social losses that are connected to the damages either in a direct or indirect way. Based on the identification of existing weaknesses, e.g. the disproportionate damage extent of a certain building typology, strengthening and retrofitting measures can be proposed. Thus, earthquake loss assessment studies can directly contribute to the prevention of future losses.

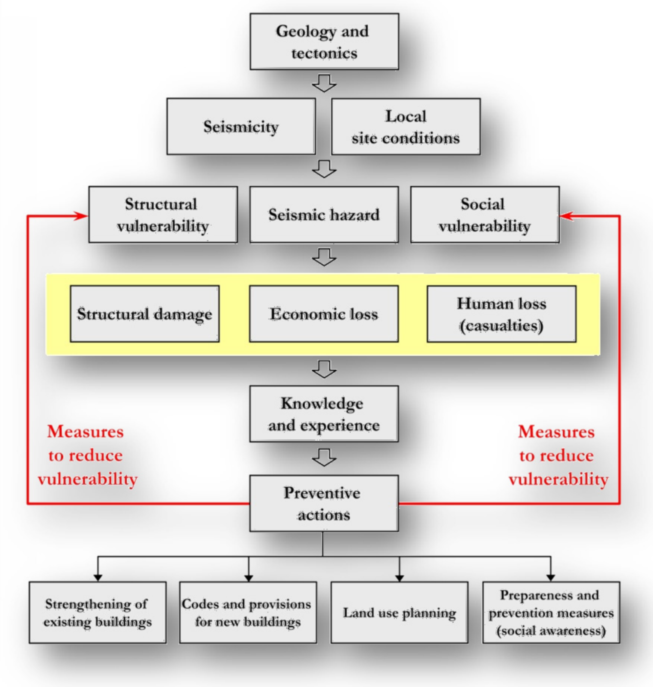

Figure 1. The causal chain from basic research disciplines to preventive actions through earthquake loss estimation. The key for reducing earthquake damages is to reduce vulnerability, building-related as well as societal, based on an underlying knowledge of earthquake hazard. A number of well-proven preventive measures can be activated for this mitigation purpose (Bungum and Lang, 2010).

Outline of the thesis and overview of supporting articles

The present thesis provides an overview of the relatively young discipline of earthquake damage and loss estimation (ELE). In doing so, the thesis will attempt to take a more critical look on the usefulness, practicability and implementation of these, mostly purely theoretical studies and how they could be applied in reality to reduce losses in future earthquake disasters.

The introductory chapter of the thesis will be followed by a chapter summarizing the current state-of-the-art of ELE, thereby illustrating the differences as well as parities between the various approaches, and trying to underline the social relevance of these studies. In the subsequent chapter, an overview of available software tools will be given highlighting the contributions of the author in the development of open-source software for ELE. This will be followed by a chapter elucidating analytical ELE studies in more detail, which have been conducted by the author in the course of several research projects in seismic regions worldwide. Before concluding the thesis, the author takes a critical look at the uncertainties involved in the process of ELE and how they can be handled.

The thesis basically summarizes the work of the author, which is represented by various publications that have been prepared in the period between 2007 and 2012. The journal publications that have been selected to corroborate this thesis formally are especially highlighted in the thesis as footnotes. In addition to these primary contributions, (secondary) publications of the author as well as of numerous researchers and research groups have been used in order to bring the issues addressed into the right perspective.

The primary journal publications written by the author, which form the basis for the present thesis, are given below:

Paper P1	Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210 [DOI: 10.1080/13632460802014055]. *The paper presents a damage and loss assessment study for the Arenella study area in Naples (Italy), which was one of the test beds investigated during the EU-SAFER project (www.saferproject.net/). The paper further discusses how damage and loss estimates could be provided in a real-time mode. The total work load of the author is estimated to be around 60%.*
Paper P2	Lang, D.H., and Gutiérrez Corea, F.V. (2010). *RISe:* Illustrating geo-referenced data of seismic risk and loss assessment studies using Google Earth, *Earthquake Spectra*, Technical Note, **26**(1), 295–307 [DOI: 10.1193/1.3283906]. *The paper presents the background and application of a software tool that has been prepared in collaboration with INETER Managua (Nicaragua). The tool RISe - Risk Illustrator for SELENA was developed in order to convert geo-referenced input and inventory files (so far customized to the risk software SELENA) into Google^{TM} Earth kml-files. The software thus easily allows any user to graphically visualize his data on an open GIS platform without requiring to purchase commercial GIS software. The open-source RISe tool is provided free-of-charge through the Sourceforge platform (http://selena.sourceforge.net/). The total work load of the author accounts to be around 60% for the software development and 80% for the technical user manual and the paper.*
Paper P3	Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269, [DOI: 10.1016/j.cageo.2009.07. 006]. *The paper represents a thorough overview of the analytical risk software SELENA, which has been developed by NORSAR and the University of Alicante (Spain) since 2005. Like RISe, SELENA is disseminated through the Sourceforge platform (http://selena.sourceforge.net/). The author has actively contributed to the further development of SELENA since 2007. The total work load of the author accounts to be around 40% for the paper, 20% for the software development and 50% for the technical user manual.*
Paper P4	Lang, D.H., Molina-Palacios, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88, [DOI: 10.1007/s10950-011-9250-y]. *This paper deals with deterministic scenarios for the city of Bucharest (Romania) and the problems connected to available inventory data and fragility information for the prevalent construction typologies. It further illustrates the set-up of a logic tree computation scheme considering various ground-motion prediction equations,*

fragility models and deterministic earthquake source parameters. The total work load of the author is estimated to be around 60%.

Paper P5 Lang, D.H., Singh, Y. and Prasad, J.S.R. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619 [DOI: 10.1193/1.4000004].

The paper includes an analytical-based damage and loss study for the city of Dehradun (Northern India) using the SELENA software. The risk estimates are compared with an earlier empirical intensity-based study. The paper illustrates problems associated with trying to generate intensity-compatible ground-motion estimates and the comparison of analytical and empirical risk studies. The total work load of the author is estimated to be around 70%.

Paper P6 Khose, V.N., Singh, Y., and Lang, D.H. (2012). A comparative study of selected seismic design codes for RC frame buildings, *Earthquake Spectra* **28**(3): 1047–1070, [DOI: 10.1193/1.4000057].

The paper identifies the differences that exist in the provisions of some of the major national seismic building codes for RC frame buildings, i.e. ASCE 7 (U.S.), Eurocode 8, New Zealand code (NZS 1170.5) and Indian code (IS 1893). A comparative study is conducted regarding the specification of hazard, site classification concepts, design response spectra, ductility classification, response reduction factors and control of drift and the cumulative effects of these factors on design base shear are presented. The different codes differ not only in terms of limiting values of various design parameters, but also show significant differences in the process of estimating them. As a result, buildings designed as per different codes will perform differently for a given level of hazard. This will also impact damage and loss estimates for the building stock in case that different building code provisions are applied for the study. The total work load of the author is estimated to be around 25%.

Paper P7 Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

The paper establishes one step towards a next generation of risk assessment procedures. In contrast to conventional risk computation where simplified point source or line source assumptions are used in order to provide the seismic demand, the effects of implementing stochastic finite fault ground-motion simulations are evaluated in this study. The differences between these approaches are investigated in terms of ground-motion and damage estimates. The total work load of the author is estimated to be around 50%.

Paper P8 Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research, Karachi (Pakistan),* Thematic Issue on Earthquakes, 73–86, October 2012.

This paper investigates the sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability components. The studies are conducted for two test beds with distinctive socio-economic characteristics, i.e., Zeytinburnu (Istanbul, Turkey) and Los Angeles (U.S.). The distribution of damage estimates shows that the respective earthquake risk models are most severely affected by the vulnerability model. Compared to that, the quality and level of detail of the building exposure database as well as the selected ground motion model (GMPE) seem to have less effect on the damage estimates. The total work load of the author is estimated to be around 40%.

Paper P9 Singh, Y., Lang, D.H., Prasad, JSR, and Deoliya, R. (2013). An analytical study on the seismic vulnerability of masonry buildings in India, *Journal of Earthquake Engineering* **17**: 399–422. [DOI:10.1080/13632469.2012.746210].

The paper proposes two analytical models for unreinforced masonry (URM) buildings in India aiming to simulate their seismic response and to estimate corresponding vulnerability functions. The proposed models are implemented in SAP 2000 nonlinear software to obtain capacity curve parameters for representative Indian URM buildings, based on a field survey and statistical analyses. Vulnerability functions are estimated using the obtained capacity curves. Damage Probability Matrices (DPMs) are obtained using the approximate PGA-intensity correlation relationship as per Indian seismic building code and are compared with the commonly used intensity scales and empirical damage data observed after the 2001 Bhuj earthquake. The total work load of the author is estimated to be around 35%.

Paper P10 Lang, D.H., Schwarz, J. and Gülkan, P. (2011). Site-structure resonance as a proxy for structural damage, *Earthquake Spectra* **27**(4), 1105–1125, [DOI: 10.1193/1.3651403].

Based on ground motion and damage data that has been collected during numerous reconnaissance missions of the German Task Force for Earthquakes to worldwide earthquake regions this paper examines whether site-structure resonance effects had contributed to building damage. The procedure is developed and applied to RC frame structures that partly experienced slight to moderate damage during a recent major event. By correlating the ranges of predominant site periods with the building's capacity curves a quick survey procedure has been developed to estimate the impact of agreements between periods of the site and the structure contributing to structural earthquake damage. This paper covers in parts topics that have been addressed by the author's PhD thesis of 2004 though being completely rewritten in 2010. The total work load of the author is estimated to be around 60%.

Earthquake damage and loss estimation (State-of-the-art)

Historical outline

The question when and where earthquake risk assessment began is controversially discussed in literature. Undoubtedly, the pioneering papers on earthquake hazard assessment by Luis Esteva (Esteva, 1967, Esteva, 1968) and Allin Cornell in 1968 (Cornell, 1968) contributed greatly to initiate the field of seismic risk assessment. Whitman *et al.* (1997), on the other hand, state that the era of earthquake loss assessment started with the 1972 NOAA[1] study for San Francisco (Algermissen *et al.*, 1972), which was followed by more than 30 earthquake loss studies for various regions of the United States (NIBS, 1994). Long before these studies, earthquake loss estimation was discussed by John Freeman in 1932 in his book *Earthquake Damage and Earthquake Insurance* (Freeman, 1932), which already points to what we nowadays understand about earthquake loss estimation (Kircher *et al.,* 1997a). After this, earthquake loss estimation was largely dominated by and confined to insurance industry with little groundbreaking work being published until Cornell's work in 1968.

Traditionally, earthquake loss studies exclusively relied on empirical observations based on a macroseismic intensity scale. The reason for this mainly lies in the fact that in earlier times when recording stations were not yet available and thus instrumental earthquake records were less common, intensities were the only measure of earthquake shaking (e.g., McGuire, 2004, Lang *et al.,* 2012b[2]). Even today, the lack of recording stations or their widespread placing in many earthquake-prone regions prohibits the conduct of earthquake loss studies based on physical parameters. Here, intensity-based studies still represent the only applicable way to predict damages and loss for a certain earthquake scenario.

Empirical, mostly intensity-based earthquake loss studies use datasets of observed damage supplemented with expert opinion (Porter and Scawthorn, 2007). In general, post-earthquake investigations are the main source of these datasets, correlating recorded damage effects to structures with an estimated ground motion level at the respective site. However, the lack of high-quality observational datasets means that

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[1] National Oceanic and Atmospheric Agency

[2] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

some of the most commonly used sets of fragility curves (e.g. ATC–13, 1985) partly (if not, extensively) rely on expert judgment (Douglas, 2007).

With the advent of the nonlinear static ('pushover') analysis (e.g., Krawinkler and Seneviratna, 1998) as well as the introduction of the Capacity Spectrum Method (CSM; Freeman *et al.,* 1975; Freeman, 1978; ATC–40, 1996) and the Displacement Coefficient Method (DCM; FEMA 273[3], 1997a; FEMA 356, 2000; FEMA 440, 2005), analytical methods found their way into the field of earthquake damage and loss assessment (Lang *et al.*, 2012a). CSM is a performance-based seismic analysis technique, with its roots in John A. Blume's Reserve Energy Technique (RET; Blume *et al.*, 1961) and which was later used as a rapid evaluation procedure for assessing the seismic vulnerability of buildings at the Puget Sound Naval Shipyard (Freeman *et al.,* 1975). Long before this innovative procedure was established as the core of ATC–40 (1996), it was applied in ATC–10 (1982) to find a correlation between earthquake ground motion and structural performance (Freeman, 2004).

Approaches for damage/vulnerability estimation

In general, earthquake damage and loss studies are based either on the traditional empirical (or statistical) approach (i.e. macroseismic intensities) or the more recent analytical (or theoretical) approach using physical ground-motion parameters such as spectral accelerations S_a or spectral displacements S_d. Especially in situations where statistical methods cannot be applied (e.g. due to lack of data or missing experience from previous earthquake damage), analytical tools may be used to supplement the loss estimation procedure, thus leading to a third, i.e. hybrid approach (Dolce *et al.*, 1995; Kappos *et al.*, 1998; Kappos *et al.*, 2002). Hybrid approaches can, e.g., combine statistical (empirical) damage data with theoretical results from nonlinear structural analyses.

In other words, it can be said that the different approaches for loss estimation in principle differ in the way earthquake ground motion is represented and building vulnerability is treated (Lang *et al.*, 2012a). With respect to the latter, the 'damageability' (acc. to Lang *et al.* 2012a[4]) or the 'damagingness' (acc. to Coburn and Spence, 2002) as a different notation of a building's vulnerability can be obtained using various methods (empirical, analytical, experimental, expert opinion or a combination of these).

According to Sandi (1982), the first is denoted as *observed vulnerability*, while the second represents *calculated* or *predicted vulnerability* (Barbat *et al.*, 1996; Coburn and Spence, 2002). Both types of vulnerability may be represented by similar means, i.e. damage probability matrices (DPMs) or fragility functions, depending on what type of data is available and which of the basic approaches is to be applied. An elaborate overview of existing methodologies for seismic vulnerability assessment is given by Calvi *et al.* (2006).

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[3] The procedure itself is actually described in FEMA 274 (1997b), i.e. the NEHRP commentary on FEMA 273.

[4] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

Empirical approach

As was already indicated, earthquake loss estimation traditionally relied on empirical studies mainly focusing on macroseismic intensities in order to characterize the earthquake shaking. In recent years, when more instrumental data in terms of (strong-motion) earthquake recordings became available, empirical studies based on physical parameters such as peak ground acceleration (PGA) were conducted as well. Since PGA in particular is a poor parameter for loss estimation studies as it shows almost no correlation to structural earthquake damage (Crowley *et al.*, 2004), it is not further addressed here.

Consequently, empirical loss studies have been mostly based on intensities as a measure of ground motion. If seismic hazard is defined by intensity, the most widely used form to represent building vulnerability is Damage Probability Matrices (DPM), which indicate the discrete probabilities of a certain building class (here: *vulnerability class*) to suffer damage of a certain grade at a certain shaking intensity. A few intensity scales are available; the most widely used include MMI (*Modified Mercalli intensity scale*[5]; Wood and Neumann, 1931), MSK (*Medvedev–Sponheuer–Karnik*; Sponheuer and Karnik, 1964, Medvedev *et al.,* 1965), EMS–98 (*European Macroseismic Scale*; Grünthal, ed., 1998) and PSI (*parameterless scale of seismic intensity*; Spence *et al.*, 1991).

The concept of DPMs was developed and first described by Whitman *et al.* (1973) and later provided the basis for ATC–13 (1985). As an example, **Table 1** illustrates a DPM for a class of Indian building typologies based upon the specifications of EMS–98 and MSK intensity scales (Prasad *et al.*, 2009; Lang *et al.*, 2012b[6]). The DPMs are provided in terms of lower- and upper-bound estimates since intensity scales (e.g. EMS–98) use qualitative terms such as ‘few’, ‘many’ and ‘most’ in order to estimate the percentage of buildings of the same class to suffer a certain damage grade (DG). However, these qualitative terms, which are purely subjective, cannot be translated into a single numeric value and thus *“are defined as three contiguous ranges of percentages* (..)*”* (EMS–98), e.g., 10–20%, 15–55%, and 55–100%.

The combination of damage probabilities and inventory data allow estimation of upper- and lower-bound values of expected damage and, since each damage grade is connected to an objective ratio of repair cost to replacement cost (Whitman *et al.*, 1973), provide more information about cumulative damage or loss, expressed by a Mean Damage Ratio (*MDR)*.

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[5] Adapted from A.H. Sieberg's Mercalli–Cancani–Sieberg (MCS) scale, later modified and published in English by Wood and Neumann (1931), and finally improved by Richter (1958).

[6] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

Table 1. Lower- and upper-bound damage probabilities for Indian building typologies MC3 and RC1 (Prasad *et al.*, 2009; Lang *et al.*, 2012b).

Intensity *I*	Damage probability [%] †)									
	Lower-bound estimates					Upper-bound estimates				
	DG 1	DG 2	DG 3	DG 4	DG 5	DG 1	DG 2	DG 3	DG 4	DG 5
VI	10	0	0	0	0	20	0	0	0	0
VII	52	10	0	0	0	67	20	0	0	0
VIII	35	55	10	0	0	0	80	20	0	0
IX	0	75	15	10	0	0	25	55	20	0
X	0	0	75	15	10	0	0	25	55	20
XI	0	0	30	55	15	0	0	0	45	55
XII	0	0	0	0	100	0	0	0	0	100

†) DG – damage grade following the definitions given in EMS–98 (Grünthal, ed., 1998)

The empirical approach, particularly when based on macroseismic intensity comes with a number of problems, including:

1. Intensity is a non-instrumental parameter primarily based on damage observations and personal impressions (feelings, sensations) of individuals. This directly implies a certain level of uncertainty due to such subjectivity.
2. DPMs rely purely on empirical damage observations. This means that (a) generally limited data is available for lower shaking intensities (i.e. intensity *I* < VI) where no observable damage is produced, and (b) data for a certain test bed is typically constricted to only one or two intensity grades. Consequently, it is necessary to use either empirical data from other earthquakes and/or countries (with similar construction practice; e.g. Roca *et al.,* 2006) or to revert to expert opinion in order to supplement the database (ATC–13, 1985; Kappos *et al.*, 1998).
3. Effects of soil and site conditions cannot be explicitly quantified as intensities are the combined result of the earthquake characteristics, the local site amplification (soil and topography), and the damageability of the building stock. Site conditions cannot be considered in intensity studies because they are "part of the effects that intensity is a record of, and part of the hazard to which the built environment is exposed to" (Grünthal, *ed.*, 1998). It is thus difficult, if not impossible, to develop site-dependent DPMs, which would allow a direct comparison with analytical studies.[7]
4. Except for the PSI scale, a macroseismic intensity scale is non-continuous, using stepped (incremental) intensity grades, which makes it difficult for predictive purposes (Coburn and Spence, 2002).
5. Building typologies are categorized into vulnerability classes based solely on work material and structural system (and partly the level of earthquake-resistant design), while neglecting the number of stories (height range). Such a classification scheme may result in the assignment of buildings of completely different materials to the same vulnerability.

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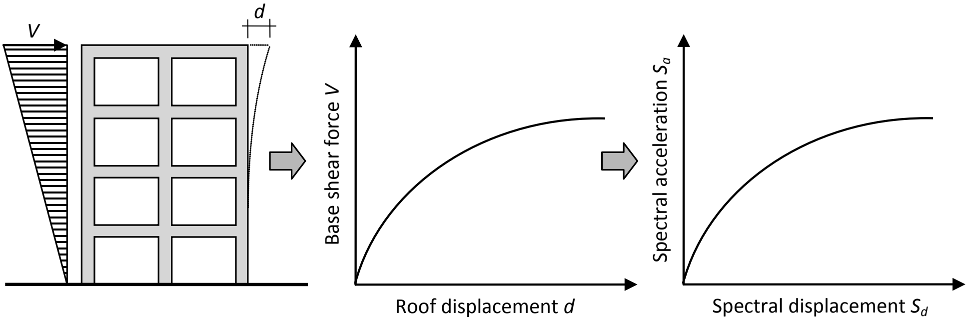
[7] See subsequent chapter *'Empirical vs. analytical approach'*.

6. Since intensity-based DPMs are based primarily on damage observations from past earthquakes, they may not be applicable for the prediction of future events (Crowley *et al.*, 2004). Particularly after major damaging events, building construction practices often change significantly, which means that the performance of these new buildings cannot be represented by these DPMs.

In addition, one of the main shortcomings when using intensities to predict earthquake damage may lie in the fact that intensity does not have any connection to the frequency (spectral) content of ground motion. Hence, any damage-contributing effect that may result from agreements between the predominant frequencies of the site and the structure are not addressed at all (see also in combination with point 3. above).

Analytical approach

The analytical approach for earthquake damage assessment may also be called a purely theoretical approach since, in contrast to the empirical approach, it is not based on observation, but rather on the theoretical simulation (i.e. prediction) of structural damage under earthquake loading. Building vulnerability is expressed in terms of a capacity curve that represents the nonlinear behavior of the structure under lateral displacement. To identify a capacity curve, which is defined as the relationship between the base shear force and the lateral displacement of a control node of the building (Goel, 2005), a nonlinear structural analysis method such as the pseudo-static "pushover" analysis method[8] (U.S. Army, 1986; ATC–40, 1996; FEMA 356, 2000) is required. This postulates the creation of a reliable structural model (e.g. using Finite Elements) of the building under consideration to which the pushover analysis can be applied (**Figure 2**).



(a) Generation of a structural model and application of the pushover analysis

(b) Force–deformation relationship illustrating the nonlinear behavior of the structure

(c) Transformation into the S_a–S_d domain assuming the structure as an equivalent SDOF system

Figure 2. Analytical way to generate building capacity curves which ideally represent the nonlinear (damaging) behavior of the building under a statically increasing lateral load V.

The second component, seismic ground motion (or seismic demand), is generally represented by a response spectrum in terms of physical parameters, i.e. accelerations

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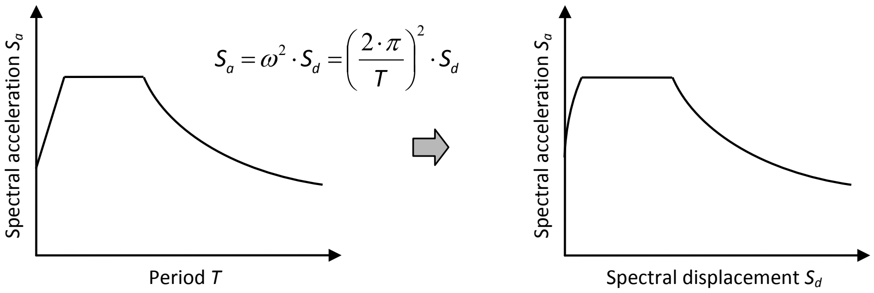
[8] Also known as Nonlinear Static Procedure (NSP).

and displacements. In order to be able to correlate the response spectrum with building capacity, it needs to be converted from the (conventional) S_a–T domain into the domain of the capacity curve, i.e. spectral acceleration–spectral displacement domain (S_a–S_d; **Figure 3**).



$$S_a = \omega^2 \cdot S_d = \left(\frac{2 \cdot \pi}{T} \right)^2 \cdot S_d$$

(a) Conventional representation of elastic response spectrum (design spectrum)

(b) Transformed response spectrum into S_a–S_d domain

Figure 3. Conversion of design response spectrum into S_a–S_d domain.

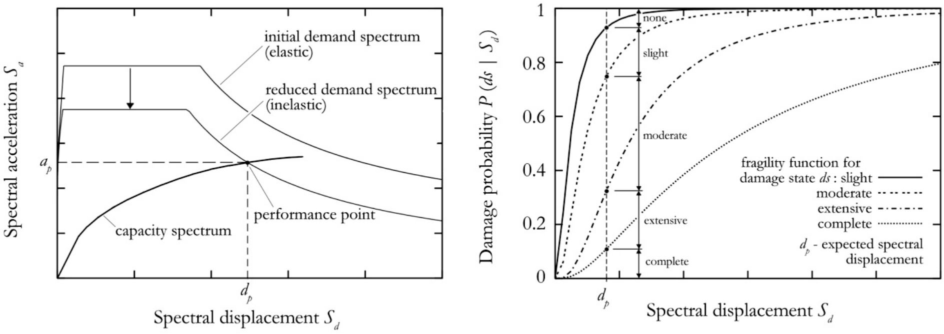
In contrast to empirical studies where ground motion can only be represented by a single parameter, e.g. a shaking intensity or PGA, a response spectrum allows the consideration of the spectral content of ground motion. Depending on the procedure chosen to correlate seismic demand with building capacity, either smooth design response spectra (as given in **Figure 3**) or randomly shaped response spectra (of recorded or predicted ground motion) can be applied to ideally mimic earthquake demand.

In order to predict analytically the structural damage that a building of a given capacity will produce under a given seismic impact, different methods are available (NORSAR, 2009):

- Capacity Spectrum Methods (CSM) (ATC–40, 1996; FEMA 440, 2005),
- Collapse-based methods (CBM) (e.g. FaMIVE, D'Ayala and Speranza, 2002; VULNUS, Bernardini *et al.,* 1990; Cosenza *et al.,* 2005),
- Displacement-based methods (DBM) (e.g. DBELA, Crowley *et al.*, 2004; Miranda, 1999),
- Displacement coefficient methods (DCM) (FEMA 273, 1997a; FEMA 356, 2000; FEMA 440, 2005),
- Incremental dynamic analysis (IDA) (e.g. Shome and Cornell, 1999; Vamvastsikos and Cornell, 2002).

CSM and DCM have received the greatest attention to date, mainly because these procedures were published as various FEMA provisions and, in the case of CSM, because this procedure established the basis for FEMA's HAZUS methodology (FEMA, 2003). Even though neither of the mentioned procedures will be discussed here in detail, it can be seen that displacement is a major component of all four methods. Each of these procedures accrued from the philosophy of performance-based seismic design (PBSD), recognizing the fact that structural damage is mainly determined by lateral displacement.

The chosen procedure, e.g. CSM, will help to identify the target displacement (or performance point) d_p. This displacement stands for the mean displacement a building typology will reach under the respective seismic demand. Hence, it represents the mean damage individual buildings of this building typology will experience. In order to compute the corresponding damage probabilities, fragility functions for damage states *DS* are required, which are closely connected to the capacity curve of the respective building typology. Fragility functions incorporate the distinct uncertainties from the geometrical building model, material parameters, seismic demand etc. (**Figure 4**).



