Task 5a – Earthquake Vulnerability

Regionally consistent risk assessment for earthquakes and floods and selective landslide scenario analysis for strengthening financial resilience and accelerating risk reduction in Central Asia (SFRARR Central Asia disaster risk assessment)

FINAL VERSION

08 December 2022

RED – Risk Engineering + Development – Pavia, Italy

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RED Risk Engineering + Development

Executive Summary

This document describes the methodology used to derive a regional vulnerability model to be used for the seismic risk assessment of residential and non-residential assets and infrastructure in Central Asia. It discusses data and references (international and local) collected, and it describes the final results and the challenges faced for the derivation of a harmonized regional model.

Section 1 introduces the topic of vulnerability model development.

Section 2 illustrates a conceptual discussion about fragility, vulnerability, and consequence functions development. Such discussion is intended to help the understanding of the following sections of the report.

Sections 3 introduces the taxonomy for residential and non-residential buildings and infrastructure and provides some insights on the approach behind the taxonomy classification.

Sections 4 to 6 present and discuss the data and the methodologies used to derive the regional vulnerability model for residential buildings, non-residential buildings, and infrastructure, respectively. They describe how we reviewed multiple sets of existing fragility and vulnerability functions from various references relevant for the region, including local studies, international literature and World Bank projects previously developed in the region. Then they describe how these functions have been used to derive a new vulnerability model to be used for seismic risk assessment in the region. In particular, they provide insights on the approaches adopted to map the information collected to the classes identified in the taxonomy, to harmonize the damage assessment and the intensity measure definition, and to represent the building vulnerability only by means of vulnerability curves. The methodology adopted to combine the available information is also discussed, and the final vulnerability model is presented.

Section 7 illustrates the approach adopted to derive a vulnerability model to assess human losses applicable to the local context. Finally, Section 8 draws some conclusion about the overall development of the regional vulnerability model, highlighting the novelties in the model proposed and its current limitations.

The approach adopted aims at deriving a new model applicable for the entire region leveraging the most recent international research outcomes and the local observations and expertise.

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1 Introduction

Vulnerability functions play a central role in the regional seismic loss assessment (Calvi et al. 2006; Rossetto and Elnashai 2003). They are derived separately for each class of buildings (e.g., reinforced concrete midrise of the 1970s era or low-rise unreinforced masonry buildings pre-1970) in the inventory of interest compatible with the building typologies where a seismic risk assessment is performed. A vulnerability function is a relationship that is utilized to predict the statistics (e.g., mean, standard deviation, 16th/50th/84th percentile) of the distribution of seismic losses expected to be suffered by an asset (e.g., a building or a bridge) as a function of an appropriate ground motion intensity measure (IM). Such loss usually represents either the repair cost (i.e., monetary losses), or the downtime (i.e., the time required to make the asset functional again), or the number of injuries or fatalities. This loss estimation process is further broken down into three distinct stages, as illustrated in the bottom panel of Figure 1: structural (demand) analysis, damage analysis and loss (consequence) analysis. The outcomes of these three steps are condensed into a vulnerability function.