(a) (b)

Figure 4. Principle of the CSM (here as provided by ATC–40, 1996) with (a) identification of the target displacement d_p, i.e. the predicted spectral displacement under an estimated seismic demand that is represented by a design response spectrum, and (b) determination of discrete damage probabilities *P* corresponding to d_p. (Figure taken from Molina *et al.,* 2010[9]).

One of the advantages of the analytical (and thus purely theoretical) approach is the fact that it can be applied even to regions of low seismicity where little or no damage has been experienced. However, there are a number of disadvantages, briefly reviewed here:

1. To develop capacity curves analytically, the generation of a structural model and the application of a pushover analysis (also Nonlinear Static Procedure, NSP) is required. This procedure is, however, limited to engineered structures for which a reliable structural model can be generated (Hancilar *et al.,* 2010). Both the modeling and the conduct of NSP for non-engineered buildings made of, for example, earthen materials (adobe), is challenging, if not impossible.
2. NSP principally is applicable only to building models that are dominated by the first natural mode and hence one will have difficulties to get a realistic representation of a building's damaging behavior using NSP for most building typologies.
3. The generation of a reliable building model is generally difficult as many variables are required that are not typically available and thus can only be generated by guesswork. This applies particularly to material parameters, reinforcement

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[9] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

detailing etc., which are generally not available for a larger building stock (Crowley *et al.,* 2004).

4. The generation of capacity curves and fragility curves requires the generation of a set of building models with varying geometry and material parameters, which is a time-consuming process, and which is characterized with inherent assumptions and uncertainties.
5. The level of detail in building classification strongly impacts the uncertainty of the derived capacity curves and fragility functions. The more narrowly a building class is defined with respect to geometry, height (story number), or code design level, the more representative will be the mean fragility parameters for each building type that belongs to this class. The associated uncertainty to describe the fragility of these building types will directly influence the reliability of predicted damage and loss estimates for the respective class.
6. In most cases, analytical capacity curves and fragility functions are only sparsely available, certainly not for all defined building typologies. This requires the use of expert opinion[10] to populate the fragility database[11].

This last point contributes significantly to the fact that only few analytical damage and loss studies have been conducted so far. The reason for this may lie in the fact that realistic vulnerability information (i.e., reliable capacity curves and fragility functions) are not yet available for a large number of building types. This is especially true for non-engineered building typologies using construction materials which require more sophisticated analysis and reliable nonlinear material properties (Lang *et al.* 2012a[12]). To date, no central database exists that collects available fragility information (e.g. capacity curves and fragility functions).

Different possibilities exist to counteract this lack in analytical fragility information (Lang *et al.,* 2012b[13]):

1. The use of expert opinion (as described above).
2. The application of fragility curves that were originally developed for the same building type but for different parts of the world (Lang *et al.,* 2012a[12]; Lang *et al.,* 2012b[13]). This requires ample information on the respective building typologies for which these curves were developed and for which these curves are to be applied.
3. The use of alternative (e.g. empirical) information or methods leading to a hybrid approach[14].

Hybrid approach

In cases where components of both analytical and empirical methods are used to describe building vulnerability, the procedure can be called hybrid. This situation occurs

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[10] See subsequent chapter *'Expert opinion'*.

[11] The consequence of this proceeding is that it is not anymore a pure analytical approach applied.

[12] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[13] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

[14] See subsequent chapter *'Hybrid approach'*.

if, for example, empirical data is not available in sufficient number or sufficient quality and needs to be complemented by analytical methods or local expert opinion (Dolce *et al.,* 1995; Barbat *et al.,* 2008). This, however, does not necessarily mean that hybrid studies are most relevant for those regions with low earthquake damage experience. A lack of empirical vulnerability studies exists even in many countries with significant seismicity (Barbat *et al.,* 1996).

Studies based upon hybrid methodologies are limited, and not many studies have been published so far. Kappos *et al.* (1998, 2006)[15] emphasize on calibrating analytical fragility curves by available empirical data. Further, they use the standard procedure by Whitman *et al.* (1973) to construct parts of the DPMs with respect to intensities, damage grades or building classes for which empirical data is available. Results of nonlinear analysis are then applied to fill in the remaining parts of the DPMs. Since structural analysis results are always related to physical parameters such as accelerations or displacements, empirical correlation relationships are used in order to scale the physical results to corresponding intensities.

Other hybrid procedures were presented by Dolce *et al.* (2002)[16], Barbat *et al.* (1996), Singhal and Kiremidjian (1996). It is generally accepted that hybrid methods are a suitable tool to generate loss estimation studies even for areas with little empirical data, though these methods may necessarily be based on some simplifications which are briefly described:

1. Damage estimates from analytical studies have to be transformed from a physical ground-motion parameter to an intensity parameter using empirical correlation relationships which are associated with large uncertainties.
2. It is necessary to generate structural building models which reflect realistic damage behavior of the respective building typology. Since no empirical data is available for these typologies, the generation of the structural models may be based entirely upon assumptions which can only be verified by damage observations from other earthquake regions. This, however, implies large difficulties and may increases the number of uncertainties related to the reliability of the chosen model.
3. The contribution of soil (in terms of soil amplification effects) cannot be quantified with empirical damage estimates, whereas input ground motions (time-histories or spectra) used for analytical studies are inevitably connected to subsoil conditions. In order to solve this problem, Kappos *et al.* (1998) suggest removing the site dependency by constructing the "average theoretically calculated response of a model", which can then be compared with the site-independent empirical damage terms of the DPMs. Needless to say, this process is cumbersome, time consuming and prone to uncertainties.
4. Vulnerability estimates that have been derived by empirical and analytical methods are not directly comparable since they include completely different uncertainties (Calvi *et al.,* 2006).

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[15] Also known as the 'Greek method' (Dolce *et al.,* 2006); probably because it was mainly developed by Greek researchers, this method makes use of damage data collected from Greek earthquakes and applied to Greek study areas.

[16] Also called the 'Italian method'; see Dolce *et al.* (2006).

Given these difficulties, the use of analytical methods in order to complement fragmentary DPMs is still considered to be a more reliable way to generate vulnerability information than to purely rely on expert opinion.

Expert opinion

In principle, each method which is used to provide building vulnerability information is based on expert opinion to some extent. In each empirical survey or analytical study, a certain number of assumptions have to be made that require the subjective opinion or decision of a (group of) expert(s), which is (are) considered as the best estimate for the given problem. These include questions such as:

1. How to collect or interpret damage data (which is in turn essential to the assignment of shaking intensity)?
2. How to choose certain (building-related) parameters which are essential to the study's outcome but often not readily available, e.g. material parameters or reinforcement detailing?
3. How to assign a vulnerability class to a building? How to categorize buildings with varying characteristics to the same building class?

The practical conduct of an expert opinion survey is described by Coburn and Spence (2002). Studies based on expert opinion surveys include the ATC–13 project (ATC, 1985) and FEMA's HAZUS loss estimation methodology (FEMA, 2003). In the latter, spectral displacement-based capacity curves are provided for a set of model building typologies for the United States based on engineering design parameters and judgment.

Which approach works best?

Since the decision on which approach to select will mainly depend on available information (e.g., quality and resolution of inventory data, type of available fragility information, and the format of existing damage statistics to which predicted loss estimates can be calibrated), a user will not typically be faced with a situation where a choice is even possible.

To briefly summarize the previous chapters, it should be noted that intensity-based procedures rely on statistics of observed damage and are thus more reliable in terms of vulnerability. This applies especially to those building typologies that show large variations of damage and are thus more problematic to model analytically. But these studies are more subjective with respect to the description of the hazard. On the other hand, the analytical (capacity spectrum-based) approach is more objective in terms of defining the seismic hazard as it considers physical measures of seismic ground motion and is at best based on instrumental recordings. Building vulnerability, however, is based on analytical models which need to be calibrated using damage statistics (hybrid methods). In the absence of this calibration, damage and loss estimates derived by analytical approaches may not be better than intensity-based results. It can therefore be concluded that the analytical approach should be preferred in cases when reliably calibrated vulnerability models are available (Lang *et al.,* 2012b[17]).

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[17] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

Empirical vs. analytical approach (DPM versus fragility functions)

Though hybrid earthquake loss estimation studies are partly based on empirical and analytical approaches, they do not allow for comparative studies between both approaches. Comparative studies between empirical (intensity-based) and analytical (spectral displacement-based) loss models are rare because of several major challenges:

1. Vulnerability estimates generated by each method are related to different ground shaking parameters. To be able to compare results, correlation relationships (e.g. intensity–PGA) need to be applied, which generally show large variations and uncertainties.
2. The two approaches use different damage classification scales, which means that disaggregated results for a certain damage class cannot be compared without correlating the damage states of both scales with each other (Lang, 2004, Reitherman, 1986).
3. The two approaches use a similar principle for the categorization of buildings based on material of construction and design code level. However, while intensity-based methods mostly categorize buildings into vulnerability classes (VC; e.g. in EMS–98, Grünthal, ed., 1998), analytical methods use model building typologies (MBT, as e.g. defined in HAZUS–MH, FEMA, 2003). Since a vulnerability class can include more than one building type, it represents a coarser description of building vulnerability. Aware of this main shortcoming of intensity-based studies, the parameterless scale of intensities (PSI) (Spence *et al.,* 1991, Coburn and Spence, 2002) uses a more refined classification of load-bearing structures of worldwide building types[18].

With respect points 1. and 2. above, Reitherman (1986) suggests a procedure to convert DPMs into fragility curves, which are either dependent on Modified Mercalli Intensity (MMI) or peak ground acceleration (PGA). This, however, again requires empirical relationships between both ground motion parameters which represents the main challenge of comparative studies.

Studies which compare loss estimates generated by different approaches are only sparsely available. Edwards *et al.* (2004) conducted a comprehensive reinterpretation of the losses for the 1989 (M_L 5.6) Newcastle earthquake in New South Wales, Australia, using both an intensity-based methodology and the analytical spectral displacement-based approach. Both approaches gave loss predictions of the same magnitude as the actual loss data provided by insurance companies after the earthquake. Edwards *et al.* (2004) strongly recommend the combined use of both approaches, especially in regions of low seismicity where instrumental recordings and earlier damage observations are not available. Thus, a calibration of the models and of the vulnerability estimates would be facilitated. While this suggestion is of course true, it does represent the ideal rather

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[18] Please refer to chapter *'Building classification schemes'*.

than the realistic case, as sufficient quality information of both types will only very rarely be available (Lang *et al.* 2012b[19]).

A comparative study between an intensity-based and analytical loss study is presented in Lang *et al.* (2012b). An empirical loss assessment for the north Indian city Dehradun was provided by Prasad *et al.* (2009) assuming a macroseismic intensity of VIII (8.0) and based on DPMs that were developed using upper and lower bound damage estimates from MSK and EMS scales and further calibrated to Indian conditions (Arya 2003). To allow for a comparison with the derived damage and loss estimates, Lang *et al.* (2012b) generated a suite of deterministic earthquake scenarios (magnitude–distance combinations) that produce comparable shaking intensities in the study area. This procedure results in physical ground motion estimates which are used to create the elastic design response spectrum for the analytical loss assessment. The required analytical capacity curves and fragility functions were not converted from the available DPMs but partly taken from literature that were originally developed for similar construction typologies in various regions worldwide. By carefully selecting and allocating these curves to the prevalent construction typologies in the test bed Dehradun, a conversion process using empirical correlations between intensity and physical ground motion parameters is avoided. The chosen procedure of not calibrating the curves further ensures that the derived results are not biased. As it can be taken from Lang *et al.* (2012b), damage and loss estimates for the different approaches show significant variations that tend to converge for scenarios of larger epicentral distances. The latter being caused by the fact that the GMPEs applied tend to produce more reliable ground motion accelerations (PGA) for larger epicentral distances. Reasons for the differences in damage and loss estimates can be ascribed to a multitude of factors, such as:

- the aleatoric uncertainty of applied magnitude-intensity relationships,
- the aleatoric uncertainty of applied empirical GMPEs,
- the epistemic uncertainties resulting from the chosen logic tree computation scheme,
- the different way building vulnerability is described with no calibration between empirical DPMs and analytical capacity curves and fragility functions,
- the different damage classification scales, though it has been attempted to establish parity between both.

These factors and the problems reported by Lang *et al.* (2012b)[20] make comparative studies between empirical and analytical approaches very difficult and it is preferable to treat each in a separate way.

As will be later discussed, a number of software tools are available for earthquake damage and loss assessment computation. With respect to comparative investigation between different approaches, the ELER software (Hancilar *et al.,* 2010), which is an

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[19] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

[20] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

updated version of KOERILoss software (Erdik and Aydinoğlu, 2002) is mentioned because it is one of the few software packages that allows both an intensity-based and analytical damage and loss assessment. However, each approach is incorporated in separate modules of ELER and therefore cannot be directly used for comparative studies. In addition, to the best of the author's knowledge, no study has yet been conducted with ELER comparing the different approaches[21]. Another tool which allows the consideration of multiple approaches is the open spreadsheet-based software SeisVARA (Seismic Vulnerability and Risk Assessment; Haldar *et al.,* 2013). It was developed in order to facilitate comparative studies of different earthquake loss assessment approaches based on various ways to specify the seismic hazard. For a given inventory database and loss model, the software provides the option to conduct empirical (intensity-based) or analytical (CSM-based) damage and loss assessment.

The success of comparative studies between the empirical and analytical approach mostly depends on how well ground motion parameters and vulnerability estimates are correlated with each other and how reliable these correlation relationships are. To develop these relationships, statistical damage observations in the immediate vicinity of recording stations are required (Coburn and Spence, 2002) in order to establish reliable correlations between empirical intensity parameters and physical ground motion parameters such as PGA, spectral accelerations or PGV. The availability of these types of studies, preferably for various earthquakes of different size, would allow the calibration of analytical building models and hence the development of more realistic fragility functions.

Application and combination of ELE approaches: PAGER

A system to estimate the human impact of earthquakes was developed at the U.S. Geological Survey and called PAGER – *Prompt Assessment of Global Earthquakes for Response* (Wald *et al.,* 2008). PAGER makes use of a suite of models to provide global estimates on economic loss and casualty numbers for a given event[22]. It can be said, that PAGER is an extension of USGS's *ShakeMaps* system (Wald *et al.,* 1999) from hazard to risk (Porter and Scawthorn, 2007). The model applied can be fully empirical (Jaiswal *et al.,* 2009; Jaiswal and Wald, 2010a), semi-empirical (Jaiswal and Wald, 2010b) or analytical (Porter *et al.,* 2008).

Dependent on the selected test bed or affected area and availability of empirical data on both building inventory and building vulnerability, PAGER decides which of the three models is most appropriate. The semi-empirical approach is used for those regions where a purely empirical or purely analytical model cannot be generated due to lack of observational data or analytical studies, respectively. The nature of this model can therefore also be called hybrid.

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[21] A comparative ELE study between ELER's analytical module (i.e. Level 2) and SELENA (Molina *et al.*, 2009) was conducted in the framework of the NERIES project (Bungum *et al.*, 2010).

[22] It needs to be stressed that PAGER is limited to the prediction of loss estimates and generally provides no information on numbers of damaged structures though damage models establish a main basis of the system.

Users and beneficiaries of ELE studies

Compared with the inherent risks associated to everyday occurrences such as car accidents, "natural disasters"[23] (including earthquakes) are associated with much lower probabilities of individual deaths. As a consequence, earthquake risk estimation catches the attention of only a few. Depending on the scale and dimension of an ELE study, a broad variety of user groups may be interested in the prediction of the likely consequences of an earthquake, ranging from private homeowners to state governments and civil protection organizations. Each of these groups has different demands for an ELE study's outcomes, particularly with respect to the type and the level of detail of the predicted loss estimates. Real-time scenarios following large earthquakes have a very clear purpose: To distribute efficiently available resources for aid, search and rescue and to "manage" the disaster in a way that follow-up consequences (secondary losses) are kept at a minimum[24].

Predictive ELE studies, as they are addressed in the present work, are in particular useful for two different sectors, i.e. disaster response/human aid organizations and (re)insurance industry[25]. The demands of both on ELE studies are completely different. While (re)insurance companies are interested foremost in the direct and indirect economic losses caused by an earthquake (i.e. direct physical damage to buildings and infrastructure components, damaged contents, loss of function/disruption of production, loss of revenue and market share of businesses, etc.), disaster response organizations are more interested in the human losses and social consequences such as numbers of casualties (deaths and injured people), numbers of affected buildings or households, numbers of severely damaged buildings and displaced people (shelter estimates). Thereby, the spatial distribution of these estimates is of particular interest in order to better organize disaster response measures and search-and-rescue operations.

Though the demands of these user groups on ELE studies are different, especially in terms of required loss parameters and their spatial resolution, the methodologies to come to the different results are the same as they are both dependent on (physical) damage to buildings and infrastructure components.

As was already indicated in the introduction, earthquake damage and loss assessment is a true multi-disciplinary field that requires the expertise of a number of people with different technical backgrounds. The same applies to potential users and beneficiaries of these studies and the derived results. In order to achieve a mutual understanding of the different professions involved, certain standards and definitions have to be adhered to with respect to terminology, taxonomy and ontology. Another requirement that contributes to better communication among the various disciplines and users is the transparency and openness of all components of an ELE study. This applies to input data,

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[23] Though this term is repeatedly used by many, it is widely known that disasters are clearly not "natural" (Mora, 2009), but man-made.

[24] Partly taken from NORSAR (2009). *GEM Memorandum on GEM1*, September 2009, (Authors: J. Crempien, D.H. Lang, E. Erduran, C.D. Lindholm), 12 pp.

[25] Though the (re)insurance industry may benefit most from ELE studies, their input to improving ELE models is quite low. This is because "the insurance industry's only reliable information relates to insured damage. Very often, the insured damage accounts for only a small part of the overall damage (..)" (Porro and Schraft, 1989).

methodologies, software and unbiased outputs of these studies. Each user (group) should have the opportunity to access this information[26].

Impact of seismic building codes

New construction vs. existing construction

Seismic building regulations, whether these are adopted into a legally binding building code or not, are strongly connected to damage and loss assessment. It is important, however, to distinguish between new and existing construction. For new construction, hazard mitigation is embedded in the process of earthquake-resistant design (ERD) (Kramer, 1996). Design codes primarily apply to new construction and typically do not include recommendations for the strengthening and rehabilitation of existing structures. The lack of consideration of existing structures in seismic building codes should therefore have a dramatic effect on expected losses during a future seismic event. This is simply because existing structures generally represent the large majority of a building stock likely to undergo a seismic event in a certain period of time and most urban building stock only changes slowly over the course of time. However, in many parts of the developing world, especially where the urban population is growing inexorably along with a boom in the development of new construction, the availability of a proper design code is of greater importance. This is particularly important because new construction has a life expectancy of 50 years or more with a high probability that these buildings will experience severe earthquake shaking in this period of time (Coburn and Spence, 2002).

With respect to existing construction, previous (earthquake) damage or so-called damage progression effects must also be taken into account. Particularly in high seismic areas, most buildings already have undergone previous earthquake shaking and thus may have suffered minor structural damage which may not be visible at first sight. This may affect their dynamic response characteristics and hence damaging behavior during a future seismic event. Lang *et al.* (2011)[27] have investigated the possibility of site-structure resonance for buildings that had already experienced previous earthquake shaking and suffered slight to moderate structural damage.

Quality of seismic design codes

Any building code, not only those which are related to the seismic safety of buildings, is a technical rule which aims to ensure the fulfillment of requirements relating to the "(..) quality, strength, effectiveness, fire resistance, durability and safety (..)" of construction (IBC–2006, ICC, 2006). In doing so, codes should reflect recognized practices current at the time of issue, without, however, preventing the progress of knowledge. Especially in the case of seismic building codes, experiences from past earthquakes lead to improvements and further development of the provisions, thus steadily increasing their quality and reliability.

Modern seismic building design codes of various countries tend to converge on issues of design methodology and the state-of-the-art. However, significant differences exist in

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[26] Please refer to chapter *'ELE software and tools'*.

[27] Paper P10: Lang, D.H., Schwarz, J., and Gülkan, P. (2011). Site-structure resonance as a proxy for structural damage, *Earthquake Spectra* **27**(4): 1105–1125.

some of the provisions of various codes. A comparative study of common provisions of some of the major national seismic building codes for RC frame buildings is presented in Khose *et al.* (2012)[28]. The provisions of ASCE 7-05 (2006), Eurocode 8 (EN 1998-1, 2004) as well as those of the New Zealand code (NZS 1170.5, 2004) and the Indian code (IS 1893, 2002), regarding specification of hazard, site classification, design response spectrum, ductility classification, response reduction factors and control of drift have been compared and their cumulative effect on design base shear studied. These codes differ not only in terms of limiting values of various design parameters, but also show significant differences in the process of estimating them. As a result, buildings designed according to different codes will perform differently for a given level of hazard (Khose *et al.,* 2012).

The current generation[29] of seismic design codes is based on force/strength-based design (FBD) criteria and elastic analysis while inelastic energy dissipation is accounted for by a response reduction factor which represents the ductility capacity of the structure and is generally a function of the construction material and the structural system. The concept of performance-based design (PBD; SEAOC, 1999) has not yet been applied for the current code generation. However, the first appearance of displacement spectrum and displacement-based analysis methods (as e.g. in EN 1998-1) indicates that the next generation of seismic codes will probably be fully based upon the concept of PBD.

Scale and resolution of risk studies

Earthquake damage and loss studies can be conducted for any scale and resolution. However, in contrast to seismic hazard studies, risk studies have certain restrictions with respect to the maximum size of the study area under consideration. The majority of ELE studies are of a deterministic character, i.e. scenario-based. The shaking effects of a scenario earthquake will thus always be constricted to a certain region where physical damage is expected. To choose an area that is too large will therefore unnecessarily increase the required inventory data, efforts for data preparation as well as computation time. But more important is the fact that a major component of earthquake risk is (building) exposure. This means that earthquake risk studies are restricted to those areas where physical assets are located, i.e. buildings and infrastructure components, and people are living. In this respect, seismic risk studies significantly differ from seismic hazard studies which solely consider earthquake activity and the expected ground motion estimates likely to occur at any site whether populated or not.

In addition to the total extent (size, scale) of the study area, the study's resolution will be of importance. As mentioned earlier, ELE studies can however be conducted for an entire country, a city or an individual project (house, industrial facility etc.), see **Figure 5**. The scale of the study is directly related to the needed resolution and level of detail of the end results. Needless to say the highest level of resolution would be to consider individual buildings and to predict damage for each and every building available.

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[28] Paper P6: Khose, V.N., Singh, Y., and Lang, D.H. (2012). A comparative study of selected seismic design codes for RC frame buildings, *Earthquake Spectra* **28**(3): 1047–1070.

[29] According to Bisch (2009) this represents the third generation of seismic building codes.

However, this would require inventory databases and computational capacities which are generally not available. On the other extreme, a study area which is too big (e.g. an entire region covering urban and rural inventory settings) will require certain assumptions and simplifications with respect to the inventory database. This means that an individual structure, for example, with all its structural peculiarities may be merged together with other building typologies into a class of buildings that are believed to show, on average, the same damage behavior under earthquake forces. This procedure of course strongly affects the reliability of the derived results for the individual structure. Therefore it can be said that the smaller the study area is, the more customized to the prevalent conditions will the ELE computations will be.

Increasing efforts for setting up the risk model →
← Increasing resolution and level of detail of results
Increasing uncertainty of results →

(a) individual structure (b) city (c) region or country

Figure 5. Different levels of the study area's size. The extent of the study area affects the study's resolution and efforts to make.

Increasing size of the geounits →
← Increasing numbers of geounits
← Increasing efforts for setting up the risk model
← Increasing resolution and level of detail of results
Increasing uncertainty of results →

(a) high resolution: geounits are represented by building blocks (b) medium resolution: geounits are represented by city districts (c) coarse resolution: geounits are represented by city sectors

Figure 6. Different ways to demarcate the geographical units (geounits). The size of the geounits affect the study's resolution and level of effort required (Lang and Aldea, 2011).

Most ELE software tools consider the minimum geographical unit (i.e., geounit, census tract) as the smallest area unit. The spatial extent (size) of these geounits determine the study's level of resolution. In most cases, geounits are related to building blocks or to smaller city districts and damage and loss computations are conducted for aggregated data within each unit. The decision on the size of each geounit and how to demarcate it has to be made considering different variables such as soil conditions, constant surface topography or level of building quality within the demarcated area (socio-economic aspects). The smaller the size of the geounits, the higher will be both the level of detail and the reliability of results for the individual building. However, this will also affect an increased number of geounits which will increase the efforts required to set up the inventory model and to run the computations (**Figure 6)**. From experience, these geounits should be (Lang and Aldea, 2011):

- so many that local variations in damage and loss estimates can be identified and a certain level of detail and resolution is provided,
- so few that their number can be handled during the course of the project.

In a practical situation, the size of the study area will be governed by the respective geographical conditions and how large the area of interest is. The resolution of the study and its results will however be decided by the level of detail of available inventory data or how much effort one is willing to spend while generating an inventory database. The resolution will further depend on the study's initial purpose and the end users of the derived results (strengthening and mitigation studies, emergency response, (re)insurance).

The low resolution of the available inventory database for Bucharest (Romania) was identified to be the major limitation of the ELE study conducted by Lang *et al.* (2012a)[30]. Data for residential occupancy is only provided on the level of six city sectors (geounits). These comparably large geounits prevent a detailed visualization of damage and loss distribution, e.g., the identification of pockets with concentrated damage, which is required by emergency management agencies to allow more targeted search and rescue operations. Instead, predicted estimates of building damage and losses only show small variations between these six geounits, which can be partly attributed to the coarse partitioning of the study area. Thereby variations in building distribution within a single sector are leveled out: higher damage in more vulnerable areas within one sector is neutralized with lower damage in areas with more resilient building stock (Bal *et al.,* 2010).

Though a higher resolution of damage and loss estimates would allow for better emergency planning and disaster recovery actions, the necessary work to achieve this higher resolution should be carefully investigated. Lessons learned from comparative ELE studies based upon inventory databases of different resolutions and levels of detail (Erduran and Lang, 2012[31]) and their impact on final damage and loss estimates, may be of interest when deciding on a database's level of resolution[32].

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[30] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[31] Paper P8: Erduran, E. and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research,* Karachi, Pakistan, Thematic Issue on Earthquakes, 73–86, October 2012.

[32] Please refer to chapters *'Alternative ways of data collection'* and *'Sensitivity of involved components'*.

ELE software and tools

Overview of available tools and their characteristics

The computation of losses of any type that result from the shaking effects of an earthquake basically requires software that is able to process available information on ground motion characteristics, inventory and building fragility. Nowadays, a great deal of ELE software exists that makes use of the different approaches described earlier. Since the loss computations described here are related to the mezo- and macrolevel, the combined use of loss computation software with Geographic Information Systems (GIS) has become common practice. Some existing ELE software is integrated in a GIS, while others are disconnected. Overviews of available ELE software tools and their main characteristics are given in Molina *et al.* (2010)[33], Haldar *et al.* (2013) or Crowley *et al.* (2010). A compiled list of ELE software tools is provided in **Appendix 1**, **Table A1**. Though this table makes no claim to be complete, it gives a fairly good overview of the computational capabilities of these tools and the methodologies and approaches they use.

Openness and open source

Though a lot of software pretend to be 'open', only a few actually are. "Open-source software (OSS) is computer software that is available in source code form: the source code and certain other rights normally reserved for copyright holders are provided under a free software license that permits users to study, change, improve and at times also to distribute the software" (Wikipedia). In this respect the term 'free' means that anyone is *free* to access the software, run the program, change the source code, and/or redistribute the code with or without changes (The GNU project, www.gnu.org). It does not mean that the software is 'free of charge', i.e. freeware. On the other hand, software that is distributed at no charge is often closed-source software (e.g., Adobe Reader). Consequently, the terms 'open source software (free software)' and 'freeware' are not synonymous and describe different types of software. In a study dealing with this issue, Danciu *et al.* (2010) evaluated the licensing status (availability) of seismic hazard software in the course of the GEM (Global Earthquake Model) initiative. The different hazard tools were classified into four groups: proprietary, free-upon-request, freely downloadable, and open-source.

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[33] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

With respect to ELE software, most available tools are at least *free of charge*. The reason for this (fortunate) situation is most likely the fact that most tools stem from university environments, where the development of commercial software is not popular and often legally not possible. In addition, the small number of users would necessitate a high price for such software, which very few users would be able or want to pay.

Irrespective of the price one has to pay to use such software, the 'open-ness' of ELE software further depends on factors that include:

- accessibility (downloadable from the internet, e.g. from www.sourceforge.net, free upon request),
- dependency on other proprietary software,
- availability of (open) documentation (user manual, input files, tutorials etc).

In this respect, an 'Open Risk Rating System (ORRS)' has been proposed by Scawthorn (2008) in order to evaluate the open-ness of a software tool. An Open Risk Score (ORS) is computed which consists of three components pointing to the open-ness of methods, data and tools. Thereby, Scawthorn (2008) explicitly evaluates the grade of protection, the reproducibility by others, and the accessibility (open-ness) of methods, underlying data and tools. The derived score facilitates the comparison of two ELE software tools with respect to its open source characteristics.

Selected ELE software and tools

A thorough and detailed presentation of a large number of ELE tools is provided by Crowley *et al.* (2010) and therefore should be not repeated herein. However, in addition to the own software developments of the author (SELENA and *RISe*), two of the most important developments are briefly presented, i.e., the World Bank's CAPRA software (http://www.ecapra.org/) and GEM's OpenQuake software (http://openquake.org/).

CAPRA – Central American Probabilistic Risk Assessment

The CAPRA software is currently probably the most advanced and wide-spread applied software in terms of natural hazard risk estimation. The CAPRA initiative and its various products originally developed from a joint project between CEPREDENAC, UNISDR and the World Bank in collaboration with the national authorities of Central America[34]. Though it was initially developed for Central America and main regional applications have focused on these countries, it has been distributed to countries all around the globe through Technical Assistance Projects (TAPs).

CAPRA's main product is the open source *CAPRA-GIS* software platform that can be used to perform probabilistic risk analyses for a multitude of natural hazards. *CAPRA-GIS* can be used along with a suite of software modules that are handling different parts of the loss assessment process. The hazard information can be provided by the *CRISIS 2007* software[35] or any other hazard software able to provide the hazard information in the *CAPRA-GIS* data format. All exposure information (i.e. building stock inventory and population) has to be provided in a standard geo-referenced format (shape files, *.SHP).

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[34] http://www.worldbank.org/

[35] http://www.ecapra.org/crisis-2007

The associated exposure module can be used during the process when collecting exposure data as well as to graphically depict it. Basically, any component of the building stock and infrastructure can be included in the loss analysis given that a vulnerability function is available for the respective asset. CAPRA requires a certain type of 'direct' vulnerability functions, which have to represent mean damage probabilities and corresponding variability against a ground motion intensity parameter. Given that the economic value of the respective asset is known, the average loss (and its variability) can be computed by simple multiplication between both parameters. CAPRA's vulnerability module *ERN-Vulnerabilidad* can be used to develop these vulnerability functions by using different methodologies. Even though most methodologies will generate other types of vulnerability functions, *ERN-Vulnerabilidad* can be applied to convert them into the CAPRA format.

OpenQuake

OpenQuake is the name of GEM's[36] web-based platform for earthquake risk computations, which tentatively will be available in 2014. It is currently[37] available as a development release without user interfaces (http://openquake.org/).

The development of OpenQuake started in 2010 after a number of existing earthquake hazard and risk software tools had been evaluated (Danciu *et al.*, 2010; Crowley *et al.*, 2010). It is therefore expected that OpenQuake will be the most advanced and most widely applied ELE software. OpenQuake will be provided as open-source software that will be used in combination with other stand-alone applications, such as OpenSHA (Field *et al.*, 2003). However, currently available information, especially on the risk computation engine, is still incomplete and it is difficult to speculate which features the final software will have.

The SELENA–*RISe* Open Risk Package

A major milestone in the development of ELE software was the first release of FEMA's and NIBS's HAZUS methodology in 1997 (HAZUS®97, FEMA, 1997c). Since then a number of releases and updates of this methodology have been published (e.g. HAZUS®99, FEMA, 1999; HAZUS®MH, FEMA, 2003). Though the HAZUS software comes with a very detailed user manual and additional documentation (e.g. the Advanced Engineering Building Module, FEMA, 2002), its source code is not open and is further built upon an integrated GIS platform that requires ArcGIS (ESRI, 2004) or MapInfo (MapInfo Corp.), which are both proprietary software. In addition, HAZUS is directly integrated with the national and regional databases of building stock and demography data of the United States (FEMA 366, 2001, 2008). This implies that HAZUS is so intimately tailored to U.S. situations that it is very difficult to apply it to other environments or geographical regions (Hansen and Bausch, 2006).

SELENA – The loss computation platform

The basic methodology and structure behind HAZUS initiated numerous other analytical ELE tools that have been developed in subsequent years. One of these tools is SELENA (short for *'Seismic Loss Estimation using a Logic Tree Approach'*) whose development

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[36] Global Earthquake Model, http://www.globalquakemodel.org/

[37] September 2012

started in 2004 under the umbrella of the *International Centre for Geohazards* (ICG)[38] in collaboration between NORSAR and the University of Alicante (Spain). The main idea behind SELENA was to develop an ELE tool that is open to any user-defined input and thus can be applied to any part of the world. Though SELENA is (and always was) provided as open-source software, earlier versions (v1.0 – v4.0; e.g. Molina *et al.* 2009; Molina *et al.* 2010[39]) were coded in MATLAB (The MathWorks, Inc.) thus requiring the user to have a full license of this proprietary software, including a number of MATLAB toolboxes to access the code and to run a risk analysis. In order to make SELENA a tool that is fully independent of any other proprietary or commercial software, it was coded in C in 2009 (version 5.0). The advantage of the C-code version is that it can be either compiled into a stand-alone binary independent of MATLAB and its toolboxes, or into binary (mex/oct) functions which can be run in the free (open-source) MATLAB clone GNU Octave (www.gnu.org). The SELENA software is described in detail in the various technical user manuals that can be accessed through http://selena.sourceforge.net.

In contrast to other ELE software tools (cf. **Table A1**), SELENA is a stand-alone application that is not tied to any particular GIS, adding versatility to the software so that it can be used across operating systems and platforms. In order to make users more comfortable and to make the whole computation process as transparent as possible, all input files required by SELENA and the generated output files are in plain ASCII text format. This allows users to use their favorite GIS for displaying the results.

RISe – Risk Illustrator for SELENA

ELE studies are dependent upon GIS and the illustration of results in the form of maps. From personal experience as well as user feedback it is known that generating suitable maps in various GIS software can be difficult and will always be constrained by a system's abilities. Moreover, due to the vast amount of different input and output data, the process can be very time-consuming. Therefore it was decided to develop *RISe* (Lang *et al.* 2009a; Lang and Gutiérrez C., 2010[40]), a software tool able to convert SELENA input and output files into KML files that can then be used with Google™ Earth freeware to illustrate these files on a satellite or aerial image.

RISe is a user-friendly, open-source software that is intended to be applied in parallel to SELENA in order to assist the user during the different stages of the risk computation process. Since *RISe* is linked to the Google™ Earth visualization, the user automatically takes full advantage of the partly high-resolution satellite images provided by Google™ Earth that can be used, for instance, to demarcate study areas or to overlay risk and loss results. The availability of *RISe* with Google™ Earth is particularly important in situations where other commercial packages do not provide a high-resolution database or for developing countries where many cities and municipalities cannot be displayed on high-resolution base maps other than Google™ Earth satellite images. The characteristics of

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[38] http://www.geohazards.no/

[39] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

[40] Paper P2: Lang, D.H., and Gutiérrez C., F.V. (2010). *RISe* — A Google Earth-based tool to illustrate seismic risk and loss results, Technical note, *Earthquake Spectra* **26**(1): 295–307.

RISe v2.0 and how it can be used in combination with SELENA is described in its technical user manual (Lang *et al.,* 2009a[41]).

Figure 7 illustrates how the two independent tools SELENA and *RISe* are connected. In principle *RISe* serves as an intermediary between SELENA and Google™ Earth to assist the user in the preparation of input files as well as the generation of the KML file input, inventory, and output files. *RISe* is intended for use before, during, and after the core loss computation process with SELENA. However, since *RISe* is provided as open-source software, a user could theoretically customize *RISe* so that it adapts to the file structure of any other ELE software.

Both tools, SELENA and *RISe*, are distributed free of charge under the GNU General Public License (GPL) through www.sourceforge.net.

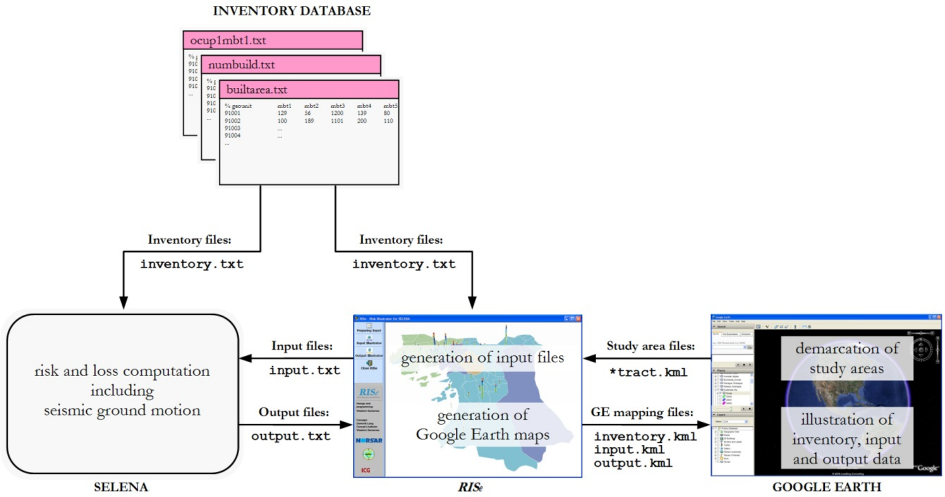

Figure 7. Flow chart illustrating the integration of *RISe* in a seismic risk and loss assessment study. *RISe* can assist the user in generating some of the input files (i.e., soilcenter.txt) as well as generating the Google Earth maps (i.e. KML files) for the inventory, input and output files. (Figure taken from Lang and Gutiérrez C., 2010[42].)

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[41] The user manual can be accessed through http://selena.sourceforge.net.

[42] Paper P2: Lang, D.H., and Gutiérrez C., F.V. (2010). *RISe* — A Google Earth-based tool to illustrate seismic risk and loss results, Technical note, *Earthquake Spectra* **26**(1): 295–307.

Application and practical conduct of analytical ELE studies

This chapter addresses the individual steps which need to be taken when performing analytical damage and loss computations. It reflects experiences and knowledge gained from various research projects in earthquake regions around the world that were conducted by NORSAR in collaboration with a large number of partner institutions and individuals (**Table 2**).

Table 2. Overview of test beds and partners of selected NORSAR earthquake risk collaboration projects between 2007 and 2012.

Project (Reference)	**Test bed**	**Partners**
SAFER (Seismic eArly warning For EuRope) (www.saferproject.net)	Arenella district, Naples (Italy)	University of Naples 'Federico II'
	Bucharest (Romania)	National Institute for Earth Physics (INFP)
GEM-1 (Global Earthquake Model) (www.globalquakemodel.org)	Los Angeles (U.S.)	EUCENTRE (Pavia)
	Zeytinburnu district, Istanbul (Turkey)	KOERI (Istanbul)
RESIS–II (Reducción de Riesgo Sísmico en Guatemala, El Salvador y Nicaragua) †) (www.norsar.no)	Managua (Nicaragua)	INETER, UNI, CIGEO, MTI (all Managua)
	Guatemala City (Guatemala)	CONRED, INSIVUMEH, AGIES, USAC (all Guatemala)
	San Salvador (El Salvador)	UES, UCA, SNET, OPAMSS, Protección Civil (all San Salvador)
	Panamá City (Panamá)	Universidad de Panamá
	Tegucigalpa (Honduras)	UNAH, COPECO (both Tegucigalpa)
	San José (Costa Rica)	OVSICORI (San José)
HIMALAYA (Earthquake Risk Reduction in the Himalayas) (www.eqrisk.info)	Dehradun (India)	IIT Roorkee
	Mussoorie (India)	IIT Roorkee
DACEA (Danube Cross-border system for Earthquakes Alert) (www.infp.ro/news/dacea-project)	Romania-Bulgaria border region	UTCB, INFP (both Bucharest)
Comuidad Valenciana (Southeast Spain) (http://riesgosismico.es/)	Almoradí (Alicante Province)	Universidad de Alicante
	San Vincente del Raspeig (Alicante Province)	

†) More partners from Europe were the *Universidad de Alicante* and the *Universidad Politécnica de Madrid* (both Spain).

Simplifications and assumptions involved

In almost every ELE study a number of simplifications and assumptions have to be made. This is mostly related to the fact that, on the one hand, huge amounts of input and inventory data are required in order to provide reliable risk estimates, which, on the other hand, cannot be handled at the highest resolution due to restrictions of processing power. For analytical ELE studies this applies to:

- damage classification (structural damage extent is categorized into a number of distinct damage states; each damage state represents a certain range of damage)
- building classification (buildings of a common typology that are expected to show the same damageability are classified into the same building class
- resolution of a building inventory database with the smallest entity being the geographical unit (census tract)
- availability of building fragility information (reliable capacity curves and fragility functions are still absent for most building typologies worldwide)
- provision of seismic ground motion estimates
    i. simplified point source/line source assumption without considering the characteristics of the finite fault or rupture directivity effects
    ii. spatial variability of seismic ground motion caused by distance effects and variability of geological subsoil conditions is neglected within the geographical unit)

Damage classification and quantification

Concepts for damage classification

The categorization of building damage into discrete damage classes represents a pragmatic simplification for ELE studies. Of course, actual earthquake damage does not follow certain damage states as it is a continuous function of earthquake demand (Kircher *et al.,* 1997b) and damage states should ideally follow a linear increase of ground shaking (Grünthal, ed., 1998). However, since a continuous scale with practically an infinite number of different damage states is not convenient and does not allow for the quantification of damage, it has become common practice to consider a manageable number of damage classes each covering a certain range of damage extent.

The classification of damage a building suffers under earthquake shaking can be done in a descriptive or empirical-analytical manner (Lang, 2004[43]). Intensity scales, such as EMS–98 (Grünthal, ed., 1998), purely rely on an observation-based description of the damage effects to a certain class of buildings (vulnerability class). EMS–98 defines five discrete damage grades (DG 1 to DG 5). The shortcomings of a purely descriptive concept as it is used for intensity scales like the EMS–98 are given in Lang (2004) and will not be repeated herein.

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[43] The topic '*Classification of structural damage*' has been also addressed in the applicant's first PhD thesis (Lang, 2004).

Analytical ELE studies mostly make use of the concept of building damage states (DS). Each damage state is thereby characterized:

- descriptively, by a qualitative description of the damaging effects to the structure, and/or,
- empirically-analytically, by assigning a damage state threshold[44] to the building's analytical capacity curve.

In general, damage states for both structural and nonstructural components of a building should be separately defined (Kircher *et al.,* 1997b). This is why damage state thresholds are separately provided in terms of spectral displacement S_d and spectral acceleration S_a in order to address structural and nonstructural damage[45], respectively.

Most analytical ELE studies are based upon the classification concept initially provided in the report 'Expected Seismic Performance of Buildings' (EERI, 1994) where four damage states *slight, moderate, extensive* and *complete*[46] were defined. This concept was later adopted for the HAZUS methodology (e.g., HAZUS®97, FEMA 1997c) and is now applied in most existing ELE software tools. For each damage state, HAZUS provides detailed descriptions of the damaging effects to each different building typology. In addition, median values of threshold spectral displacements $\overline{S}_{d,k}$ are provided for each damage state *k*, which are based on drift ratio δ_k (at the threshold of damage state *k*), fraction of the building height α_2 at the location of the first mode displacement, and typical roof level height *H*:

$$\overline{S}_{d,k} = \delta_k \cdot \alpha_2 \cdot H \qquad \text{eq. (1)}$$

In addition to this empirical definition of damage state thresholds, two different sets of criteria are provided in *HAZUS Advanced Engineering Module* (FEMA, 2002; **Table 3**) where damage state medians are related to:

a) the fraction of structural components reaching a certain control point (C, respectively E) on an idealized component load versus deformation curve (capacity curve; **Figure 8**), and

b) the point where 50% of the structural components have reached their yield point (i.e., control point B) on the component load versus deformation curve (**Figure 8**[47]).

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[44] Thresholds for damage states are either defined as a physical parameter (e.g. spectral displacement value) or in terms of structural limit states (e.g. as a factor of yield displacement or ultimate displacement).

[45] Nonstructural components can be either drift- or acceleration-sensitive (Freeman *et al.,* 1985; Kircher *et al.,* 1997b).

[46] Though not explicitly defined as a damage state, the undamaged state of a building (*no damage*, *none*) is considered as well and estimates of the number of undamaged buildings are just as important in ELE.

[47] The two criteria sets are described in detail in *HAZUS Advanced Engineering Module* (FEMA, 2002; section 6.2) as well as by Kumar (2011).

Table 3. Relating component (i.e., element) deformations to average interstory drift ratios of structural damage state medians (after FEMA, 2002).

Damage state	Criteria set no. 1			Criteria set no. 2		
	Fraction	Limit	Factor	Fraction	Limit	Factor
Slight	> 0%	C	1.0	50%	B	1.0
Moderate	≥ 5%	C	1.0	50%	B	1.5
Extensive	≥ 25%	C	1.0	50%	B	4.5
Complete	≥ 50%	E	1.0 - 1.5	50%	B	12

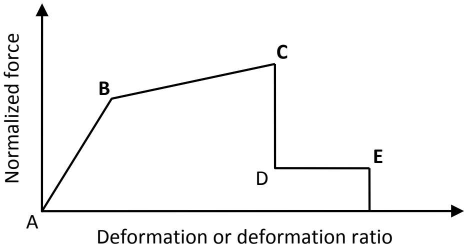

Figure 8. Idealized component load–deformation curve with control points A to E (after *NEHRP Guidelines for Seismic Rehabilitation of Buildings*, FEMA 1997a).

Other damage classifications characterize the thresholds of damage states in terms of capacity curve characteristics, i.e. yield and ultimate spectral displacement, S_{dy} and S_{du}, respectively. These classifications have been developed by Giovinazzi (2005), Barbat *et al.* (2006) and Kappos *et al.* (2006). Their proposed damage classifications and damage state thresholds are listed in **Table 4**, respectively. Another attempt to define damage limit states (light damage, significant damage and collapse) to a point on the capacity curve has been suggested by Borzi *et al.* (2006).

Table 4. Damage state thresholds dependent on capacity curve parameters S_{dy} and S_{du} (Giovinazzi, 2005, Barbat *et al.,* 2006, Kappos *et al.,* 2006).

Damage state	*K*	Median value of threshold spectral displacement $\overline{S}_{d,k}$			*k*	Damage state
		Giovinazzi (2005)	Barbat *et al.* (2006)	Kappos *et al.* (2006)		
Slight	1	$0.7 \cdot S_{dy}$	$0.7 \cdot S_{dy}$	$0.7 \cdot S_{dy}$	1	Slight
Moderate	2	$1.5 \cdot S_{dy}$	$1.0 \cdot S_{dy}$	$1.0 \cdot S_{dy}$	2	Moderate
Extensive	3	$0.5 \cdot (S_{dy} + S_{du})$	$S_{dy} + 0.25 \cdot (S_{du} - S_{dy})$	$2.0 \cdot S_{dy}$	3	Substantial to heavy
Complete [†)]	4	S_{du}	S_{du}	$0.7 \cdot S_{du}$	4	Heavy to very heavy
				S_{du}	5	Collapse

[†)] According to HAZUS–MH, damage state 'complete' covers completely damaged buildings as well as those suffering collapse. The share of buildings of damage state complete suffering collapse is defined by the collapse rate (e.g., 15% for URM buildings).

As indicated earlier, the definition of damage states is a necessary simplification yet at the same time represents a good compromise. It is a compromise because it provides the user with information in sufficient, but not too detailed, resolution. To present building damage in five (or six) different "severity grades" sheds light on various direct and indirect aspects related to a considered scenario, e.g. numbers or the percentage of

a) undamaged buildings *(no damage)*: these are seen as a general indicator of the severity of the event,
b) extensively and completely damaged buildings: these are associated with the number of displaced people and shelter requirements,
c) collapsed buildings: these are directly related to the number of casualties and fatalities.

Quantification of damage

During the conduct of various ELE studies (e.g., Lang *et al.* 2008[48], Lang *et al.* 2012a[49], Lang *et al.* 2012b[50], Sørensen and Lang, submitted[51]) and especially when trying to compare the damage estimates for different scenarios or building typologies, the disaggregation of damage estimates for different damage states may differ significantly, though average damage estimates are of comparable order. In addition, disaggregated damage estimates may not allow for an evaluation of the average damage of a building class. It is tried to illustrate this effect by **Figure 9**, which shows the damage distribution of two different building typologies for the same scenario and test bed. From the damage distribution alone, it is impossible to do a one-to-one comparison of the two sets of damage estimates and thus identify the building typology suffering higher structural damage on average (Lang *et al.,* 2012a). In both cases, a global measure of damage is required where the damage extent of the different damage states is merged into a single variable.

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[48] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

[49] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[50] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

[51] Paper P7: Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

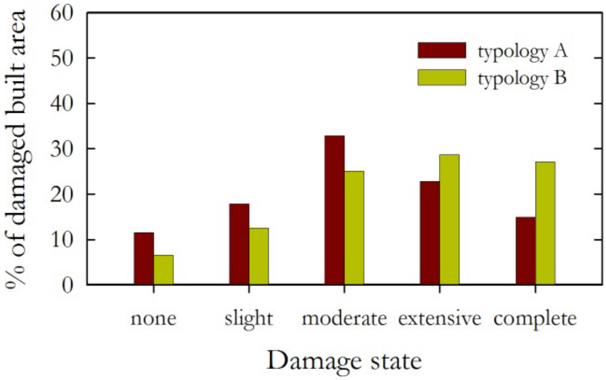

Figure 9. Comparison of damage estimates disaggregated to five damage states for two different building typologies.

Suitable parameters for this global measure are total economic loss or Mean Damage Ratio (MDR). To be able to compute total economic loss caused by the damage to a certain building typology specific reconstruction and repair values are required. The quantification of building damage by economic loss is, however, connected with some difficulties, as reliable reconstruction and repair costs:

- are often difficult to obtain,
- change with time due to effects of inflation or increased construction costs (both for labor and construction materials) in the aftermath of an earthquake (due to increased demand),
- vary because different ways to repair or reconstruct a building are available (Coburn and Spence, 2002),
- will frequently differ from the actual loss since owners try to reconstruct or repair a building in a better, less vulnerable way,
- will largely depend on the decision whether to repair or reconstruct a building (in many cases, the complete reconstruction of a severely damaged building is cheaper than to repair and strengthen it; Coburn and Spence, 2002)
- often do not consider the costs for demolition and debris disposal,
- are largely affected by the considered currency (variation of exchange rate, etc.).

These aspects make the computation of economic loss estimates less reliable than damage parameters such as MDR that are independent of construction values given in absolute values. According to FEMA (2003), MDR is a useful parameter in order to be able to compare the risk estimation for different test beds (e.g. geounits within a city) or between different cities or countries.

An advantage when computing MDRs is that no absolute values for structural repair or reconstruction costs are required, and it is therefore a stable parameter uninfluenced by the factors listed above. To calculate MDR for a certain study area or building typology, damage extent N_k (in terms of damaged building floor area) is required for the different damage states *k* (i.e., *slight*, *moderate*, *extensive*, and *complete*). Further, it requires respective cost ratios DR_k^i for each damage state *k* as well as building typology *i*:

$$MDR^i = \frac{DR_S^i \cdot N_S + DR_M^i \cdot N_M + DR_E^i \cdot N_E + DR_C^i \cdot N_C}{N_T^i} \qquad \text{eq. (2)}$$

where subscripts *S, M, E* and *C* represent the four damage states *slight, moderate, extensive* and *complete,* respectively, N_k^i is the building floor area of building typology *i* suffering damage state *k*, DR_k^i is the ratio of the repair cost for damage state *k* to the reconstruction cost[52], and N_T^i is the total building floor area of building typology *i* including the undamaged building floor area (Bal *et al.,* 2008, Molina *et al.,* 2010[53], Lang *et al.,* 2012a[54], Erduran and Lang, 2012[55]).

However, even though mean damage estimates or total economic loss have their advantages, the availability of damage estimates in disaggregated damage states are of high interest when predictions on social losses (casualties) are concerned. Since lower damage states do only contribute to less severe injuries, it is damage state complete (particularly collapse) that results in the majority of casualties and fatalities.

Damage grades vs. damage states[56]

The fact that different concepts for damage classification exist, which are even based on different numbers of damage severity levels, i.e. five-stage damage grades (DG) vs. four-stage damage states (DS), impede direct comparisons of damage estimates. This becomes obvious when empirical (intensity-based) and analytical ELE studies are compared with each other. Since the descriptive characterization of most damage grades (DG) does not match with damage states (DS), a one-to-one comparison of damage estimates of a certain severity can only be done approximately. Possibilities to resolve this problem include:

- cumulative damage estimates that combine all five DG and four DS, respectively[57],

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[52] DR_k values are strongly dependent on building typology; e.g. for RC buildings in Istanbul (Turkey) DR_k values were chosen 0.16, 0.33, 1.05, and 1.04 for *slight*, *moderate*, *extensive* and *complete* damage states, respectively (Bal *et al.,* 2008). (Values greater than 100% of the total cost of the buildings are often to be used for the *extensive* and *complete* damage states, since repair costs for these damage states include not only the reconstruction cost but also costs for the demolition and removal of debris.) Other studies, e.g. for Bucharest (Romania, Lang *et al.,* 2012a) use individual DR_k values for each building typology.

[53] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

[54] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[55] Paper P8: Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, NED University Journal of Research, Karachi (Pakistan), Thematic Issue on Earthquakes, 73–86, October 2012.

[56] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

- estimates of undamaged building mass,
- estimates of combined DGs with a single DS that address the same type of damage.

The latter solution was tested by Lang et al. (2012b)[58] who compared EMS-98 damage grades DG 4 (very heavy) and DG 5 (destruction) with HAZUS DS 'complete'. According to HAZUS-MH (FEMA, 2003), approximately 15%[59] of the total floor area of unreinforced masonry buildings (URM) suffering complete damage is expected to collapse. It follows from this that 85% of DS 'complete' can be compared with DG 4, while the remaining 15% of DS 'complete' are then compared with DG 5. The corresponding damage estimates of an empirical (intensity-based) and analytical ELE studies for the city of Dehradun, a test bed located in the Himalayan state Uttarakhand (northern India), are given in **Table 5**.

Table 5. Comparison of predicted damage derived with empirical approaches (MSK–EMS estimates, PSI estimates) and the analytical approach. Numbers represent damaged building floor areas in square meters. (Table taken from Lang *et al.*, 2012b.)

Intensity-based scenarios (Prasad *et al.,* 2009):	Total damage area DG 4 + DG 5	DG 4 (very heavy damage)	DG 5 (destruction)	Observed collapse rate
MSK–EMS upper-bound estimates	689,106 m^2	620,382 m^2	68,724 m^2	10%
MSK–EMS lower-bound estimates	395,614 m^2	360,289 m^2	35,325 m^2	9%
PSI estimates	674,086 m^2	499,566 m^2	174,520 m^2	26%

Analytical scenarios:	Total damage area DS Complete	85% of DS Complete	15% of DS Complete	Assumed collapse rate
M 5.6 – R_e = 5 *km*	2,205,397 m^2	1,874,587 m^2	330,810 m^2	15%
M 6.0 – R_e = 10 *km*	1,938,707 m^2	1,647,901 m^2	290,806 m^2	15%
M 6.4 – R_e = 15 *km*	1,725,235 m^2	1,466,450 m^2	258,785 m^2	15%
M 6.7 – R_e = 20 *km*	1,509,810 m^2	1,283,339 m^2	226,471 m^2	15%
M 7.0 – R_e = 30 *km*	1,027,935 m^2	873,745 m^2	154,190 m^2	15%
M 7.6 – R_e = 50 *km*	866,838 m^2	736,813 m^2	130,025 m^2	15%

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[57] To compare cumulative damage estimates could be substituted by estimates of total economic loss or casualty numbers as these also combine the single effects of each damage severity level on the total loss.

[58] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

[59] Collapse rates are dependent on building typology. The identification of the share of completely damaged buildings that suffer collapse is necessary to better estimate casualty numbers (since especially death estimates are steered by building collapse).

Building classification schemes

The division of a considered building stock into distinct classes of buildings is a major step that should be done at the very beginning of any ELE study. The demand to define building classes in ELE studies stems from the impossibility of considering each building with its individual structural (and non-structural) peculiarities for an area or region with hundreds, often thousands of individual buildings. The grouping of buildings into a certain number of building classes thereby allows a more manageable and efficient study.

The main purpose of any building classification is to group buildings or building typologies that show comparable overall performance during earthquake shaking, i.e. that demonstrate similar vulnerability. The building classification to be applied in any study will, however, not only be dependent on those parameters affecting structural vulnerability but also on the extent and level of detail of data available (Coburn and Spence, 2002). Particularly when one is required to use an existing building stock inventory (with predetermined and often limited data) instead of being able to generate a customized building stock inventory, the set-up of a detailed building classification scheme is difficult to accomplish[60].

According to many, if not most authors, the main parameter influencing structural vulnerability is the structural system which is a combination of the construction materials used and the primary load-bearing structure. Secondarily, parameters such as overall building height[61], level of code design and period of construction can have a strong impact on building vulnerability and are thus used as further classification criteria.

An alternative method to classifying buildings is used in intensity scales (such as MSK or EMS) where buildings are categorized into vulnerability classes[62]. Vulnerability classes are assigned primarily according to the main construction material and then refined according to structural peculiarities, construction type (or in case of the EMS: level of ERD)[63]. This concept, understandably, represents a major simplification and comes with a number of difficulties, including:

1. Building height is not addressed. This especially applies to engineered building typologies such as RC or steel, where all height ranges are common and height has a major effect on vulnerability. This leads to the fact that corresponding DPMs represent mean damage estimates for each VC over all height ranges, which can be regarded as a bad solution as it is associated with significant uncertainties.

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[60] The challenges involved with building stock inventory databases are elucidated in detail in the subsequent chapter *'Availability and collection of inventory data'*.

[61] Overall building height is often represented by number of stories or height range. The latter distinguishing between low-, mid- and high-rise buildings that are of, e.g., 1–3, 4–6, and 7+ stories, respectively.

[62] The three MSK vulnerability classes A–C were basically adopted by EMS and address adobe/rubble stone masonry (A), brick masonry (B) and reinforced concrete (C) buildings. EMS expands to vulnerability classes D–F in order to be able to address improved levels of earthquake resistant design (ERD), other work materials (steel, timber) or more recent construction typologies (i.e. reinforced/confined masonry).

[63] ERD - earthquake resistant design.

2. The concept of vulnerability classes principally allows that buildings of completely different construction typologies are assigned the same vulnerability class, hence sharing the same DPM and expecting to demonstrate the same damage extent.

Table 6. Overview of major building classification schemes.

Name	Regional applicability	No. of typology classes	Classification criteria			Reference
			(Wall) construction material	Load-bearing structure	Height range	
PAGER	Global	81 typologies over 9 material classes	✓	✓	✓	Jaiswal and Wald (2008) †)
WHE ‡)	Global	45 subtypes over 14 load-bearing typologies	✓	✓	×	www.world-housing.net
UN–Habitat	Global	20 wall type classes	✓	×	×	UN Habitat (2007)
RISK–UE	Europe	65 typologies over 23 building classes	✓	✓	✓	Lungu *et al.* (2001); Milutinovic and Trendafiloski (2003)
HAZUS–MH	U.S.	36 model building types over 15 building classes	✓	✓	✓	FEMA (2003)
PSI	Global	worldwide typologies	✓	✓	×	Spence *et al.* (1998)
RESIS–II	Central America	24 typologies	✓	✓	✓	Lang *et al.* (2009b)
HIMALAYA	India	34 typologies over 12 wall/framing types	✓	✓	✓	Haldar *et al.* (2013) #)
SAFER	Bucharest	31 typologies over 7 wall/framing types	✓	✓	✓	Lang *et al.* (2012a)[64]
DACEA	Romania	8 typologies over 4 material classes	✓	✓	✓	Lang and Aldea (2011), Erduran *et al.* (2012) §)
CENTRAL ASIA-II	Central Asia	17 typologies over 4 material classes	✓	✓	✓	Lang *et al.* (2012)

†) See also http://pager.world-housing.net.

‡) The purpose of this classification scheme provided by the World Housing Encyclopedia (WHE) is to allow contributors/users an easier categorization of housing typologies.

#) Based upon the classification schemes in Prasad *et al.* (2009) and Lang *et al.* (2012b).

§) Based upon the RISK–UE classification scheme (Lungu *et al.,* 2001).

For analytical ELE studies, building typology classes (or model building types) are applied which are precisely described in terms of construction typology, height (range), level of code design and/or period of construction. The building classification scheme should preferably cover all types of conventional buildings that are available and that are representative for the target area. In doing so, local experts such as structural engineers or architects have to be consulted in order to identify the local construction typologies and to identify their major characteristics (Lang and Aldea, 2011). It is advisable to build

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[64] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

upon existing building classification schemes covering global or regional building typologies in order to avoid misinterpretations particularly with respect to taxonomy and the unambiguous characterization of building typologies, construction materials and methods. The most widely-used classification schemes for either global or regional (e.g. Europe) construction typologies are listed in **Table 6** along with the different classification criteria.

Customized classification schemes for investigated test beds

Table 6 also lists several customized classification schemes that have been either developed or compiled during recent and ongoing ELE studies in worldwide earthquake regions. As can be seen, these studies only partially applied existing classification schemes. Reasons for this include the following:

1. The building inventory database already includes a certain building typology classification, e.g. the building census for Romania (Marmureanu, 2007). Based on the given information on the structural characteristics, some building typologies cannot be clearly assigned to the building typology classes of any of the global/regional classification schemes.
2. The information on local construction typologies is of exceptional detail so that none of the global/regional classification schemes can account for. An example is the building classification scheme for (northern) India, where unreinforced masonry buildings are distinguished according to mortar type and roofing/flooring type.
3. The study area consists of building typologies that are not covered by any of the global/regional classification schemes. This may often be the case in rural areas where traditional (vernacular) building typologies of locally available materials and/or construction expertise are prevalent.

Availability and collection of inventory data

In the ELE context, the term ‘inventory’ basically implies a variety of information on the physical assets (i.e., buildings, infrastructure facilities, contents etc.) of a study area and its inhabitants. An inventory database, at best, should include geo-referenced information on each building’s geographical location, structural information that allows a clear designation of each building’s typology class (see previous chapter), as well as socioeconomic information (value, replacement and repair costs, occupancy pattern, occupancy rates etc.). The latter type of information is primarily required to compute economic loss estimates and casualty numbers directly caused by the respective structural damage.

The collection of inventory data and the compilation of an inventory database may be the most cumbersome and time-consuming component of any ELE study. Two main cases have to be distinguished (Lang and Aldea, 2011):

- Case 1: No inventory information exists and a database has to be developed
- Case 2: An inventory database (of any type or quality) exists

Both cases have their advantages and disadvantages which are given in **Table 7**. However, irrespective of the existence of a database, additional processing of inventory data cannot be avoided as any ELE software will require a certain standardized (predefined) format for the inventory data.

Table 7. Pros and cons of the two cases whether or not an inventory database is available.

Case 1: Inventory database not available	Case 2: Inventory database available
Can be customized to needs and criteria defined by the users	Information not available in the required format or terminology defined for the study
	Often only residential occupancy covered while excluding business occupancy or other security-relevant facilities (e.g. army, power plants)
	Often address/cadaster information missing because of data privacy protection
Large effort in terms of data collection (e.g. by time-consuming walk-down surveys)	Large efforts in post-processing and often characterized by compromises as certain assumptions have to be made †)
Higher reliability, though (maybe) characterized by large uncertainties due to subjective judgment of the screeners	Lower reliability
Up-to-date (when prepared for the current study)	Often outdated ‡)

†) e.g., instead of the building typology (building class) only wall material (and roof material) are provided; the building typology class can be coarsely estimated through the implementation of logic algorithms (IF wall_type = 1 AND roof_type = 2 AND story_number =1, then building_class = 4).

‡) An available inventory database for a study area is most likely provided by the national population and housing census which is generally taken every 10 years (United Nations, 2008).

The changing environment

In Lang *et al.* (2008)[65], building inventory data (along with soil conditions and population) was considered to be static[66]. However, this was more in comparison with other input information, such as the earthquake source parameters of a scenario earthquake. Otherwise, static inventory data may only apply to certain regions, particularly in the developed world, such as many parts of Europe where population growth has practically come to an end, construction development has come to a standstill and rural-to-urban migration does not exist anymore. In most parts of the world, especially the developing world, any inventory database will be outdated as soon as it is completed. Urban environments all over the developing world are not only growing in size, they are also changing dramatically in composition[67]. But not only are cities changing over time, so are rural environments, which often experience the reverse effect of negative population growth. One of the main explanations for the change of both urban and rural environments simply is rural-to-urban migration (Saunders, 2011).

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[65] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

[66] i.e. slowly changing over time and hence this data can be prepared long before an ELE study is conducted (e.g. in a real-time context).

[67] This circumstance has a severe effect on inventory databases that are often based on the recent national census that is often only conducted every 10 years.

In addition, while cities grow and expand in size, surrounding villages and rural settlements are incorporated into the city, hence becoming "urbanized" (UN–HABITAT, 2008/2009). According to Saunders (2011) these two phenomena, rural-to-urban migration and "urbanization of the village" are the main reasons for our changing environment.

A changing environment with a general increase in population and population density may also affect the vulnerability of a building inventory. Particularly in situations where the demand for a quick construction development is high, the quality of construction may be negatively affected due to time pressure and associated sloppiness.

Alternative ways of data collection

Understandably, the most reliable way to develop an inventory database is by collecting the required information through walk-down surveys. This in combination with a thorough preparation of the survey, including the definition of a suitable building classification scheme and the availability of building footprint maps of the respective study area, will guarantee a successful preparation of a high-quality inventory database. However, this is also the most time-consuming and labor-intensive way to collect data and the benefit should be weighed against the effort required. Alternative ways to generate or compile an inventory database may be considered, including the use of:

- (random) sample surveys: Instead of conducting a walk-down survey of the complete building stock, a smaller number of geounits are investigated that are representative of different socioeconomic occupancy levels. Afterwards, the results are extrapolated to the total number of buildings[68] or occupants in the geounits of the same socioeconomic level. Here, special diligence is required in the selection of representative clusters, as there may be significant variations even between clusters of the same socioeconomic level (Prasad *et al.*, 2009[69]).
- proxy data: Towards the development of a global building inventory database, the U.S. Geological Survey's PAGER project (Jaiswal and Wald, 2008) collected and compiled estimates of the fractions of building types observed in a large number of countries. Percentage estimates of the number of buildings that are categorized according to the PAGER building classification scheme are separately provided for residential and non-residential occupancy as well as for rural and urban building stock. These numbers are often only rough estimates that are based on expert opinion or simply taken from region-specific research studies and that represent averaged estimates of an entire country's building stock composition without any further differentiation. The quality of data and the source(s) are considered by a confidence rating.

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[68] Total number of buildings can be identified through satellite images or other remote sensing techniques.

[69] For generating the building stock inventory database of Dehradun (India), the "stratified random sample survey approach" (Burt and Barber, 1996) was applied. The database was based on walk-down surveys conducted in 47 out of Dehradun's 254 socioeconomic clusters (geounits). These 47 clusters were selected so that each of eight different cluster types would be sufficiently represented (see Paper P5: Lang *et al.*, 2012b).

Erduran and Lang (2012)[70] investigated to what extent the proxy data provided by PAGER are consistent with locally available building stock inventory databases. This was initially[71] done for the three test beds of Managua (Nicaragua), Los Angeles (U.S.), and Zeytinburnu (district of Istanbul, Turkey). A comparison of the percentage distributions of available inventory databases is given in **Figure 10**. Locally available databases from these three test beds are compared with proxy estimates provided by PAGER (Jaiswal and Wald, 2008). In the case of the test bed Managua, a third building typology distribution can be compared that stems from a walk-down survey that was conducted in a smaller district of Managua by NORSAR (Lang *et al.*, 2009b). In each of the three test beds, significant differences in the building stock composition become visible. These differences mainly result from the fact that the local databases are based on the actual building stock of the respective city or district while the PAGER proxy data solely represents average estimates on the (here: urban) building stock of the respective country in general. Other uncertainties may also come from different understanding of the building classification schemes applied.

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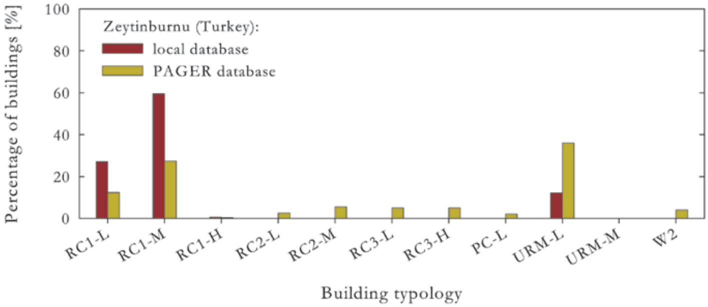
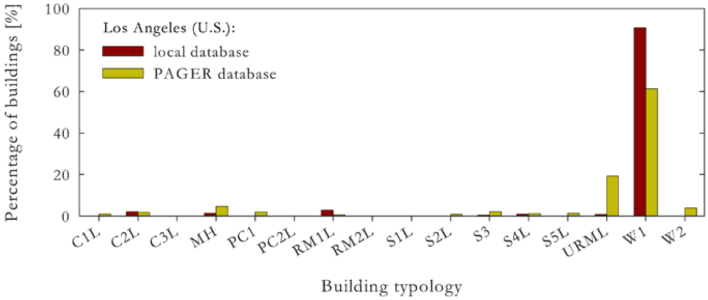
[70] Paper P8: Erduran, E. and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research*, Karachi, Pakistan, Thematic Issue on Earthquakes, 73–86, October 2012.

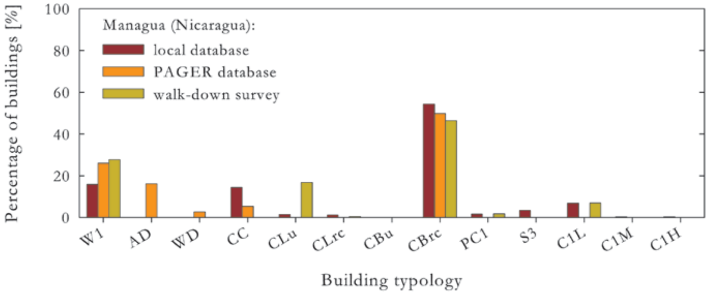
[71] The test bed Managua (Nicaragua) is not included in Paper P8: Erduran and Lang (2012).



(a) test bed Zeytinburnu (Istanbul, Turkey)



(b) test bed Los Angeles (U.S.)



(c) test bed Managua (Nicaragua)

Figure 10. Comparison of percentage building typology distributions that are based on local building stock inventory databases with proxy estimates provided by PAGER (Jaiswal and Wald, 2008) as well as walk-down surveys (in case of Managua). (Figures partly taken from Erduran and Lang, 2012[72].)

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[72] Paper P8: Erduran, E. and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research*, Karachi, Pakistan, Thematic Issue on Earthquakes, 73–86, October 2012.

Number of buildings versus building floor area

The fact that building typologies are different in size (footprint dimensions, story number) inevitably affects the total floor area of these buildings. This may not be of interest when only damage estimates are of interest. However, to compute estimates of economic losses, the available inventory database should include numbers of the floor area since reconstruction values are mostly provided in relative cost estimates, i.e., amount of money (in a given currency) per square meter.

Figure 11 illustrates the building stock composition of the city of Bucharest (Romania) both in terms of numbers of buildings and building floor area (Lang *et al.*, 2012a[73]). It can be seen that each distribution type for the seven building typologies are quite different, demonstrating the importance of collecting data on building floor area during the compilation of the building stock inventory database.

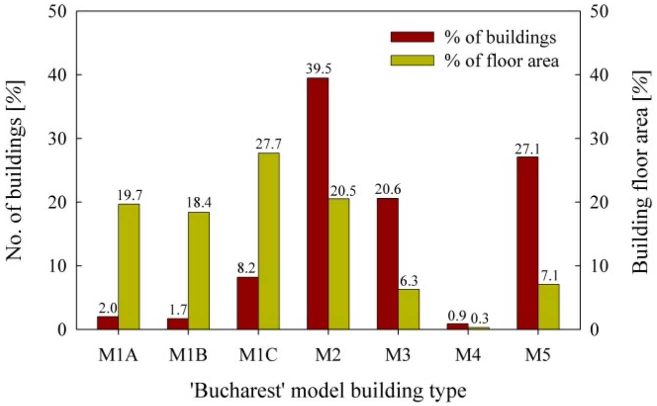

Figure 11. Illustrating the difference between number of buildings and total building floor areas for the building stock of Bucharest (Romania). There is a smaller number of engineered building typologies (e.g. M1A – RC shear walls, M1B – RC large panels, M1C – RC frames) with large plan dimensions and higher story numbers that contribute to larger shares of total building floor area. In contrast, a larger number of non-engineered typologies (e.g. M5 – adobe) with smaller plan dimensions and low story numbers contribute to smaller shares of total building floor area. (Figure taken from Lang *et al.*, 2012a.)

Vulnerability (fragility) information

Availability of fragility functions

As was already discussed earlier, there is a severe lack of reliable capacity curves and fragility functions that are required for the conduct of analytical ELE studies (Lang *et al.*, 2012b[74]). Ideally, these curves should be available for any building typology in any part

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[73] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[74] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

of the world. However, so far only a limited number of these curves are (openly) available. This may lead to certain building typologies being excluded from ELE studies or fragility functions that were originally developed for buildings of the same type but for a different country or region being (erroneously) applied[75].

So far, no central database exists that allows for the collection and open provision of available fragility information (e.g. capacity curves and fragility functions) of worldwide building typologies. It is assumed that reliable curves are produced and collected by numerous individuals and institutions worldwide, but that they never find their way to a larger audience through proper publication. An attempt to tackle this issue was made by Lang and Jaiswal (2011) who proposed to start an initiative to collect, compile and publicize available worldwide fragility information on an open internet platform/portal. This endeavor would have been built on the World Housing Encyclopedia (WHE)[76], an open web-based database on housing construction in earthquake regions around the world. The WHE provides architectural, structural and socio-economic information on different building typologies, though analytical vulnerability information that can be directly used for either analytical or empirical computations is not included.

Realizing the urgent need to develop new and to understand existing capacity curves and fragility functions, the WHE-PAGER project decided to work in this direction under its third phase in 2009[77]. The main purpose of this endeavor was to develop fragility curves for non-HAZUS building typologies, preferably for countries other than the United States. A number of expert groups from all over the world were asked to generate reliable models of construction typologies that are prevalent in the respective country or region, to conduct analytical investigations and to provide capacity curves and fragility functions that can later be utilized to compute more reliable earthquake loss estimates in worldwide earthquake regions[78].

Generation of fragility functions

According to the *HAZUS Advanced Engineering Module* (FEMA, 2002), fragility functions can be defined as "(..) lognormal functions that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given median estimates of spectral response, for example spectral displacement S_d. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking". It is very important to understand that fragility curves are based on capacity curve parameters and hence originate out of these curves.

As already described in a previous chapter, capacity curves represent the nonlinear behavior of a model (here the structural building model) that is subject to a nonlinear

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[75] The use of alternative vulnerability information (here: capacity curves and fragility functions) has been controversially discussed by the author many times. Though this may not be an optimal solution, it should be legitimate to use functions that were originally developed for the same building typology until customized functions are available.

[76] The WHE is a joint project by the Earthquake Engineering Research Institute (EERI) and the International Association for Earthquake Engineering (IAEE); see http://www.world-housing.net/.

[77] http://pager.world-housing.net/

[78] In the course of WHE-PAGER Phase III, Singh *et al.* (2009) developed analytical capacity curves for claybrick masonry buildings in India. The study was later extended with respect to generating corresponding fragility functions (**Paper P9:** Singh *et al.,* 2013; see also subsequent subchapter).

structural analysis method[79]. The generation or development of these capacity curves can be done in various ways:

1. Analytically: Through the generation of a structural model and the conduct of a nonlinear analysis method (as previously described). This procedure is considered to be the most reliable way to develop capacity curves.
2. Empirically/deterministically: Through deterministic relationships between various (expected) engineering design parameters[80] of the respective building. This procedure principally results in the generation of single control points that describe the capacity curve, i.e. yield point and ultimate point.
3. Experimentally: Through full- or small-scale laboratory tests of building (or single wall) samples.
4. Expert opinion: Through judgment and expertise of trained engineering professionals[81].

Once the capacity curve or a set of capacity curves are available, the fragility functions can be developed which "(..) define the probability that the expected global damage of a structure exceeds a given damage state ds_i, as a function of a parameter quantifying the severity of the seismic action" (Barbat *et al.*, 2008). This means that each damage state *ds* has a corresponding fragility function, which is basically described by a mean spectral displacement $S_{d,ds}$ (previously also defined as median values of threshold spectral displacements) and a standard deviation β_{ds}[82]. Again, both parameters can be derived on different ways, partly also dependent on the way how the capacity curves were developed[83].

It should be stressed that most fragility functions will not be developed for an individual building but rather for a certain building typology that comprises buildings of the same structural type (as well as height range and/or code design level) but smaller to moderate variations in structural dimensions (e.g. bay widths, column/beam dimensions, detailing of reinforcement, quality of work materials, etc. In fact, the modeling of a number of buildings of the same typology varying these different parameters first allows the generation of fragility functions as the variations in the different capacity curves (leading to different damage state thresholds for each model) will result in the standard deviation β_{ds} for each damage state. Therefore, fragility functions should not be used as damage predictor for individual buildings or facilities. These functions "are more reliable as predictors of damage for large, rather than small, population groups" (HAZUS-MH; FEMA, 2003).

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[79] Given that the "pushover" method is applied, the capacity curve can also be called 'pushover curve'.

[80] The control points of the capacity curves developed for HAZUS-MH (FEMA, 2003) are based on parameters such as design strength coefficient, elastic natural building period, modal mass coefficient, overstrength factor, ductility ratio etc. (see Advanced Engineering Building Module, FEMA 2002). A similar procedure was applied by Cattari *et al.* (2004) to develop the capacity curve parameters for different types of masonry buildings in Italy.

[81] The capacity curve parameters for HAZUS-MH (FEMA, 2003) are partly based on engineering judgment.

[82] The prerequisite for this is that the fragility functions follow a lognormal probability distribution Φ.

[83] This is already described in subchapter *'Damage classification and quantification'*.

Case study: Fragility functions for masonry building typologies in India [84]

In India, unreinforced brick masonry (URM) construction is the most common type of construction in rural as well as urban areas due to its lower cost, ease of construction, good thermal and sound insulation, and good aesthetics. The construction of these buildings usually takes place without any engineering expertise and most without any consideration of earthquake code provisions.

It has been observed during past earthquakes in India that in the case of masonry buildings with flexible roofs and without ties at the floor/roof level, the failure is generally caused by out-of-plane failure of the walls, while in the case of masonry buildings with rigid flat roofs with adequate bearing on the walls, the out-of-plane failure of the walls is generally avoided and the seismic response is primarily governed by the in-plane action of the walls. The present study focused on the seismic vulnerability of masonry buildings with flat rigid floors/roofs, simulating the in-plane behavior of URM walls using equivalent frame analysis (Magenes and Della Fontana, 1998, Kappos *et al.*, 2006, Pasticier *et al.*, 2008).

The structural models investigated for the present study are representative for Indian housing conditions and were chosen using a statistical procedure out of a set of various (mostly irregular) plan shape geometries (**Figure 12**). Capacity curve parameters were derived using the nonlinear static (pushover) analysis both for one- and two-story models as well as considering different plan shapes and three different mortar types, i.e. cement, lime-surkhi and clay mud.

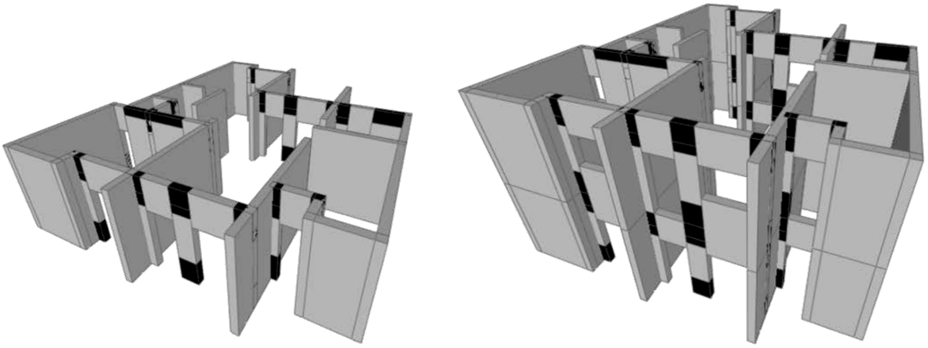

Figure 12. Extruded views of the frame models for one- and two-story masonry buildings.

Figure 13a shows the bilinearized capacity curves of one and two-story buildings for five different plan shapes (Cases 1–5). The effect of the variation in story number is much more predominant than the effect of variation in plan shape. Accordingly, the building classes have been considered based on story number and the effect of variation in plan shape has been considered through variability in capacity curves for a given class. In contrast, **Figure 13b** illustrates the capacity curves for a single plan shape (Case 1) but for different mortar types. It can be seen that mortar type has a more significant effect on the capacity of the building than the plan shape.

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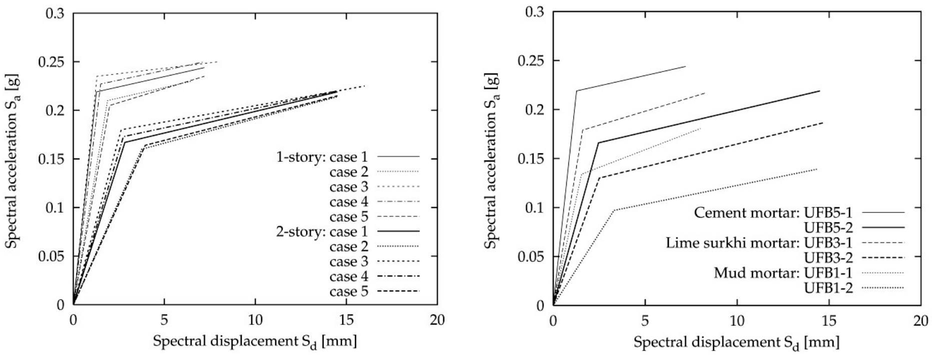
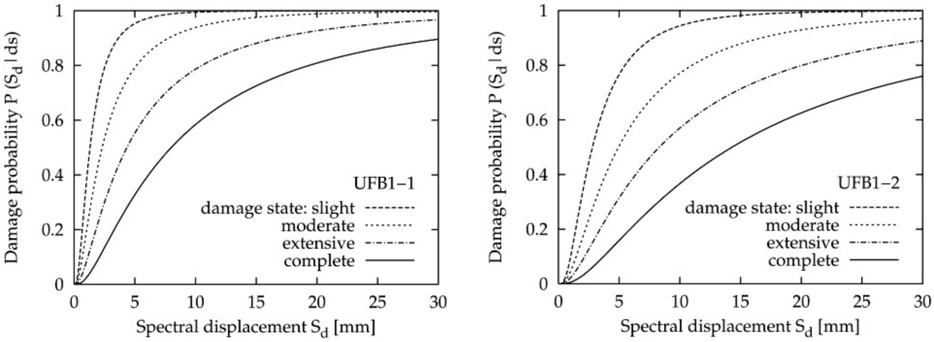
[84] Paper P9: Singh, Y., Lang, D.H., Prasad, JSR, and Deoliya, R. (2013). An analytical study on the seismic vulnerability of masonry buildings in India, *Journal of Earthquake Engineering* **17**: 399–422.



(a) (b)

Figure 13. Bilinearized capacity curves for (a) one and two story masonry buildings with 1:6 cement-sand mortar for the five different plan shapes (Cases 1 – 5), and for (b) building model of Case 1 and various types of mortar.

The parameters of the corresponding fragility curves (i.e., median spectral displacement $S_{d,ds}$ and standard deviation β_{ds} for each damage state ds) were derived in various ways. Median spectral displacements were analytically identified from the results of the structural analyses while values for standard deviation β_{ds} were chosen from the values provided by HAZUS (*Advanced Engineering Building Module,* FEMA, 2002) through expert opinion. A selection of fragility curves are shown in **Figure 14**.



(a) one story (b) two story

Figure 14. Fragility curves for unreinforced masonry buildings with mud mortar.

Hazard description

As discussed earlier, analytical ELE studies make use of a demand response spectrum to represent the seismic ground motion input. The spectral and amplitude characteristics of the response spectrum are determined by the considered seismic hazard which may include local soil (and site)[85] conditions. The seismic hazard is basically represented by peak ground acceleration (PGA) and/or spectral acceleration values at different periods *T*. Different ways exist to model the seismic hazard and hence to derive these input parameters for ELE studies. A nice overview of these different descriptions of seismic hazard and their potential risk outputs was given by Crowley *et al.* (2010), see **Table 8**.

Table 8. Available hazard descriptions and corresponding risk outputs (taken from Crowley *et al.*, 2010).

Seismic hazard description	Risk output
Deterministic events, maps of ground shaking	Damage/loss maps (i.e. spatial distribution of damage and/or loss) that are conditional on a given event (earthquake) occurring
Hazard maps	Damage/loss maps that are conditional on the hazard with a given return period
Hazard curves	Single asset "loss curves" (better known as loss exceedance curves) and damage/loss for a given probability of exceedance/return period
Probabilistic events-based ground-motion fields	Multiple asset (aggregate) loss curves and aggregate damage/loss maps with a given probability of exceedance/return period

Though seismic hazard can be described in different ways, the majority of ELE studies are deterministic. In doing so, various techniques exist in order to provide ground motion estimates at the site of interest, including:

a) considering a single earthquake event with a given location and magnitude and computing ground motion values by using suitable ground-motion prediction equations (GMPE),

b) similar to a) but considering a series of earthquakes with varying source and/or site parameters (i.e. magnitude, focal depth and distance),

c) directly taking the ground motion estimates from empirical or probabilistic ground motion shake maps[86],

d) considering ground motion values that were identified at (nearby) seismic recording instruments (usually strong motion accelerometers)[87].

The main benefit of deterministic scenarios may consist in the fact that it is a tangible way to derive the expected losses for a certain event and to visualize how these losses change if the source or site parameters vary. In contrast to that, probabilistic-based ELE studies are generally more abstract and one may not be able to directly see a direct connection between the hazard input and loss output. While probabilistic studies or studies that are based on hazard curves for a certain probability of exceedance (return period) are useful to provide loss estimates for different types of assets and hence could be of special interest for the insurance industry, deterministic studies may be helpful for

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[85] In addition to soil amplification effects, other site-related effects (e.g., topographic effects) may play a role.

[86] This deterministic method is often mistakenly considered to be probabilistic.

[87] The use of real ground motion data that was recorded at nearby recording stations provides the basis for real- or near-real-time loss assessment (see subsequent subchapter *'(Near) real-time damage estimation'*).

emergency planning or post-earthquake rapid loss assessment (Crowley *et al.*, 2010) where loss estimates can be used to better coordinate the aftermath of an earthquake.

Defining a single deterministic event is the simplest and most applied way to conduct ELE studies. In many cases, the source parameters of the event are chosen so as to repeat a historical event, to consider a best- and worst-case scenario, or to produce ground motion values that are equivalent to what is predicted in a seismic code or zoning map.

The repeat of a historical event and its entanglements is described by Lang *et al.* (2012a)[88] who define deterministic earthquake scenarios that are potentially generated by the Vrancea seismic zone and their effects to the city of Bucharest (Romania). The source parameters of these scenarios are modeled considering the major damaging events in the past century. In this study, the authors refrained from repeating a single historical event, such as the 1977 Vrancea earthquake (M_w 7.4; Mândrescu *et al.*, 2007), because of the large uncertainties in its source parameters[89]. Beyond that, to study a repeat of a historical event that dates back several years or even decades may be questionable in the first place. Any comparison between occurred and (theoretically) predicted damages and losses will be of no meaning since the entire inventory model including building stock and population have changed considerably in the meanwhile[90]. Due to these reasons, Lang *et al.* (2012a) decided instead to model a set of deterministic scenarios with varying source parameters in order to cover the best- and worst-case earthquake scenarios generated by the Vrancea zone for the city of Bucharest. **Table 9** reproduces the upper and lower limits of source parameters considered for the scenario events. Another ELE study based on repeating a historical event was completed by Lang *et al.* (2008)[91] for the Arenella district (Naples, Italy). In this study, a repeat of the 1980 Irpinia earthquake (M_s 6.9) and its effects on the building stock of Arenella were investigated while shifting its epicenter closer to the city of Naples and considering various epicentral distances.[92]

In Lang *et al.* (2012b)[93], deterministic events are generated that produce comparable shaking intensities in the study area as those described by the national zoning map and investigated in a previous study by Prasad *et al.* (2009). Using various magnitude-intensity correlation relationships, macroseismic magnitudes were derived for distinct values of epicentral distances R_e between 5 km and 50 km (see **Table 10**). The intensity-

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[88] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[89] The focal parameters (epicentral coordinates, focal depth, and magnitude) of the 1977 event delivered by different agencies show significant variations while the earthquakes was only recorded by one accelerometer station located in Bucharest (Lang *et al.*, 2012a).

[90] This may also be affected by the appearance of other (earthquake) disasters, launch of new building codes, changes in construction practice, political upheaval or societal change.

[91] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

[92] The epicenter of the 1980 Irpinia earthquake was located in a 95 km distance to Naples and did not produce any significant damage to the building stock in the Arenella district. For the ELE study, the epicentral coordinates were relocated and shifted closer to the study area (Lang *et al.*, 2008).

[93] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

based risk studies by Prasad *et al.* (2009) assumed an MSK intensity I = VIII (8.0) for the entire urban area of Dehradun, which corresponds to the maximum intensity assigned for the respective region located in Zone IV according to the Indian code IS 1893 (Part 1): 2002 (BIS, 2002).

Table 9. Distinct estimates of focal parameters for the scenario events. (Table taken from Lang *et al.*, 2012a[94].)

Parameter	Estimate			Comment
	min	med	max	
Epicentral distance *D*, *km*	100	130	160	Ardeleanu *et al.* (2005): "Macroseismic and early instrumental data have shown that the seismicity in the Vrancea zone is dominated by intermediate depth events located in a well defined volume. The epicentral area is confined to about 40×80 km (..)".
Focal depth *h*, *km*	60	100	150	Ardeleanu *et al.* (2005): "Most earthquakes occur at depths between 60 km and 180 km within an almost vertical column (e.g., Radu, 1974; Fuchs *et al.,* 1979; Oncescu *et al.,* 1999)."
Magnitude	*M* 7.0	*M* 7.5	*M* 8.0	Mârza *et al.* (1991), Lungu *et al.* (1999): "(..) maximum magnitude for the Vrancea zone was accepted to be M = 8.0 (..)"

Table 10. Derivation of macroseismic magnitudes corresponding to MSK intensity *I* = VIII (8.0) using available magnitude-intensity correlations with a focal depth *h* = 10 km. (Table taken from Lang *et al.*, 2012b.)

Intensity I	VIII (8.0)					
Epicentral distance R_n	5 *km*	10 *km*	15 *km*	20 *km*	30 *km*	50 *km*
Sponheuer (1962) †)	*M* 5.26	*M* 5.74	*M* 6.02	*M* 6.22	*M* 6.52	*M* 6.90
Ahorner (1983) †)	*M* 5.42	*M* 6.03	*M* 6.39	*M* 6.65	*M* 7.03	*M* 7.51
Sørensen *et al.* (2009) ‡)	*M* 5.92	*M* 6.22	*M* 6.54	*M* 6.83	*M* 7.32	*M* 8.04
Bakun and Wentworth (1997) #)	*M* 5.61	*M* 6.43	*M* 6.67	*M* 7.09	*M* 7.69	*M* 8.44
Atkinson and Wald (2007) §)	*M* 5.88	*M* 6.07	*M* 6.27	*M* 6.46	*M* 6.77	*M* 7.22
Decided magnitude *M*	*M* 5.6	*M* 6.0	*M* 6.4	*M* 6.7	*M* 7.0	*M* 7.6

†) With absorption coefficient $\alpha = 0.0025$.

‡) Based on Equation 14 for epicentral distance (R_{epi}).

#) Based on Equation 4 and Equation 6 using logarithmic distance term for epicentral distance (R_{epi}).

§) Based on Equation 1 for epicentral distance (R_{epi}) and coefficients for central and eastern United States (CEUS).

Insufficiencies in traditional deterministic scenarios

Irrespective of the approach applied, most ELE studies are based on certain assumptions and simplifications with respect to providing the seismic hazard and in which way the seismic ground motion is represented. For empirical, purely intensity-based ELE studies,

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[94] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

ground shaking hazard is solely provided by a macroseismic shaking intensity. For ELE studies, this way to provide hazard is especially insufficient in terms of the following aspects:

- Spatial small-scale variations of ground shaking (due to changing geology, site effects) usually are not adequately covered by intensity shaking maps.
- The spectral characteristics of earthquake ground motion cannot (directly) be considered by the parameter intensity, thus avoiding the investigation of e.g. site-structure resonance effects (Lang *et al.,* 2011[95]).
- Any characteristics of the finite earthquake source or features of the rupture process cannot be reflected by intensity.

Due to these reasons, physical ground motion parameters (e.g. spectral accelerations) that would allow analytical ELE computations may be preferable given that adequate information is available. However, the traditional and most applied way to represent ground motion for analytical ELE studies is connected to certain simplifications as well. Subsequently, two of these simplifications generally used for analytical ELE studies are discussed in more detail.

Code design spectrum vs. actual response spectrum

Many ELE software tools (e.g. HAZUS–MH, FEMA, 2003) or procedures (e.g. ATC–40, 1996) use a standardized (design) response spectrum, as provided by seismic buildings codes, to characterize and represent the seismic ground motion. It is expected that the smoothed shape of the design response spectrum approximately follows the shape of an actual response spectrum for the respective earthquake scenario. From a numerical point of view, this procedure considerably shortens and simplifies the procedure to generate the demand spectrum as its shape is solely dependent on PGA and/or distinct spectral acceleration values S_a for one or two periods T [96]. To deterministically generate an actual response spectrum would require the computation of spectral accelerations S_a for a considerable number of periods T (dependent on how detailed the spectrum's resolution shall be). From a technical point of view, it is expected that the consequences of this simplification are negligible as "(..) differences between the shape of an actual spectrum and the standard spectrum tend to be significant only at periods less than 0.3 second and at periods greater than T_{VD}[97], which do not significantly affect the methodology's estimation of damage and loss" (HAZUS–MH; FEMA, 2003). In contrast to that, Erduran and Lindholm (2012) investigated if this rather bold statement is justified or not. They studied damage estimates for six different building typologies prevalent in

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[95] Paper P10: Lang, D.H., Schwarz, J., and Gülkan, P. (2011). Site-structure resonance as a proxy for structural damage, *Earthquake Spectra* **27**(4): 1105–1125.

[96] For example, European code EN 1998-1 (CEN, 2004) stipulates that design spectra are only anchored to PGA, while the American code (e.g. IBC–2006) requires spectral acceleration values S_a at periods $T = 0.2$ and 1.0 seconds in order to construct the design spectra.

[97] T_{VD} is the corner period demarcating the constant velocity (V) from the constant displacement (D) domain of the spectrum. T_{VD} is the reciprocal of corner frequency f_c, which is proportional to the earthquake's stress drop $\Delta\sigma$ and seismic moment M_0. Following Boore (1983) and Joyner and Boore (1988), corner frequency f_c can be estimated as a function of moment magnitude M, i.e. $f_c = 10^{-(M-5)/2}$.

the test bed Managua, Nicaragua (Lang *et al.*, 2009b[98]). In addition to the six building typologies, three different soil types and 2 different GMPEs were investigated by Erduran and Lindholm (2012). The design response spectra of IBC–2006 (ICC, 2006), HAZUS–MH (FEMA, 2003) and EN 1998:1 (Eurocode 8, Type 1; CEN, 2004) using two different GMPEs are compared to the fully predicted response spectra using the very same GMPE. In almost every case, strong differences can be observed between both the generated response spectra and the derived damage estimates for the various building typologies. The differences in damage estimates are dependent on building typology, i.e. range of the building's fundamental period. These differences are large if the differences in the respective period range of response spectra are large and vice versa.

Erduran and Lindholm (2012) conclude that the alternative use of a design response spectrum can lead to both an overestimation but also an underestimation of predicted ground motion and building damage. Given that a design spectrum actually should represent a conservative (envelope type) estimate of a set of realistic response spectra for a site, this observation is of high importance when using design response spectra for ELE studies.

Point/line source assumption vs. finite fault simulation[99]

In contrast to this, more advanced possibilities exist to provide the seismic hazard for analytical ELE studies. Deterministic earthquake scenarios are generally based on a simple fault plane characterized by certain focal parameters (i.e. magnitude, focal depth, strike and dip angle, focal mechanism) combined with a ground-motion prediction equation. These parameters are used to estimate PGA and/or spectral accelerations S_a for discrete periods T dependent on a distance term R.[100] Though this implies a simplified consideration of certain fault plane parameters, the fault plane is more or less reduced to a simple point source or line source. In addition, no effects that are related to directivity can be handled by this procedure.

In order to investigate in which cases this simplified procedure is justified and for which circumstances more elaborate procedures to generate seismic ground motion are required, simulated ground motion accelerograms that consider more realistic parameters of the finite earthquake fault plane and the rupture process are generated. The comparison between this simulated ground motion model and the simplified GMPE-based model is done on the level of ground motion parameters as well as damage and loss estimates. The general procedure applied for the study is schematically indicated in **Figure 15** (Sørensen and Lang, submitted[99]).

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[98] The building stock inventory for the city of Managua was originally compiled by INETER Managua (http://www.ineter.gob.ni/). Based on random sample surveys in different pockets of the city, a building classification scheme was generated by NORSAR (Lang *et al.*, 2009b).

[99] Paper P7: Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

[100] The distance term applied is in principal determined by the ground-motion prediction equation and the distance term used therein. Most widely used are epicentral distance R_{epi}, hypocentral distance R_{hypo}, or 'Joyner–Boore' distance R_{JB} (closest distance to the vertical surface projection of the fault rupture plane, which is approximately equal to the epicentral distance for events of $M < 6$; Joyner and Boore, 1981, 1982).

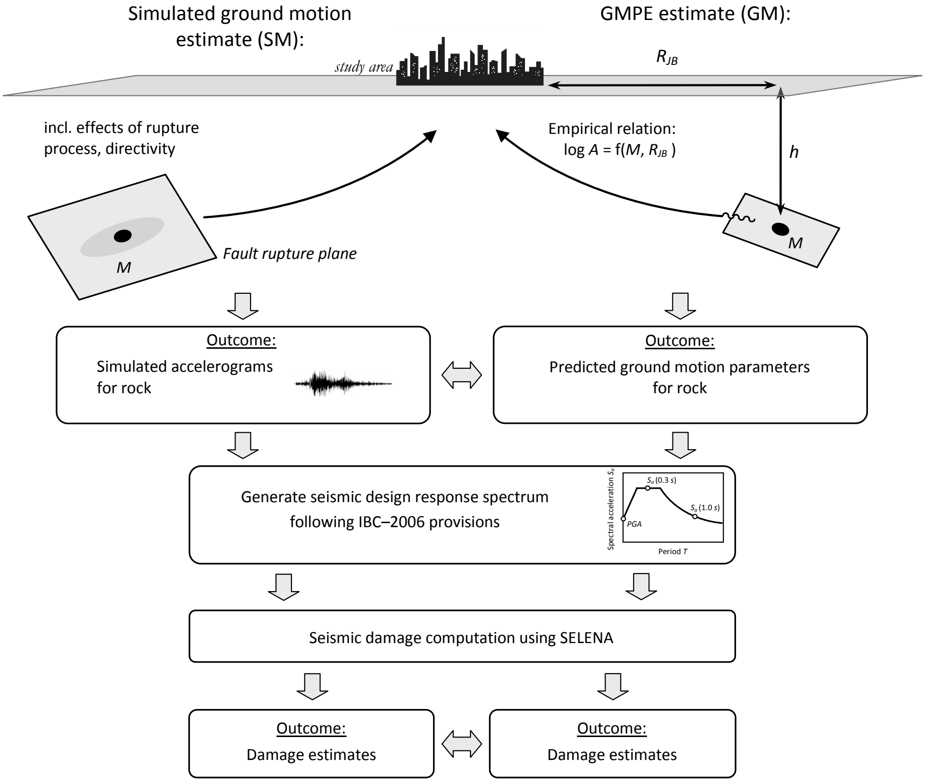

Figure 15. Sketch illustrating the procedure applied for comparative seismic damage and loss computations. (Figure taken from Sørensen and Lang, submitted[99].)

The comparative study should of course be based upon the very same inventory and vulnerability model, while seismic hazard, represented by the ground motion estimates in the study area, is provided in different ways (compare with **Figure 15**):

(1) Standard deterministic scenarios based on a finite fault and conventional GMPEs are defined. The computation of ground motion estimates is taken over by the ELE software SELENA (Molina *et al.*, 2009[101]). Expected values of the finite fault's rupture length and downdip rupture width are based on the relationships of Wells and Coppersmith (1994). The hypocenter is located in the geometrical center point of the fault plane.

(2) Scenarios complying with (1) in terms of magnitude, fault mechanism and fault location, but based on simulated time histories considering the effect of rupture dynamics (e.g., rupture directivity, slip distribution) are defined. To simulate the ground motion accelerograms, the FINSIM (Beresnev and Atkinson, 1998) as well as the EXSIM code (Motazedian and Atkinson, 2005)

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[101] For the GMPE-based computations, SELENA's deterministic analysis type is applied using the provided earthquake parameters and implemented GMPEs that are defined by the user.

are applied[102]. The required ground motion parameters (i.e., PGA and S_a at periods T = 0.3 and 1.0 seconds) are read off the accelerograms and handed over to SELENA[103].

By comparing the derived ground motions of both procedures as well as the predicted damage and loss estimates for the respective test bed, recommendations are derived in which cases more sophisticated ways to model earthquake ground motions are required in order to properly account for effects of the finite fault, rupture process or directivity. The suggested methodology can in principle be applied to any test bed given that a certain level of information on the potential finite fault is available.

Case study: The 1991 Uttarkashi earthquake and the test bed Dehradun, India[104]

To calibrate the procedure and to adjust the parameters used for the simulations, the ground motion parameters recorded by 13 strong motion stations in the region (PESMOS, 2011) are used. In a second step, scenarios of different magnitudes are virtually located at different distances and azimuths to Dehradun (**Figure 16**). Thereby, the importance of source and directivity effects is studied as a function of magnitude, azimuth and distance. With respect to estimates ground motion estimates the following observations are made:

1. As expected, ground motions of GM scenarios generally decrease with increasing distance.
2. The same can be observed with the SM scenarios, though, this decrease is not smooth, and the behavior of ground motion is much more complex than for the GM scenarios. The observations reveal that these effects are associated with radiation pattern and directivity effects, which can cause rather large variations overs short distances.
3. SM scenarios show clear directivity effects leading to asymmetric ground motion contours around the fault plane. In general, this results in higher ground motions values in case that the rupture propagates towards the study area than for those cases where the rupture propagates parallel to or away from the study area.
4. In the near field, GM scenarios provide rather non-conservative ground motion estimates. At large distances, GM estimates tend to become larger than the SM type A estimates. This is most likely connected to the fact that conventional GMPEs are not well constrained for large distances and magnitudes.

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[102] The original submitted manuscript was solely based on applying the FINSIM code to generate the ground motion simulations. The use of FINSIM was later replaced by its updated version EXSIM as FINSIM is only valid for ground motion simulation above 1 Hz and hence will not be able to properly cover directivity effects.

[103] For the simulation-based computations, SELENA's probabilistic analysis type is applied.

[104] Paper P7: Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

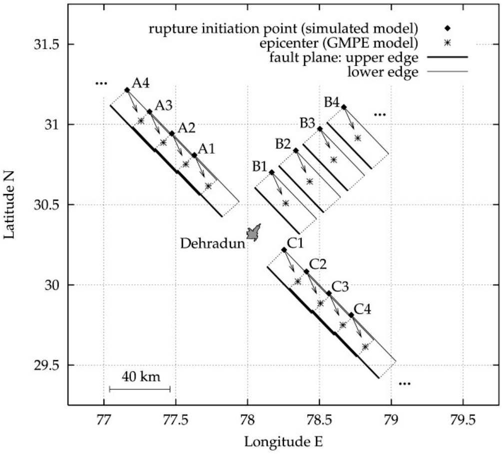

Figure 16. Map indicating the locations of the fault planes (scenarios A1–C8) and their orientation with respect to the study area Dehradun, here for the M 6.8 fault plane. Arrows indicate the direction of rupture propagation. For reasons of clarity, only four of the eight fault planes are illustrated for each scenario A, B and C. (Figure taken from Sørensen and Lang, submitted[105].)

In terms of damage estimates, two parameters are investigated, i.e. mean damage ratio (MDR) and absolute change in mean damage ratio between the SM and the GM scenario, Δ_{MDR}. The damage estimates generally follow the trend that has been earlier observed with ground motion estimates. This means, that for the GM scenarios, MDR values decrease with distance until they become zero. For the SM scenarios, the trend of MDR values goes along with what has been observed for spectral acceleration values at $T = 0.3$ *s*. This can be used as an indicator that structural damage to the building stock in Dehradun is more or less governed by the short-period range, i.e. the part of the (design) response spectrum, which corresponds to the period range of low- to mid-rise brick masonry buildings, the most prevalent building typology in Dehradun (Prasad *et al.*, 2009; Lang *et al.*, 2012b[106]). Considering the amplitude behavior of MDR results for the three scenario types A, B and C, directivity effects can be clearly observed. With respect to the differences in MDR values between the SM and GM scenarios the following observations can be summarized:

1. Scenarios of type A (rupture propagation towards the test bed) lead to higher MDR values up to a certain distance threshold, beyond which similar results are obtained for the GM and SM models. This distance threshold varies with magnitude, but seems to be around 2.5 fault lengths.
2. Similarities between MDR estimates for scenarios of type B (rupture propagation parallel to the test bed) and GMPE model scenarios vary with magnitude. The

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[105] Paper P7: Sørensen, M.B., and Lang, D.H. (submitted). Incorporating simulated ground motion in seismic risk assessment – Application to the Lower Indian Himalayas, *Earthquake Spectra* (submitted).

[106] Paper P5: Lang, D.H., Singh, Y., and Prasad, JSR. (2012b). Comparing empirical and analytical estimates of earthquake loss assessment studies for the city of Dehradun, India, *Earthquake Spectra* **28** (2): 595–619.

greater the magnitude, the larger the difference between SM and GM estimates. This may be used as an indicator that directivity effects become more important with increasing magnitude. Here, differences persist up to about 1.5 fault lengths distance.

3. Difference between MDR estimates for SM scenarios of type C (rupture propagation away from the test bed) and GM scenarios are smallest, and more or less independent of magnitude and distance.

Based on the observations made during this case study, it is strongly recommended to consider earthquake rupture effects in future seismic risk studies, especially when near-field scenarios within distances of 2–2.5 fault lengths of the rupturing fault are studied. This will allow for better-constrained damage and loss estimates in addition to a more comprehensive treatment of the uncertainties associated with the estimated losses. In cases where parameters of the fault and the rupture propagation process are not well constrained, a range of scenarios with varying rupture directivity should be considered, thereby allowing for a more thorough estimation of the range of possible ground motions and losses.

(Near) Real-time damage estimation

Deterministic earthquake scenarios that are based on deterministic events or maps of ground shaking may be applied in real- or near real-time to come up with rapid estimates of expected damage and losses. On a global scale, this type of loss estimation is at best accomplished by the PAGER system[107] (Wald *et al.,* 2008) which provides "fatality and economic loss impact estimates following significant earthquakes worldwide"[108]. While these estimates are represented by total numbers of losses to be expected in the region or country affected by the earthquake, a spatial distribution of the losses may be enabled on a smaller geographical scale. This, however, not only requires a fairly reliable inventory model of the respective region or city but also the spatial distribution of the assets under investigation, i.e., geo-referenced information on the location of each building or infrastructure facility.

In principle, (near) real-time damage and loss estimation was possible not until rapid (automatic and semi-automatic) determination of hypocenters and even fault ruptures following a large earthquake was available. This allows the generation of (near) real-time shake maps illustrating the areal distribution of shaking effects, i.e., intensity, ground acceleration (e.g. USGS ShakeMaps; Wald *et al.*, 1999; Wald *et al.*, 2005). A further step in the same direction is to compute, based on these ground motion shake maps, damage and death-toll estimates (e.g., Wyss, 2005) and to spatially prepare this information on geographic maps that are provided to emergency and civil protection agencies in order to support search and rescue operations (Lang *et al.*, 2008[109]). Among the objectives for

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[107] Other systems for global or regional loss assessment were e.g. developed by WAPMERR (www.wapmerr.org), the United Nations in collaboration with the European Commission (GDACS; www.gdacs.org) or during the SAFER (www.saferproject.net) and NERIES (www.neries-eu.org) projects funded by the European Commission.

[108] See http://earthquake.usgs.gov/earthquakes/pager/.

[109] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

(near) real-time damage scenarios, one of the most important is that after a disastrous earthquake a reasonable damage information overview is difficult to obtain during the first hours or even days. During the first days and weeks following the earthquake, overview maps that indicate relative and absolute damage distribution may be of great importance for rescuing lives and property, and for providing relief (Wyss, 2006). In recent years, near real-time damage and loss assessment systems have been developed and successfully implemented e.g. in Istanbul (Erdik *et al.*, 2003), Taiwan/Yokohama (READY), and Tokyo (Tokyo Gas Co., SUPREME) (see Erdik *et al.*, 2010).

Lang *et al.* (2008)[110] designed a processing scheme for a (near) real-time damage and loss estimation system customized for the analytical ELE software SELENA (Molina *et al.*, 2009) which is schematically illustrated in **Figure 17**. Even though the basic underlying approach of this procedure is different from the empirical approach-based EPEDAT tool (Eguchi *et al.*, 1997), the operation sequences of both show some similarities. Following an earthquake, the seismic network will first detect the information and then sends it to the different national or international seismological observatories where a rapid automatic location process is initiated. Irrespective of the fact that in most cases a more precise determination of the source parameters is conducted with some time delay, the parameters of the first event detection may be used for the (near) real-time process. In case of a larger magnitude event, it may also be necessary to identify the extent of the fault rupture since ground-motion characteristics will strongly depend on the rupture length and the distance between the fault rupture plane and the area of interest. This is naturally more critical for those events that include multiple segment ruptures (Eguchi *et al.*, 1997).

In general, it should be noted that the ground shaking estimation process for a study region will differ, mainly depending on three aspects:

- level of seismicity (high-, intermediate-, and low-seismicity regions);
- population density (densely populated, sparsely populated, or remote regions);
- development status and level of prosperity.

The level of seismicity can indicate whether or not the region has experience with local earthquake disasters and if knowledge of the seismic hazard might be already available. In case of high-seismicity regions, for example, the location of the causative fault (source) may be mapped in detail and its seismic hazard may be so well known that a kind of 'scenario library' can be produced a priori, containing the ground-motion shake maps for the respective city or municipality at risk (**Figure 17**). This scenario library could contain not only shake maps of recent earthquakes but also for events in the past processed in order to allow a comparison with recent events (Wald *et al.*, 1999). In addition, information on damage statistics during past events could be used to calibrate the assumptions for the risk scenario such as geological soil conditions or applied ground-motion prediction relationships. In contrast to that, a scenario library will be difficult to establish for areas with low or intermediate seismicity, where much less is known about the earthquakes that are likely to occur.

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[110] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

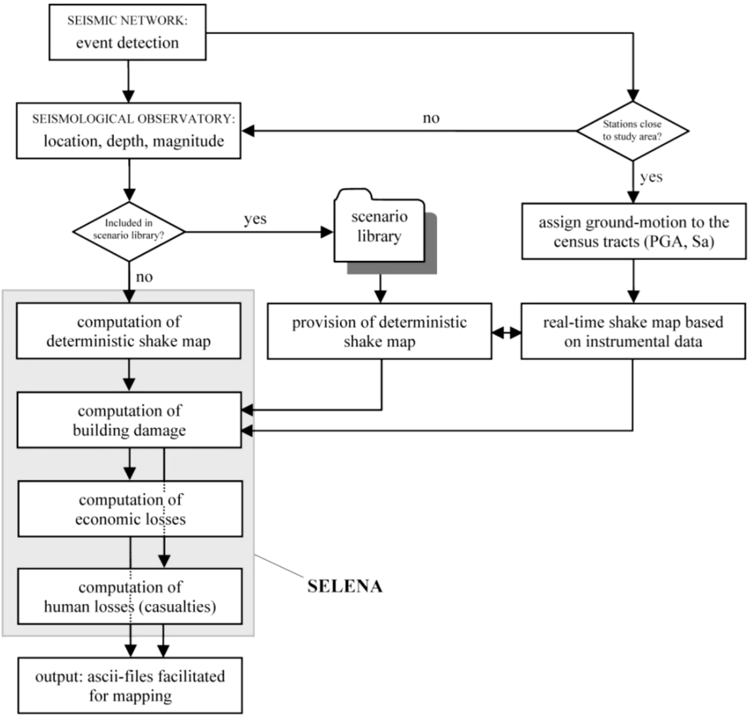

Figure 17. Flowchart of a near real-time damage and loss assessment procedure using the software tool SELENA. The components in the shaded box indicate the computation steps to be conducted within SELENA. (Figure taken from Lang *et al.*, 2008[111].)

Case study: Real-time ELE system for the Romanian–Bulgarian border region[112]

Under the umbrella of the EU-funded DACEA project[113], a real-time loss assessment system was developed that will provide damage and loss estimates immediately after a major event in the region. These estimates are provided in the form of easy-to-grasp damage distribution maps that are intended to assist local emergency management agencies in the coordination of emergency operations as well as search and rescue operations. These maps convey the basic message of earthquake damage and loss studies, and for this reason many hazard or risk studies are exclusively presented in the form of maps. One of the great advantages of such maps is that the results presented in this way may be understandable by many while still maintaining professional quality (Lang *et al.*, 2008).

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[111] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

[112] The final system is presented in Erduran *et al.* (2012). The single steps of the system's development are documented in the individual project reports, i.e., Lang and Aldea (2011), Lang *et al.* (2011), Lang and Erduran (2011), Erduran and Lang (2011a), Erduran and Lang (2011b), Erduran and Lang (2011c).

[113] DACEA – *Danube Cross-border System for Earthquakes Alert* funded by the European Union. The real-time ELE system was collaboratively developed by the Technical University of Civil Engineering (Bucharest, Romania), the National Institute of Physics (INFP, Romania), and NORSAR (Norway).

Figure 18 presents the flowchart of the system that has been in operation at the INFP premises since 2011. The system was designed to be able to integrate the USGS ShakeMap software (Wald *et al.*, 1999; Wald *et al.*, 2005) that was already in operation at INFP and the analytical damage and loss assessment package SELENA–RISe (Molina *et al.*, 2009; Lang et al., 2009a). Both software packages are installed on separate servers, i.e., the *ShakeMap server* and the *Risk server*. The *ShakeMap server* generates and provides the *ShakeMaps* using available ground motion data recorded by the national seismic network and ground-motion prediction equations applicable to the respective region (i.e., Sokolov *et al.*, 2009). Once the ShakeMaps are prepared, they are handed over to the *Risk server* where this hazard input is utilized by SELENA and combined with the regional inventory database and vulnerability model in order to compute the loss estimates. Since the inventory database of the region (Marmureanu, 2007) and the vulnerability model for the regional building typologies are of static character (compare with Lang *et al.*, 2008[114]), they are already in place and may be updated from time to time, e.g. if an updated census or improved vulnerability information on certain building typologies are available.

Finally, geographic maps that depict the derived damage and loss estimates are automatically prepared as soon as the damage assessment is completed by the *Risk* server. Both, the format of these maps and the chosen parameters to represent damage and loss are crucial for the end users, particularly regional emergency management agencies. As a result of several discussions with responsible agencies, it was decided that the risk maps should be prepared in two different (electronic) formats, i.e. portable document format *(PDF)* and the Google Earth *KML*-format. While the electronic maps in *KML*-format can be used to spatially illustrate damage and loss results on Google Maps or Google Earth, hosted on a website, or sent out by email, the maps in *PDF*-format are useful if the maps are to be printed out and faxed to emergency management agencies.

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[114] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

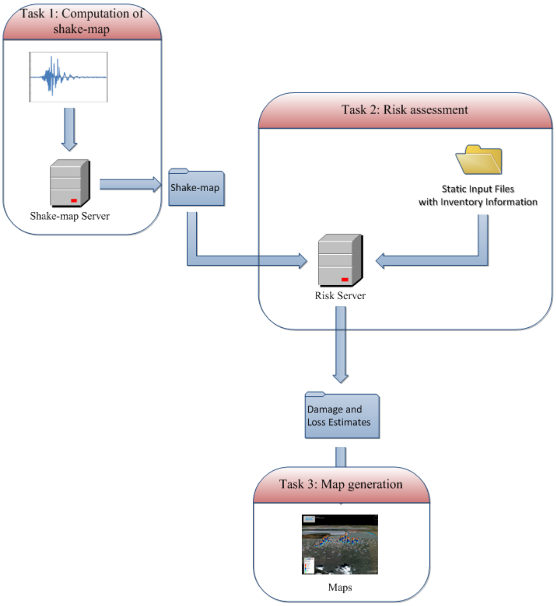

Figure 18. Flowchart of the developed system. (Figure taken from Erduran *et al.*, 2012.)

The system uses an inventory database that is available for entire Romania and which is based on the recent census from the year 1999 (Marmureanu, 2007). This inventory database is the most recent available and, though significant changes have taken place over the past 10 years, it is still regarded as adequate (Lang *et al.*, 2012a[115]). The database covers residential occupancy for the entire country at four different administrative levels, i.e., *comuna*, *municipiu*, *oras*, and *sector* (the latter in case of the capital Bucharest). **Figure 19** illustrates the subdivision of the Romanian test region into these geographical units. This level of resolution is regarded suitable for the current project's purpose, as a further refinement of the spatial detail would lead to a too large number of geographical units as well as input and output information that cannot be managed.

In order to provide maximum information on the severity and quantity of expected damage and loss, different parameters are depicted on the generated maps, i.e., Mean Damage Ratio *(MDR)*[116], ratio of buildings that are expected to be in life-threatening damage states (i.e., *extensive* and *complete*) to the total number of buildings in the respective geounit, as well as the total number of buildings in the respective geounits[117]. The chosen way to illustrate these different parameters on a single map is shown in **Figure 20**.

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[115] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

[116] *MDR* is computed assuming a repair cost for all damage states and calculating the total repair cost as a proportion of the reconstruction cost. See also chapter '*Quantification of damage*'.

[117] The geounit is represented by *commune*.

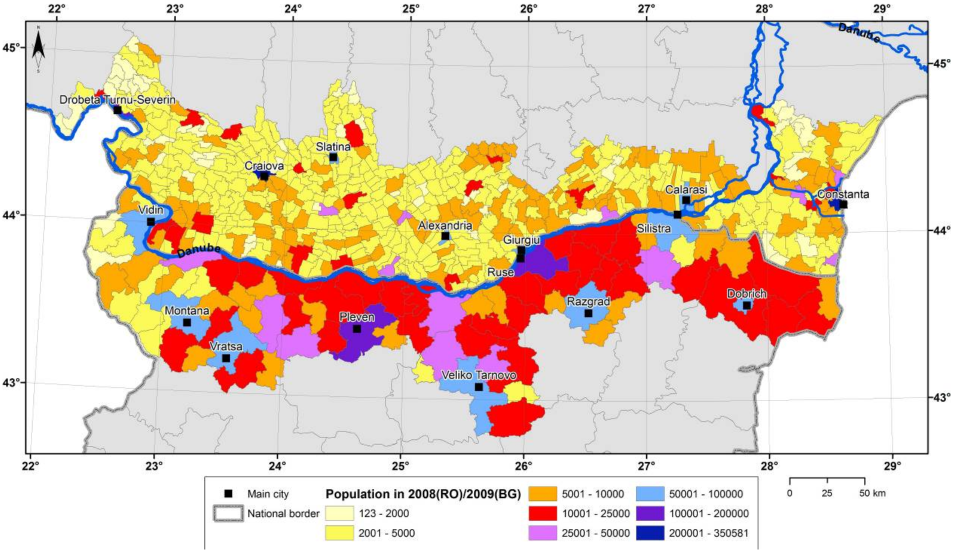

Figure 19. Population numbers in the different communes (Romania) and municipalities (Bulgaria).[118] (Figure taken from Erduran *et al.*, 2012.)

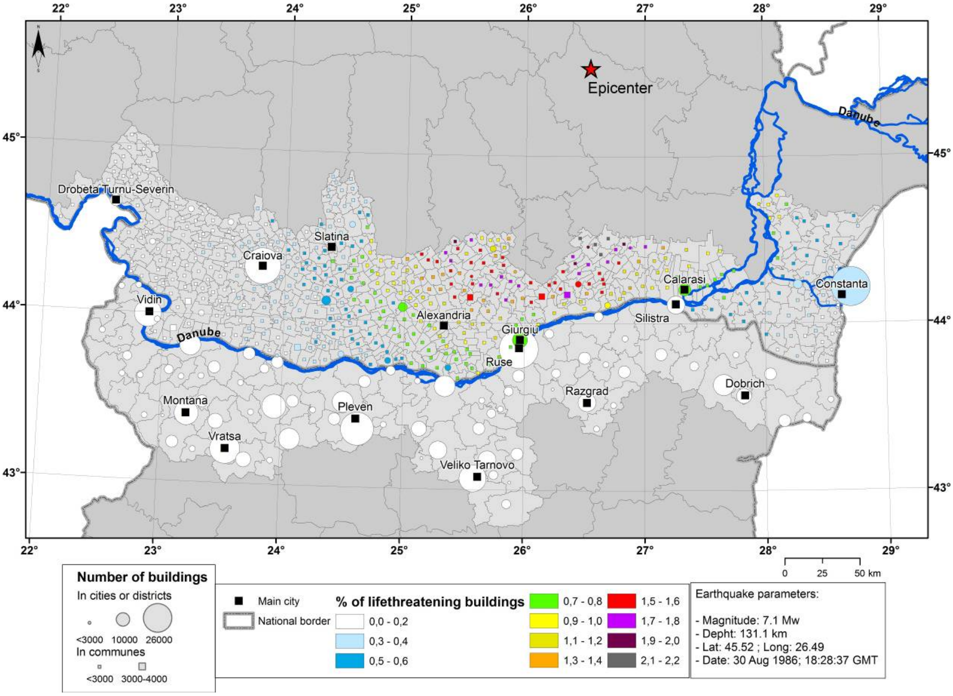

Figure 20. Final presentation of results of the damage assessment. (Figure taken from Erduran *et al.*, 2012.)

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[118] Special thanks to D. Toma-Danila (INFP) for graphical realization.

Uncertainty in ELE studies

In the previous chapter, the range of earthquake damage and loss assessment with its individual components has been reviewed. It should be clear from this review, that the predictions of potential damages and losses to be expected during a certain seismic event are subject to large uncertainties that stem from each component involved and that may stack up for the final damage and loss results.

According to Wikipedia[119], "*uncertainty* applies to predictions of future events, to physical measurements already made, or to the unknown." In the context of ELE, the term *uncertainty* thus refers to a large variety of unknowns starting with the uncertainties connected to the occurrence of a certain earthquake or the exceedance of a certain ground motion level, via the uncertainties connected to the physical (and geometrical) parameters of the building stock inventory to the uncertainties that are connected to the unknown, e.g. how the building stock inventory will change over time.

To come up with appropriate predictions of expected damage and loss, reliable risk models have to be generated, which consider the local peculiarities as well as spatial variations of the three main components: earthquake hazard, exposure and vulnerability of the available assets at risk (Erduran and Lang, 2012[120]). Each one of these three components is associated with an intrinsic uncertainty. As such, the final risk results will also carry a certain level of uncertainty, both of aleatory and epistemic character (Budnitz *et al.*, 1997[121]). Aleatory uncertainties are those that are due to randomness and cannot be improved. The most common example for aleatory uncertainty is probably the intrinsic uncertainty in ground-motion prediction equations (GMPE) that is caused by the randomness of earthquake events and the great dispersion of median ground motion values (Douglas, 2010a, Douglas, 2010b). However, the majority of the uncertainties associated with earthquake risk analysis are epistemic (due to lack of knowledge), which means that they can, in theory, be reduced if sufficient resources are allocated to improve the models (Crowley *et al.*, 2005).

In seismic hazard analysis, a proper treatment of epistemic uncertainty that is related to the use of different ground-motion prediction relations can be achieved through the use

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[119] Wikipedia contributors, 'Uncertainty', Wikipedia, The Free Encyclopedia, 1 September 2012, 17:38 UTC, <http://en.wikipedia.org/wiki/Uncertainty> [accessed 2 September 2012]

[120] Paper P8: Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research,* Karachi (Pakistan), Thematic Issue on Earthquakes, 73–86, October 2012.

[121] In seismic hazard assessment (SHA), the terms aleatory and epistemic uncertainty (e.g. Budnitz *et al.*, 1997) substitute the terms randomness and uncertainty, respectively (Bommer *et al.*, 2005).

of a logic-tree approach (Bommer *et al.*, 2005; Bommer and Scherbaum, 2008). Given that a variety of GMPEs are to be considered, each should be assigned a separate branch of the logic tree with its own weight and own aleatory uncertainty (Douglas *et al.*, 2006). For the first time, Molina and Lindholm (2005) extended the logic-tree computation principle to the HAZUS damage and loss computation methodology defining not only branches to different GMPEs but also to three different types of capacity curves/fragility functions. This expansion of the logic-tree computation scheme was later incorporated into the SELENA software tool (e.g., Molina *et al.*, 2009) allowing the user to consider epistemic uncertainties of any type of input data (**Figure 21**). The diversification of each input type leads to a sudden increase in the number of logic tree branches. This, in turn, leads to an increase in damage and loss computation runs and hence computation time (Molina *et al.*, 2010[122]). The effect of computation time, especially with respect to its application in a real-time context was investigated by Lang *et al.* (2008)[123].

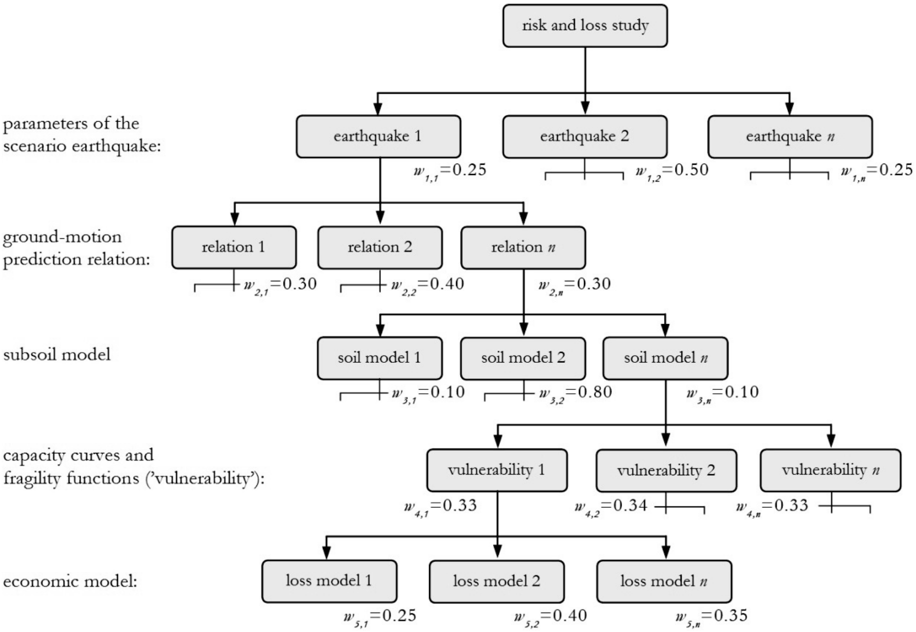

Figure 21. Principle of the logic-tree computation scheme incorporated in the SELENA software. Any component (e.g. soil model 1) of each branch of the logic tree is assigned a certain weight $w_{i,j}$ in order to compute expected values and confidence ranges. (Modified figure taken from Molina *et al.*, 2010.)

As stated earlier in this work, the majority of ELE studies are conducted in a deterministic manner. This effectively means that any aleatory uncertainty (i.e.

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[122] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

[123] Paper P1: Lang, D.H., Molina, S., and Lindholm, C.D. (2008). Towards near-real-time damage estimation using a CSM-based tool for seismic risk assessment, *Journal of Earthquake Engineering* **12**(S2), 199–210.

uncertainty that is associated with ground motion models considered) is ignored in case that only the median values are considered (Bommer *et al.,* 2005). The epistemic uncertainties that are related to incomplete knowledge of any input information required for the ELE study can be handled by a logic tree computation scheme, as illustrated in **Figure 21**. Given that an input parameter is connected to a certain level of uncertainty, a certain number of branches can be defined according to the number of potential choices that are considered meaningful and that can be handled. While the definition of branches is, in most cases, an easy task, the assignment of normalized weights to the different branches is more challenging and probably the most difficult job when setting up the logic tree. Assigned weights shall ideally reflect the confidence in the respective parameter relative to the other choice(s), and "the weights are generally, but not necessarily, centered on a best estimate" (Bommer *et al.,* 2005). To assign the weights, no predetermined analytical procedure is available. The final weights used are based more on subjective opinion of the analyst with respect to the information available for the different choices. For example, Lang *et al.* (2012a)[124] assigned weights for different ground-motion prediction models based on their representativeness to the respective region, i.e., if the GMPEs are based on regional seismicity data and if the GMPE is applicable to the magnitude and distance range considered in the study (**Table 11**).

Table 11. Overview of available ground-motion prediction equations for intermediate-depth earthquakes of the Vrancea zone and assigned weighting factors for the logic tree computation scheme. (Table taken from Lang *et al.*, 2012a.)

Authors (Year)	Database	Magnitude range	Depth range	Distance range	Weight for the logic tree
Marmureanu *et al.* (2006) †)	records of 4 events (1977, 1986, 1990, 1990)	*M* 6.4 – *M* 7.4	60–150 *km*	10–310 *km*	0.08 (eq. (2)) 0.08 (eq. (4)) 0.09 (eq. (17))
Lungu *et al.* (2007) ‡)	records of 3 events (1977, 1986, 1990)	*M* 7.0 – *M* 7.5	91–133 *km*	10–250 *km*	0.25
Sokolov *et al.* (2008)	based on simulations	*M* 5.0 – *M* 8.0	60–160 *km*	1–500 *km*	0.25
Stamatovska (2002)	records of 4 events (1977, 1986, 1990, 1990)	*M* 6.1 – *M* 7.2	89–131 *km*	10–310 *km*	0.25

†) only those equations are applied which depend on hypocentral distance R_h and which are (acc. to the authors themselves) believed to be reliable, i.e., eqs. (2), (4) and (17) of Marmureanu *et al.* (2006)

‡) based on Lungu *et al.* (1997) and Lungu *et al.* (1999)

Sensitivity of individual components

The improvement of ELE models through minimizing or reducing the epistemic uncertainties in the various components is a difficult task. To do that, the model's

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[124] Paper P4: Lang, D.H., Molina, S., Lindholm, C.D., and Balan, S. (2012a). Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania, *Journal of Seismology* **16**(1): 67–88.

sensitivity towards uncertainties in hazard, exposure and vulnerability should be investigated to make a more targeted enhancement of the model (Erduran and Lang, 2012[125]). So far, very few studies have focused on evaluating the sensitivity of earthquake risk models to the associated uncertainties (e.g., Crowley *et al.*, 2005; Karaca, 2004; Molina and Lindholm, 2007).

The sensitivity of ELE models to uncertainties in the three components has been investigated by Erduran and Lang (2012). The results are quantified and evaluated in terms of overall damage estimates, i.e. MDR, for two test beds with differing characteristics in terms of size, building stock composition, code design level and grade of development[126]. With respect to the results for the test bed Los Angeles, U.S. (**Figure 22** and **Figure 23**) the following conclusions can be summarized:

a) Seismic hazard component:
    a. The GMPEs applied do not seem to significantly affect the overall damage estimates.
    b. Damage estimates of different building typologies relative to one another do not seem to be affected by the GMPE used.
    c. However, damage estimates are largely affected by the GMPE's aleatory uncertainty, i.e. whether median, lower or upper bound estimates are considered.

b) Exposure component:
    a. The exposure database shows the least effect on all the output parameters.
    b. Despite the sometimes significant differences between locally available and global (proxy) exposure databases, differences in the estimated damage distribution are minimal, if not negligible[127].
    c. The MDR estimates for individual building typologies are not significantly affected by the exposure database for both test beds.
    d. Though local exposure databases are the most reliable and accurate, global exposure databases, as e.g. provided by PAGER (Jaiswal and Wald, 2008), or those obtained by extrapolation of (random) walk-down surveys provide sufficient accuracy.

c) Vulnerability component:
    a. The vulnerability functions, i.e. capacity curves and fragility functions, have the most significant effect on the earthquake risk models.

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[125] Paper P8: Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research,* Karachi (Pakistan), Thematic Issue on Earthquakes, 73–86, October 2012.

[126] In Erduran and Lang (2012) analysis results for the two test beds Los Angeles (U.S.) and Zeytinburnu (a district of Istanbul, Turkey) are presented. Originally, the study covered a third test bed, i.e. Managua (Nicaragua).

[127] Compare with chapter *'Alternative ways of data collection'* where the differences between the available exposure databases are illustrated.

b. The overall damage distribution of both test beds was significantly influenced by the vulnerability model used in the earthquake risk assessment. Further, the vulnerability functions were also observed to significantly affect the mean damage estimates of each individual building typology relative to the others.

The main conclusion of the above observations is that resources available should be directed towards improving the vulnerability models of prevalent building typologies rather than on optimizing GMPEs or improving exposure databases by more thorough data collection. Especially the models' steadfastness towards changes in the exposure databases that are based on partly different building classification schemes, is one of the most striking observations made in this study.

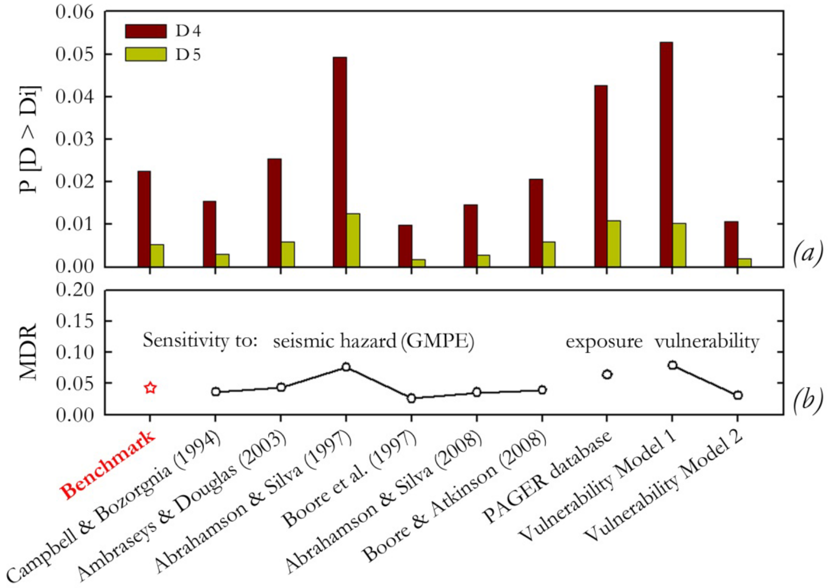

Figure 22. Variation of (a) Probability of exceedance of extensive and complete damage states and (b) MDR in terms of different hazard, exposure and vulnerability models for Los Angeles. (Figure taken from Erduran and Lang, 2012[128].)

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[128] Paper P8: Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research,* Karachi (Pakistan), Thematic Issue on Earthquakes, 73–86, October 2012.

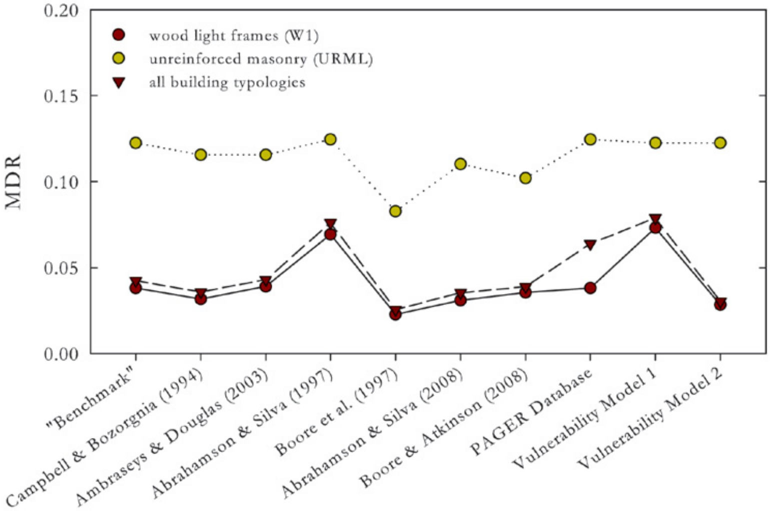

Figure 23. Variation of MDR for prevalent building typologies with different hazard, exposure and vulnerability models for Los Angeles. (Figure taken from Erduran and Lang, 2012[129].)

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[129] Paper P8: Erduran, E., and Lang, D.H. (2012). Sensitivity of earthquake risk models to uncertainties in hazard, exposure and vulnerability parameters, *NED University Journal of Research,* Karachi (Pakistan), Thematic Issue on Earthquakes, 73–86, October 2012.

Concluding remarks

In the work at hand the author has attempted to shed light on various aspects of earthquake damage and loss estimation (ELE), a research field in which the author has worked extensively during the past decade. ELE is a true multi-disciplinary research area that requires technical expertise from many different groups of professionals. There are also many different components in ELE, making it both an interesting research field but, at the same time, a topic that is characterized by a multitude of uncertainties. These uncertainties stem from the various components involved, i.e. seismic hazard and the provision of seismic ground motion, exposure of buildings, infrastructure and population, and the vulnerability of these assets. In some cases, the number of uncertainties may raise legitimate doubts about an ELE study's credibility and the credibility of its final results. These uncertainties further come with a number of simplifications and assumptions in the models and methodologies as discussed in the various chapters. For this reason, the title of this treatise was amended with the phrase *'Predicting the Unpredictable'*.

Of course, ultimately, it will only be a large damaging earthquake that can fully verify or refute a risk model and its chosen methodologies and assumptions (Molina *et al.*, 2010[130]). The calibration of these assumptions against experience and an updated empirical basis will be of great value for future ELE studies. However, the fairly precise prediction of damage and loss may only be one purpose of ELE, which, realistically, may never be achieved. The fact that ELE studies raise awareness and hence create the basis for prevention and mitigation actions is probably of even higher value. Though ELE studies and their results may not be used immediately to reduce existing vulnerabilities, these studies identify the existing weaknesses and shortcomings that may be eliminated in the longer run.

The contributions of the author in this direction are:

- (Co)developing open-source software tools that allow the computation of analytical and empirical loss estimates and the communication of these results to the public.
- (Co)developing appropriate vulnerability information (fragility functions and DPMs) for various building typologies.

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[130] Paper P3: Molina, S., Lang, D.H., and Lindholm, C.D. (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure, *Computers & Geosciences* **36** (2010): 257–269.

- Applying and testing of different ELE methodologies and approaches as well as highlighting their differences and similarities in the framework of comparative studies.
- Identifying the sensitivity of final damage and loss estimates to various parameters.
- Planning and conducting ELE studies in earthquake-affected areas worldwide.

In summary, ELE represents the basis and is one prerequisite for earthquake disaster risk management. The occurrence along with the often unexpectedly large dimension of worldwide earthquakes in the past 15 years or so have demonstrated that one cannot be surprised if “a never seen in history” disaster (Mora, 2010) happens. This applies particularly to some recent events, including the 2010 Haiti earthquake (DesRoches *et al.*, 2011) and the 2011 Tohoku (Japan) earthquake and tsunami. The argument that the large efforts required to set up a risk model are disproportionate to potentially mitigated losses is no longer valid. Rather, it is necessary to continue working in the field of ELE towards improving existing methods as well as developing new approaches and tools in order to minimize or even eliminate some of the uncertainties involved.

Oslo, October 2012

References[131]

Ahorner, L. (1983). Seismicity and neotectonic structural activity of the Rhine Graben system in Central Europe, in: *Seismicity and seismic risk in the offshore North Sea area*, A.R. Ritsema and A. Gürpinar (eds), D. Reidel Publishing Company, Dordrecht, 101–111.

Algermissen, S.T., Rinehart, W.A., Dewey, J., Steinbrugge, K.V., Degenkolb, H.J., Cluff, L.S., McClure, F.E., Gordon, R.F., Scott, S., and Lagorio, H.J. (1972). *A study of earthquake losses in the San Francisco Bay Area: data and analysis,* Washington, D.C.: Office of Emergency Preparedness and National Oceanic and Atmospheric Administration.

Anagnostopoulos, S., Providakis, C., Salvarieschi, P., Athanasopoulos, G., and Bonacina, G. (2008). Seismocare: An efficient GIS tool for scenario-type investigations of seismic risk of existing cities, *Soil Dynamics and Earthquake Engineering* **28**(2): 73–84.

Applied Technology Council (1982). *An investigation of the correlation between earthquake ground motion and building performance, Report No. ATC–10,* Redwood City, CA.

Applied Technology Council (1985). *Earthquake damage evaluation data for California, Report No. ATC–13,* Redwood City, CA.

Applied Technology Council (1996). *Seismic evaluation and retrofit of concrete buildings, Report No. ATC–40,* Redwood City, CA.

Applied Technology Council (2009). *Guidelines for Seismic Performance Assessment of Buildings, Report ATC–58 50% Draft,* April 2009, Redwood City, CA.

Ardeleanu, L., Leydecker, G., Bonjer, K.-P., Busche, H., Kaiser, D., and Schmitt, T. (2005). Probabilistic seismic hazard map for Romania as a basis for a new building code, *Natural Hazards and Earth System Sciences* **5**: 679–684.

Arya, A.S. (2003). *Rapid Visual Screening of Buildings in Various Seismic Zones in India,* Capacity Building Advisor, Technical Report, Government of India-United Nations Development Programme (GOI-UNDP), Disaster Risk Management (DRM) Programme, New Delhi, India.

ASCE 7-05 (2006). *Minimum design loads for buildings and other structures,* American Society of Civil Engineers Reston, Virginia.

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[131] The list of references does not include the author's own papers which are used to corroborate this thesis.

Atkinson, G.M., and Wald, D.J. (2007). "Did You Feel It?" intensity data: A surprisingly good measure of earthquake ground motion, *Seismological Research Letters* **78**(3): 362–368.

Bakun, W.H., and Wentworth, C.M. (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bulletin of the Seismological Society of America* **87**(6): 1502–1521, December 1997.

Bal, I.E., Crowley, H., Pinho, R., and Gülay, G. (2008). Detailed assessment of structural characteristics of Turkish RC building stock for loss assessment models, *Soil Dynamics and Earthquake Engineering* **28**: 914–932.

Bal, I.E., Bommer, J.J., Stafford, P.J., Crowley, H., and Pinho, R. (2010). The influence of geographical resolution of urban exposure data in an earthquake loss model for Istanbul, *Earthquake Spectra* **26**(3): 619–634.

Barbat, A.H., Moya, Y.F., and Canas, J.A. (1996). Damage scenarios simulation for seismic risk assessment in urban zones, *Earthquake Spectra* **12**(3): 371–394.

Barbat, A.H., Pujades, L.G., and Lantada, N. (2006). Performance of buildings under earthquakes in Barcelona, Spain, *Computer-Aided Civil and Infrastructure Engineering* **21**(8): 573–593.

Barbat, A.H., Pujades, L.G., and Lantada, N. (2008). Seismic damage evaluation in urban areas using the capacity spectrum method: Application to Barcelona, *Soil Dynamics and Earthquake Engineering* **28**: 851–865.

Beresnev, I.A., and Atkinson, G.M. (1998). FINSIM – a FORTRAN program for simulating stochastic acceleration time histories from finite faults, *Seismological Research Letters* **69**: 27–32.

Bernardini, A., Gori, R. and Modena, C. (1990). Application of coupled analytical models and experimental knowledge to seismic vulnerability analyses of masonry buildings, in: *Engineering Damage Evaluation and Vulnerability Analysis of Building Structures,* A. Koridze (ed.), Omega Scientific, Oxon, U.K.

Bisch, P. (2009). *Chapter 1, Introduction: Seismic design and Eurocode 8,* in: Seismic design of buildings to Eurocode 8, A. Elghazouli (ed.), Spon Press, 318 pp.

Blume, J.A., Newmark, N.M., and Corning, L.M. (1961). *Design of multi-story reinforced concrete buildings for earthquake motions,* Portland Cement Association, Chicago, U.S.

Borzi, B., Pinho, R., and Crowley, H. (2006). Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings, *Engineering Structures* **30**(3): 804–820.

Bommer, J.J., Scherbaum, F., Bungum, H., Cotton, F., Sabetta, F., and Abrahamson, N. A. (2005). On the use of logic trees for ground-motion prediction equations in seismic hazard analysis, *Bulletin of the Seismological Society of America* **95**(2): 377–389.

Bommer, J. J., and Scherbaum, F. (2008). The use and misuse of logic trees in probabilistic seismic hazard analysis, *Earthquake Spectra* **24**(4): 997–1009.

Boore, D.M. (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, *Bulletin of the Seismological Society of America* **73**: 1865–1894.

Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A., and Morris, P.A. (1997). *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts,* U.S. Nuclear Regulatory Commission Report NUREG/CR-6372.

Bungum, H., and Lang, D.H. (2010). Haiti vil rammes igjen, *aftenposten*, 20 January 2010. http://www.aftenposten.no/fakta/innsikt/article3473823.ece, http://www.norsar.no/pc-70-99-Why-Haiti,-and-what-now.aspx.

Bungum, H., Lang, D.H., Crempien, J., Erduran, E., and Lindholm, C.D. (2010). *Comparative damage assessment for the Zeytinburnu District, Istanbul using SELENA and ELER,* NERIES Report, v1.0, Kjeller (Norway), March 2010, 30 pp.

Burt, J.E., and Barber, G.M. (1996). *Elementary Statistics for Geographers*, Guilford Press, New York, NY.

Calvi, G.M., Pinho, R., Magenes, G., Bommer, J.J., Restrepo-Vélez, L.F. , and Crowley, H. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years, *ISET Journal of Earthquake Technology* **43**(3): 75–104.

Campos Costa, A., Sousa, M., Carvalho, A., and Coelho, E. (2006). Seismic loss scenarios based on hazard disaggregation. Application to the Metropolitan Region of Lisbon, Portugal, in: Oliveira, C.S., Roca, A., and Goula, X. (eds.), *Assessing and Managing Earthquake Risk,* Springer Netherlands, 449–462.

Campos Costa, A., Sousa, M.L., Carvalho, A., and Coelho, E. (2010). Evaluation of seismic risk and mitigation strategies for the existing building stock: application of LNECloss to the metropolitan area of Lisbon, *Bulletin of Earthquake Engineering* **8**: 119–134.

Cattari, S., Curti, E., Giovinazzi, S., Lagomarsino, S., Parodi, S., and Penna, A. (2004). A mechanical model for the vulnerability assessment of masonry buildings in urban areas, *Proceedings of the VI National Congress “L’ingegneria Sismica in Italia”,* Genova, Italy (in Italian).

Coburn, A., and Spence, R. (2002). *Earthquake protection,* Second edition, John Wiley & Sons Ltd., 420 pp.

Cornell, C.A. (1968). Engineering seismic risk analysis, *Bulletin of the Seismological Society of America* **58**(5): 1583–1606.

Cosenza, E., Manfredi, G., Polese, M. and Verderame, G.M. (2005). A multi-level approach to the capacity assessment of existing RC buildings, *Journal of Earthquake Engineering* **9**(1): 1–22.

Crowley, H., Pinho, R., and Bommer, J.J. (2004). A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation, *Bulletin of Earthquake Engineering* **2**: 173–219.

Crowley, H., Bommer, J.J., Pinho, R., and Bird, J. (2005). The impact of epistemic uncertainty on an earthquake loss model, *Earthquake Engineering and Structural Dynamics* **34**: 1653–1685.

Crowley, H., Colombi, M., Crempien, J., Erduran, E., Lopez, M., Liu, H., Mayfield, M., Milanesi, M. (2010). *GEM1 Seismic Risk Report: Part 1,* GEM Technical Report 2010-5, GEM Foundation, Pavia, Italy.

Crowley, H., Monelli, D., Pagani, M., Silva, V., and Weatherill, G. (2011). *OpenQuake Book,* GEM Foundation, Pavia, Italy, September 2011, 102 pp.

Crowley, H., Monelli, D., Pagani, M., Silva, V., and Weatherill, G. (2012). *OpenQuake User's Manual,* version 0.1 (V0.1), GEM Foundation, Pavia, Italy, 126 pp.

Danciu, L., Monelli, D., Pagani, M., and Wiemer, S. (2010). *GEM1 Hazard: Review of PSHA software,* GEM Technical Report 2010-2, GEM Foundation, Pavia, Italy.

D'Ayala, D., and Speranza, E. (2002). An integrated procedure for the assessment of seismic vulnerability of historic buildings, *Proceedings of the 12th European Conference on Earthquake Engineering*, London, U.K., Paper no. 561.

DesRoches, R., Comerio, M., Eberhard, M., Mooney, W., and Rix, G.J. (2011). Overview of the 2010 Haiti earthquake, *Earthquake Spectra* **27**(S1): S1–S21.

Dolce, M., Kappos, A., Zuccaro, G., and Coburn, A.W. (1995). State of the art Report of WG3 – Seismic Risk and Vulnerability, *Proceedings of the 10th European Conference of Earthquake Engineering,* Vienna, Austria, 3049–3077.

Dolce, M., Masi, A., and Marino, M. (2002). EAEE-ESC Task Group 3 – Seismic risk and earthquake damage scenarios – report of the activities, *Proceedings of 12th European Conference on Earthquake Engineering*, 2002.

Dolce, M., Kappos, A., Masi, A., Penelis, G., and Vona, M. (2006). Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies, *Engineering Structures* **28**: 357–371.

Douglas, J. (2010a). Assessing the epistemic uncertainty of ground-motion predictions, *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering*, Paper no. 219.

Douglas, J. (2010b). Consistency of ground-motion predictions from the past four decades, *Bulletin of Earthquake Engineering* **8**(6): 1515–1526.

Douglas, J., Bungum, H., and Scherbaum, F. (2006). Ground-motion prediction equations for Southern Spain and Southern Norway obtained using the Composite Model Perspective, *Journal of Earthquake Engineering* **10** (1): 33–72.

Douglas, J. (2007). Physical vulnerability modeling in natural hazard risk assessment, *Natural Hazards and Earth System Sciences* **7**: 283–288.

Edwards, M.R., Robinson, D., McAneney, K.J., and Schneider, J. (2004). Vulnerability of residential structures in Australia, *Proceedings of the 13th World Conference on Earthquake Engineering,* 1–6 August 2004, Vancouver, Canada, Paper No. 2985.

EERI Committee on Seismic Risk (1984). Glossary of terms for probabilistic seismic risk and hazard analysis, *Earthquake Spectra* **1**: 33–40.

EERI Ad Hoc Committee on Seismic Performance (1994). *Expected seismic performance of buildings,* Oakland, CA.

Eguchi, R.T., Goltz, J.D., Seligson, H.A., Flores, P.J., Heaton, T.H., and Bortugno, E. (1997). Real-time loss estimation as an emergency response decision support system: the early post-earthquake damage assessment tool (EPEDAT), *Earthquake Spectra* **13**: 815–832.

EN 1998-1 (2004). *Eurocode 8 – Design for Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings,* European Committee for Standardization (CEN), Brussels, Belgium, December 2004.

Erdik, M., and Aydinoğlu, N. (2002). Earthquake risk to buildings in Istanbul and a proposal towards its mitigation, *Proceedings of the Second Annual IIASA-DPRI Meeting on Integrated Disaster Risk Management: Megacity Vulnerability and Resilience,* Laxenburg, Austria, 1–10.

Erdik, M., Aydinoglu, N., Fahjan, Y., Sesetyan, K., Demircioglu, M., B. Siyahi, Durukal, E., Ozbey, C., Biro, Y., Akman, H., and Yuzugullu, O. (2003). Earthquake risk assessment for Istanbul Metropolitan Area, *Earthquake Engineering and Engineering Vibration* **2**(1): 1–25.

Erdik, M., Sesetyan, K., Demircioglu, M., Hancilar, U., Zulfikar, C., Cakti, E., Kamer, Y., Yenidogan, C., Tuzun, C., Cagnan, Z., and Harmandar, E. (2010). Rapid earthquake hazard and loss assessment for Euro-Mediterranean Region, *Acta Geophysica* **58**(5): 855–892.

Erduran, E., and Lang, D.H. (2011a). Earthquake Risk in the Romanian–Bulgarian Border Region, Part 2 – Regional analysis, *Delivery 4: Implementation of SELENA in real-time mode,* July 2011.

Erduran, E., and Lang, D.H. (2011b). Earthquake Risk in the Romanian–Bulgarian Border Region, Part 2 – Regional analysis, *Delivery 5: Implementation of the Static Data in SELENA,* September 2011.

Erduran, E., and Lang, D.H. (2011c). Earthquake Risk in the Romanian–Bulgarian Border Region, Part 2 – Regional analysis, *Delivery 6: Automatic Display of Google Maps on screen,* September 2011.

Erduran, E., and Lindholm, C.D. (2012). A critical look at the use of design spectrum shape for seismic risk assessment, Technical Note, *Earthquake Spectra* **28**(4). DOI: 10.1193/1.4000086.

Erduran, E., Lang, D.H., Lindholm, C.D., Toma-Danila, D., Balan, S.F., Ionescu, V., Aldea, A., Vacareanu, R., and Neagu, C. (2012). Real-time earthquake damage assessment in the Romanian-Bulgarian border region, *Proceedings of the 15th World Conference on Earthquake Engineering,* Lisbon (Portugal), 10 pp.

ESRI (2004). *ArcGIS 9 – what is ArcGIS?* Report of ESRI, Redlands, United States. URL: http://www.esri.com/library/whitepapers/pdfs/what_is_arcgis.pdf.

Esteva L. (1967). Criterios para la construcción de espectros para diseño sísmico, *Proceedings of the XII Jornadas Sudamericanas de Ingeniería Estructural y III Simposio Panamericano de Estructuras,* Caracas, 1967. (Published later in *Boletín del Instituto de Materiales y Modelos Estructurales,* Universidad Central de Venezuela, No. 19, 1967.)

Esteva L. (1968). Bases para la formulacion de decisiones de diseño sísmico, *Ph.D. thesis and Report 182,* Universidad Autonoma Nacional de México, August 1968.

Fajfar, P. (2000). A nonlinear analysis method for performance-based seismic design, *Earthquake Spectra* **16**: 573–591.

Federal Emergency Management Agency (1997a). *NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 273,* Washington, D.C., October 1997.

Federal Emergency Management Agency (1997b). *NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings, FEMA 274,* Washington, D.C., October 1997.

Federal Emergency Management Agency (1997c). *HAZUS®97 Earthquake Loss Estimation Methodology,* User Manual. Federal Emergency Management Agency, Washington, D.C., United States, 197 pp.

Federal Emergency Management Agency (1999). *HAZUS®99 Earthquake Loss Estimation Methodology,* User Manual. Federal Emergency Management Agency, Washington, D.C., United States, 314 pp.

Federal Emergency Management Agency (2000). *Prestandard and commentary for the seismic rehabilitation of buildings, FEMA 356,* Prepared by American Society of Civil Engineers, Reston, Virginia, United States, November 2000.

Federal Emergency Management Agency (2001). *HAZUS®99-SR1 estimated annualized earthquake losses for the United States, FEMA 366,* Report of the Federal Emergency Management Agency, Washington, DC, United States, 33 pp.

Federal Emergency Management Agency (2002). *HAZUS®99-SR2 (Service Release 2), Advanced Engineering Building Module, Technical and User's Manual,* Federal Emergency Management Agency, FEMA and National Institute of Building Sciences, NIBS, Washington D.C.

Federal Emergency Management Agency (2003). *HAZUS-MH MR4 Technical Manual.* Washington, D.C.

Federal Emergency Management Agency (2005). *Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA 440,* Prepared by Applied Technology Council (ATC-55 Project), Washington, D.C., United States, June 2005.

Federal Emergency Management Agency (2008). *HAZUS-MH Estimated annualized earthquake losses for the United States, FEMA 366,* Report of the Federal Emergency Management Agency, Washington, DC, United States, 66 pp.

Field, E.H., Jordan, T.H., and Cornell, C.A. (2003). OpenSHA: A developing community-modeling environment for seismic hazard analysis, *Seismological Research Letters* **74**(4): 406–419.

Freeman, J.R. (1932). *Earthquake Damage and Earthquake Insurance: Studies of a rational basis for earthquake insurance, also studies of engineering data for earthquake-resisting construction,* McGraw-Hill Book Co., New York, 1932.

Freeman, S.A., Nicoletti, J.P., and Tyrell, J.V. (1975). Evaluations of existing buildings for seismic risk - A case study of Puget Sound Naval Shipyard, Bremerton, Washington, *Proceedings of U.S. National Conference on Earthquake Engineering*, Berkeley, 113–122.

Freeman, S.A., Messinger, D.L., Casper, W.L., Mattis, L.W., Preece, F.R., and Tobin, R.E. (1985). Structural moments no. 4. drift limits: Are they realistic? *Earthquake Spectra* **1**: 203–390.

Freeman, S.A. (1978). *Prediction of response of concrete buildings to severe earthquake motion*, Publication SP-55: 589–605, American Concrete Institute, Detroit, Michigan.

Freeman, S.A. (2004). Review of the development of the capacity spectrum method, *ISET Journal of Earthquake Technology* **41**(1): 1–13.

Fuchs, K., Bonjer, K.-P., Bock, G., Cornea, I., Radu, C., Enescu, D., Jianu, D., Nourescu, A., Merkler, G., Moldoveanu, T., and Tudorache, G. (1979). The Romanian earthquake of 4 March 1977, II. Aftershocks and migration of seismic activity, *Tectonophysics* **53**: 225–247.

Giovinazzi, S. (2005). *The Vulnerability Assessment And The Damage Scenario In Seismic Risk Analysis,* Dissertation, University of Florence and Technical University of Braunschweig.

Goel, R.K. (2005). Evaluation of Modal and FEMA Pushover Procedures Using Strong-Motion Records of Buildings, *Earthquake Spectra* **21**(3): 653–684.

Grünthal, G., ed. (1998). *European Macroseismic Scale 1998 (EMS–98),* Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 15, Luxembourg.

Haldar, P., Singh, Y., Lang, D.H., and Paul, D.K. (2010). IVARA - a tool for seismic vulnerability and Risk Assessment of Indian Housing, *Proceedings of the 14th Symposium on Earthquake Engineering*, Department of Earthquake Engineering, IIT Roorkee, 1405–1415.

Haldar, P., Singh, Y., Lang, D.H., and Paul, D.K. (2013). Comparison of seismic risk assessment based on macroseismic intensity and spectrum approaches using 'SeisVARA', *Soil Dynamics and Earthquake Engineering* (2013), http://dx.doi.org/10.1016/j.soildyn.2013.01.016.

Hancilar, U., Tuzun, C., Yenidogan, C., and Erdik, M. (2010). ELER software – a new tool for urban earthquake loss assessment, *Natural Hazards and Earth System Sciences* **10**: 2877–2696.

Hansen, R., and Bausch, D. (2006). A GIS-based methodology for exporting the Hazards US (HAZUS) earthquake model for global applications, *Proceedings of the Earthquake Workshop*, Malta, 64 pp, http://www.usehazus.com/docs/gis_global_hazus_paper.pdf.

Haselton, C.B., Goulet, C.A., Mitrani-Reiser, J., Beck, J.L., Deierlein, G.G., Porter, K.A., Stewart, J.P., and Taciroglu, E. (2008). *An assessment to benchmark the seismic performance of a code-conforming reinforced concrete moment-frame building,* PEER Report 2007/12, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, August 2008, 382 pp.

IDNDR (1999). *Radius: Risk Assessment Tool for Diagnosis of Urban Areas against Seismic Disasters,* International Decade for Natural Disaster Reduction (IDNDR), Geneva, Switzerland.

International Code Council (2006). *2006 International Building Code (IBC–2006),* Washington, D.C., 679 pp.

IS 1893 (2002). *Part I: Criteria for earthquake resistant design of structures - General provisions and buildings,* Bureau of Indian Standards, New Delhi, India.

Jaiswal, K.S., and Wald, D.J. (2008). *Creating a global building inventory for earthquake loss assessment and risk management,* U.S. Geological Survey Open-file report 2008-1160, 106 pp.

Jaiswal, K., Wald, D.J., and Hearne, M. (2009). *Estimating Casualties for Large Earthquakes Worldwide Using an Empirical Approach*, USGS Open File Report, OF 2009-1136, 83 pp., (http://pubs.usgs.gov/of/2009/1136/).

Jaiswal, K., and Wald, D.J. (2010a). An Empirical Model for Global Earthquake Fatality Estimation, *Earthquake Spectra* **26**(4): 1017–1037.

Jaiswal, K., and Wald, D.J. (2010b). Development of a semi-empirical loss model within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System, *Proceedings of the 9th US National and 10th Canadian Conference on Earthquake Engineering*, Paper No. 1095, July 25–29, 2010, Toronto, Canada.

Joyner, W.B., and Boore, D.M. (1981). Peak horizontal acceleration and velocity form strong-motion records including records from the 1979 Imperial Valley, California, earthquake, *Bulletin of the Seismological Society of America* **71**: 2011–2038.

Joyner, W.B., and Boore, D.M. (1982). Prediction of earthquake response spectra, *Proceedings of the 51 Annual Convention of Struct. Eng. Assoc. of California,* also U.S. Geological Survey Open-file Report 82-977, 16 pp.

Joyner, W.B., and Boore, D.M. (1988). Measurement, characterization, and prediction of strong ground motion, *Proceedings of Earthquake Engineering & Soil Dynamics* **II**: 43–102, Park City, Utah, 27 June 1988. New York: Geotechnical Division of the American Society of Civil Engineers.

Kamer, Y., Abdulhamitbilal, E., Demircioglu, M.B., Erdik, M., Hancilar, U., Sesetyan, K., Yenidogan, C., and Zulfikar, A.C. (2009). *Earthquake Loss Estimation Routine ELER v1.0* – User Manual, prepared under the NERIES project.

Kappos, A.J, Stylianidis, K.C, and Pitilakis, K. (1998). Development of seismic risk scenarios based on a hybrid method of vulnerability assessment, *Natural Hazards* **17**(2): 177–192.

Kappos, A.J., Pitilakis, K.D., Morfidis, K., and Hatzinikolaou, N. (2002). Vulnerability and risk study of Volos (Greece) metropolitan area, *Proceedings of the 12th European Conference on Earthquake Engineering,* London, CD ROM Proceedings (Balkema), Paper 074.

Kappos, A.J, Panagopoulos, G., Panagiotopoulos, C., and Penelis, G. (2006). A hybrid method for the vulnerability assessment of R/C and URM buildings, *Bulletin of Earthquake Engineering* **4**(4): 391–413.

Karaca, E. (2004). *Uncertainty in seismic loss estimation,* MAE Center Annual Meeting and RA Symposium 2004.

Kircher, C.A., Reitherman, R.K., Whitman, R.V., and Arnold, C. (1997a). Estimation of earthquake losses to buildings, *Earthquake Spectra* **13**(4): 703–720.

Kircher, C.A., Nassar, A.A., Kustu, O. and Holmes, W.T. (1997b). Development of building damage functions for earthquake loss estimation, *Earthquake Spectra* **13**(4): 663–682.

Kramer, S.L. (1996). *Geotechnical earthquake engineering,* Prentice–Hall, Inc., New Jersey, U.S., 653 pp.

Krawinkler, H., and Seneviratna, G.D.P.K. (1998). Pros and cons of a pushover analysis for seismic performance evaluation, *Engineering Structures* **20**: 452–464.

Kumar, R. (2011). Modelling and seismic performance evaluation of Indian RC frame buildings, *Ph.D. thesis,* Department of Earthquake Engineering, Indian Institute of Technology Roorkee (IITR), Roorkee, Uttarakhand, India, 217 pp.

Lang, D.H. (2004). Damage potential of seismic ground motion considering local site effects, *Ph.D. thesis,* Institute of Structural Engineering, Bauhaus-University Weimar, 294 pp.

Lang, D.H., Gutiérrez Corea, F.V., and Lindholm, C.D. (2009a). *RISe – Risk Illustrator for SELENA – User Manual v2.0,* NORSAR, Kjeller, Norway, 24 pp.

Lang, D.H., Molina, S., Crempien, J., and Erduran, E. (2009b). *Earthquake Risk Reduction in Guatemala, El Salvador, and Nicaragua with Regional Cooperation to Honduras, Costa Rica, and Panama,* Task 1: Mapping of Typical Buildings, Project Report No. 09–02, December 2009, 43 pp.

Lang, D.H. and Aldea, A. (2011). *Specifications of Inventory Data for Earthquake Risk Assessment,* Report 1.0 for Project 'Earthquake Risk in the Romanian–Bulgarian Border Region', April 2011, 19 pp.

Lang, D.H., and Jaiswal, K. (2011). *Global Database on Seismic Vulnerability Information: Building on the WHE–PAGER Network,* Project Proposal presented to Global Facility for Disaster Reduction and Recovery (GFDRR), Washington, D.C., July 2011.

Lang, D.H., and Erduran, E. (2011). *Earthquake Risk in the Romanian–Bulgarian Border Region,* Part 2 – Regional analysis, Report 2 (version 1.0): Development of inventory maps, May 2011.

Lang, D.H., Erduran, E., and Toma-Danila, D. (2011). *Earthquake Risk in the Romanian–Bulgarian Border Region,* Part 2 – Regional analysis, Report 1 (version 1.0), May 2011.

Lang, D.H., Erduran, E., Kumar, A., Yasunov, P., and Tailiakova, J. (2012). *Building typology classification for Central Asia,* unpublished document, Draft 3.0 (March 2012).

Lungu, D., Zaicenco, A., Cornea, T., and van Gelder, P. (1997). Seismic hazard: recurrence and attenuation of subcrustal (60–170 km) earthquakes, *ICOSSAR'97*, Kyoto, Japan, Nov 24–28, 1997.

Lungu, D., Cornea, T., and Nedelcu, C. (1999). Hazard assessment and site-dependent response for Vrancea earthquakes, in: F. Wenzel *et al.* (eds.), *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation,* Kluwer, Dordrecht, 251–267.

Lungu, D., Aldea, A., Arion, A., Vacareanu, R., Petrescu, F., and Cornea, T. (2001). *RISK-UE – An advanced approach to earthquake risk scenarios with applications to different European towns,* WP1 Report: European distinctive features, inventory database and typology, December 2001.

Lungu, D., Cornea, T., and Nedelcu, C. (1999). Hazard assessment and site-dependent response for Vrancea earthquakes, in: Wenzel, F. et al. (eds), *Vrancea earthquakes: tectonics, hazard and risk mitigation.* Kluwer, Dordrecht, 251–267.

Lungu, D., Arion, C., Aldea, A., and Vacareanu, R. (2007). Seismic hazard, vulnerability and risk for Vrancea events, in: *International Symposium on Strong Vrancea Earthquakes and Risk Mitigation,* Oct. 4–6, 2007, Bucharest, Romania.

Magenes, G., and Della Fontana, A. (1998). Simplified non-linear seismic analysis of masonry buildings, *Proceedings of the British Masonry Society* **8**: 190–195.

Marmureanu, G. (2007). *Internal Report,* National Institute for Earth Physics (NIEP), Bucharest, Romania.

Marmureanu, G., Androne, M., Radulian, M., Popescu, E., Cioflan, C.O, Placinta, A.O., Moldovan, I.A., and Serban, V. (2006). Attenuation of the peak ground motion for the special case of Vrancea intermediate-depth earthquakes and seismic hazard assessment at NPP Cernavoda, *Acta Geodaetica et Geophysica Hungarica* **41**(3-4): 433–440.

Mândrescu, N., Radulian, M., and Mărmureanu, Gh. (2007). Geological, geophysical and seismological criteria for local response evaluation in Bucharest urban area, *Soil Dynamics and Earthquake Engineering* **27**(1997): 367–393

Mârza, V.I., Kijko, A., and Mäntyniemi, P. (1991) Estimate of earthquake hazard in the Vrancea (Romania) region, *Pure and Applied Geophysics* **136**: 143–154.

McGuire, R.K. (2004). *Seismic hazard and risk analysis,* EERI Original Monograph Series MNO-10, Earthquake Engineering Research Institute, Oakland, U.S., 221 pp.

Medvedev, S.W., Sponheuer, W., and Karnik, V. (1965). *Seismic intensity scale version MSK 1964,* United Nation Educational, Scientific and Cultural Organization, Paris, 7 pp.

Milutinovic, Z.V., and Trendafiloski, G.S. (2003). *RISK-UE, an advanced approach to earthquake risk scenarios with applications to different European towns,* Report to WP4: Vulnerability of current buildings, September 2003, 109 pp.

Miranda, E. (1999). Approximate seismic lateral deformation demands in multistory buildings, *Journal of Structural Engineering* **125**(4): 417–425.

Mitrani-Reiser, J. (2007). *An ounce of prevention: probabilistic loss estimation for performance-based earthquake engineering,* Earthquake Engineering Research Laboratory Technical Report EERL 2007-01, California Institute of Technology, Pasadena, California, United States, 175 pp.

Molina, S., Lang, D.H., and Lindholm, C.D. (2009). *SELENA v4.1 – User and Technical Manual v4.1,* NORSAR, Kjeller, Norway, 85 pp.

Molina, S., Lang, D.H., Lingvall, F., and Lindholm, C.D. (2010). *User Manual for the Earthquake Loss Estimation Tool: SELENA (v5.0),* July 2009, 75 pp.

Molina, S., and Lindholm, C. (2005). A logic tree extension of the capacity spectrum method developed to estimate seismic risk in Oslo, Norway, *Journal of Earthquake Engineering* **9**(6): 877–897.

Molina, S., and Lindholm, C.D. (2007). Estimation of the confidence of earthquake damage scenarios: examples from a logic tree approach, *Journal of Seismology* **11**(3): 399–410.

Mora, S. (2009). Disasters are not natural: risk management, a tool for development, *Geological Society London, Engineering Geology Special Publication* **22**: 101–122.

Mora, S. (2010). Disasters should not be the protagonists of Disaster Risk Management, in: *Geologically Active: Proceedings of the 11th IAEG Congress,* (eds.: A.L. Williams, G.M. Pinches, C.Y. Chin, T.J. McMorran, and C.I. Massey), Auckland, New Zealand, 5-10 September 2010.

Motazedian, D., and Atkinson, G. (2005). Stochastic finite fault modeling based on a dynamic corner frequency, *Bulletin of the Seismological Society of America* **95**: 995–1010.

Mouroux, P., and Le Brun, B. (2006). Risk-UE Project: An Advanced Approach to Earthquake Risk Scenarios with Application to Different European Towns, in: Oliveira, C.S., Roca, A. and Goula, X. (eds.), *Assessing and Managing Earthquake Risk*, Springer Netherlands, 1–14.

Muto, M., Krishnan, S., Beck, J. L., and Mitrani-Reiser, J. (2008). Seismic loss estimation based on end-to-end simulation, in: *Proceedings of the First International Symposium on Life-cycle Civil Engineering,* Varenna, Lake Como, Italy, 215–232.

National Institute of Building Sciences (1994). *Assessment of state-of-the-art earthquake loss estimation methodologies, FEMA-249.* Report prepared for the Federal Emergency Management Agency, Washington, D.C.

Naeim, F., Alimoradi, A., Hagie, S., and Comartin, C. (2007). PACT – Performance Assessment Calculation Tool – User Guide for Beta Version 1.0, May 27, 2007. *ATC-58 Guidelines for Seismic Performance Assessment of Buildings,* Report prepared for Department of Homeland Security, Federal Emergency Management Agency, Washington, DC, United States, 29 pp.

NZS 1170.5 (2004). *Structural design actions Part 5: Earthquake actions – New Zealand*, Standards New Zealand, Wellington 6020.

NORSAR (2009). *GEM Memorandum on GEM1*, September 2009, (Authors: J. Crempien, D.H. Lang, E. Erduran, C.D. Lindholm), 12 pp.

Oncescu, M.-C., Mârza, V.I., Rizescu, M., and Popa, M. (1999). The Romanian earthquake catalogue between 984 - 1996, Vrancea Earthquakes, in: Wenzel, F., Lungu, D. (eds) *Tectonics, Hazard, and Risk Mitigation,* Kluwer Academic Publishers, 43–48.

Pasticier, L., Amadio, C., and Fragiacomo, M. (2008). Non-linear seismic analysis and vulnerability evaluation of a masonry building by means of the SAP2000 V.10 code, *Earthquake Engineering and Structural Dynamics* **37**(3): 467–485.

PESMOS (2011). *Programme for Excellence in Strong Motion Studies,* Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India, http://www.pesmos.in/.

Porro, B., and Schraft, A. (1989). Investigation of insured earthquake damage, *Natural Hazards* **2**(2): 173–184.

Porter, K., and Scawthorn, C. (2007). *Open-Source Risk Estimation Software*, Report prepared for the Southern California Earthquake Center and U.S. Geological Survey, 112 pp.

Porter, K., Jaiswal, K., Wald, D.J., Greene, M., and Comartin, C. (2008). WHE-PAGER Project: A new initiative in estimation global building inventory and its seismic vulnerability, *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China.

Prasad, J.S.R., Singh, Y., Kaynia, A.M., and Lindholm, C.D. (2009). Socio-economic clustering in seismic risk assessment of Indian urban housing stock, *Earthquake Spectra* **25**(3): 619–641.

Radu, C. (1974) Investigation of the seismicity of Romania and its comparison with the seismicity of south-eastern France, *Ph.D. thesis,* Université Strasbourg, France, 404 pp. (in French).

Reese, S., Bell, R.G., and King, A.B. (2007). RiskScape—A new tool for comparing risk from natural hazards, *Water & Atmosphere* **15**(3): 24–25.

Reitherman, R. (1986). Background paper on the conversion of Damage Probability Matrices into fragility curves, *Whitepaper written for Panel on Earthquake Loss Estimation*, National Research Council, December 1986, 11 pp.

Richter, C.V. (1958). *Elementary seismology*, W.H. Freeman, San Francisco.

Roca, A., Goula, X., Susagna, T., Chávez, J., González, M., and Reinoso, E. (2006). A simplified method for vulnerability assessment of dwelling buildings and estimation of damage scenarios in Catalonia, Spain, *Bulletin of Earthquake Engineering* **4**: 141–158.

Sabetta, F., Goretti, A., and Lucantoni, A. (1998). Empirical Fragility Curves from Damage Surveys and Estimated Strong Ground Motion, *Proceedings of the 11th European Conference on Earthquake Engineering*, Paris, France.

Sandi, H. (1982). Seismic vulnerability and seismic intensity, *Proceedings of the Seventh European Conference on Earthquake Engineering*, Vol. 2, Athens, Greece.

Saunders, D. (2011). *Arrival City – How the largest migration in history is reshaping our world,* Windmill Books, London, U.K., 364 pp.

Scawthorn, C. (2008). Opening risk analysis, *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China.

SEAOC (1999). *Recommended Lateral Force Requirements and Commentary (SEAOC Blue Book),* Structural Engineers Association of California, Seventh Edition, 440 pp.

Shome, N., and Cornell A. (1999). *Probabilistic Seismic Demand Analysis of Nonlinear Structures,* Report No.RMS-35, Department of Civil Engineering, Stanford University.

Singh, Y., Prasad, J.S.R., Lang, D.H., and Deoliya, R. (2009). *Development of seismic capacity curves for claybrick masonry buildings in India,* Short report and presentation during the PAGER Project Phase III Workshop, Oakland, CA, September 23, 2009.

Singhal, A., and Kiremidjian, A.S. (1996). A method for probabilistic evaluation of seismic structural damage, *Journal of Structural Engineering* **122**(12): 1459–1467.

Sinha, R., Aditya, K.S.P., and Gupta, A. (2008). GIS-based urban seismic risk assessment using Risk.IITB, *ISET Journal of Earthquake Engineering* **45**(3-4).

Sokolov, V., Bonjer, K-P., Wenzel, F., Grecu, B., and Radulian, M. (2008). Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes, *Bulletin of Earthquake Engineering* **6**: 367–388.

Sokolov, V., Wenzel, F., and Mohindra, R., (2009). Probabilistic seismic hazard assessment for Romania and sensitivity analysis: A case of joint consideration of intermediate-depth (Vrancea) and shallow (crustal) seismicity, *Soil Dynamics and Earthquake Engineering* **29**(2): 364–381.

Spence, R.J.S., Coburn, A.W., Sakai, S., and Pomonis, A. (1991). A parameterless scale of seismic intensity for use in seismic risk analysis and vulnerability assessment, in: *Earthquake Blast and Impact: Measurement and effects of vibration*, (The Society for Earthquake & Civil Engineering Dynamics, eds.), Elsevier Applied Science, Amsterdam, Netherlands, 19–28.

Spencer, B., Elnashai, A., Myers, J., Hampton, S. (2008). *MAEvizOverview,* Mid-America Earthquake Center, http://mae.cee.uiuc.edu/ software_and_tools/maeviz.html.

Sponheuer, W., (1962). Untersuchungen zur Seismizität von Deutschland, *Veröffentlichungen des Instituts fuer Bodendynamik und Erdbebenforschung Jena* **72**: 23–52 (in German).

Sponheuer, W., and Karnik, V. (1964). Neue seismische Skala, *Proceedings of the 7th Symposium of the ESC*, (W. Sponheuer, ed.), Jena 1962, Veröffentlichungen des Instituts für Bodendynamik und Erdbebenforschung Jena **77**, 69–76 (in German).

Stamatovska, S. (2002). A new azimuth dependent empirical strong motion model for Vranchea subduction zone, *Proceedings of the Twelfth European Conference on Earthquake Engineering*, London, UK, Paper no. 324.

Sørensen, M.B., Stromeyer, D., and Grünthal, G. (2009). Attenuation of macroseismic intensity: A new relation for the Marmara Sea Region, Northwest Turkey, *Bulletin of the Seismological Society of America* **99**(2A): 538–553, April 2009, doi: 10.1785/0120080299.

Trendafiloski, G., Wyss, M., and Rosset, Ph. (2009). Loss estimation module in the new generation software QLARM, *Proceedings of the Second International Workshop on Disaster Casualties*, Cambridge, June 2009.

Tyagunov, S., Grünthal, G., Wahlström, R., Stempniewski, L., and Zschau, J. (2006). Seismic risk mapping for Germany, *Natural Hazards and Earth System Sciences (NHESS)* **6**(4): 573–586.

UN–HABITAT (2007). *Housing in the world – Demographic and Health Survey, in: Jaiswal and Wald (2008), Creating a Global Building Inventory for Earthquake Loss Assessment and Risk Management,* Open-File Report 2008–1160, U.S. Geological Survey.

UN–HABITAT (2008/2009). *State of the World's Cities 2008/2009 – Harmonious Cities,* http://www.unhabitat.org/content.asp?cid=5964&catid=7&typeid=46.

United Nations (2008). *Principles and Recommendations for Population and Housing Censuses,* Statistical Papers: Series M No. 67/Rev.2. p8. [ISBN 978-92-1-161505-0].

U.S. Army (1986). *Seismic Design Guidelines for Essential Buildings*, Departments of the Army (TM 5-809-10-1), Navy (NAVFAC P355.1), and the Air Force (AFM 88-3, Chapter 13, Section A), Washington, D.C.

Vamvastsikos, D. and Cornell, A.C. (2002). Incremental dynamic analysis, *Earthquake Engineering and Structural Dynamics* **31**(3): 491–514.

Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W., and Worden, C.B. (1999). TriNet 'ShakeMaps': Rapid generation of peak ground motion and intensity maps for earthquakes in southern California, *Earthquake Spectra* **15**: 537–555.

Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L. (2005). *ShakeMap Manual: Technical manual, user's guide, and software guide,* U.S. Geological Survey, 132 pp.

Wald, D.J., Earle, P.S., Allen, T.I., Jaiswal, K.S., Porter, K.A., and Hearne, M. (2008). Development of the U. S. Geological Survey's PAGER system (Prompt Assessment of Global Earthquakes for Response), *Proceedings of the 14th World Conference on Earthquake Engineering*, October 2008, Beijing, China, Paper No. 10-0008.

Webb, T.M. (1999). *NHEMATIS: Project overview and future framework,* Report of the Nobility Environmental Software Systems Inc., Vancouver, BC for Emergency Preparedness Canada, 23 pp.

Wells, D.L., and Coppersmith, K.J. (1994). New empirical relationships among magnitude, rupture length, rupture width and surface displacement, *Bulletin of the Seismological Society of America* **84**: 974–1002.

Whitman, R.V., Reed, J., and Hong, S.-T. (1973). Earthquake Damage Probability Matrices, *Proceedings of the Fifth World Conference on Earthquake Engineering*, Vol. 2, International Association for Earthquake Engineering, Rome, Italy.

Whitman, R.V., Anagnos, T., Kircher, C.A., Lagorio, H.J., Lawson, R.S., Schneider, P. (1997). Development of a National Earthquake Loss Estimation Methodology, *Earthquake Spectra* **13**(4): 643–661.

Wood, H.O., and Neumann, F. (1931). Modified Mercalli Intensity Scale of 1931, *Bulletin of the Seismological Society of America* **21**: 277–283.

Wyss, M. (2005). Earthquake loss estimates applied in real time and to megacity risk assessment, *Proceedings of the Second International ISCRAM Conference,* Brussels, Belgium, Carle, B. and van de Walle, B., eds., 297–299.

Wyss, M. (2006). The Kashmir M7.6 shock of 8 October 2005 calibrates estimates of losses in future Himalayan earthquakes, *Proceedings of the Third International ISCRAM Conference,* Newark, Van de Walle B. and Turoff M., eds., 5 pp.

Yeh, C.H., Loh, C.H., and Tsai, K.C. (2006). Overview of Taiwan Earthquake Loss Estimation System, *Natural Hazards* **37**(1-2): 23–37.