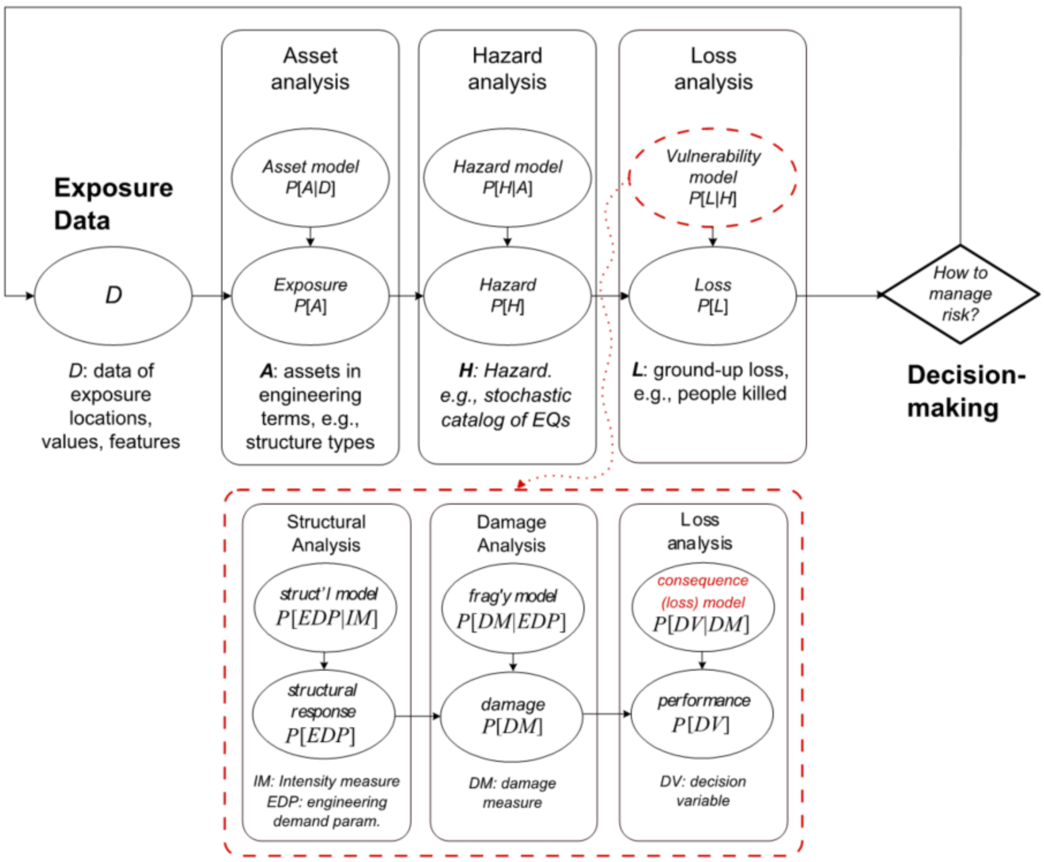


Figure 1. Conceptual workflow of a risk analysis procedure. Upper row illustrates the three major analysis components, while the bottom row provides a zoomed view of the sub-components of analytical (which is very often adopted) vulnerability modelling stage.

In the process of a portfolio loss estimation, based on the required accuracy as well as data availability, different approaches have been proposed and utilized to derive vulnerability functions for specific building classes: 1) empirical, 2) expert opinion, 3) analytical/mechanical, and 4) hybrid methods.

In empirical methods, data on the actual structural damages or losses observed in a building class after an earthquake are collected and used for generating vulnerability/fragility functions (Charles A. Kircher 1997; Colombi et al. 2008; Noh 2015; 1999; Porter et al. 2007; Rossetto et al. 2014; Rossetto and Grant 2013; Rota et al. 2008; Straub 2008). A literature review of the existing empirical fragility/vulnerability function can be found in Rossetto and Grant (2013). Assuming that enough damage/loss data are available and that the ground motion experienced by the damaged buildings can be estimated with a reasonable accuracy, this is the most reliable of all approaches. Empirical vulnerability functions, nevertheless, typically have several shortcomings:

1. Often in the post-event surveys, no clear distinction between buildings of different classes, which are categorized by material, height, and seismic design provisions, is made. No building-class-specific vulnerability functions can be developed from such aggregated data.
2. Most of the collected data is for buildings that were indeed damaged by an event. Almost never data in the affected region is available for all the remaining buildings, often the large majority, which were undamaged or only experienced minor cracks. Using these data for developing a vulnerability function would inevitably lead to an overestimation of damage when applied to portfolio loss estimation.
3. Insurance claims data are scarce and often proprietary. Even when available, claims data are often plagued with many possible sources of both positive and negative biases. Systematic overestimation of damage to avoid lawsuits and closing claims in a reasonable time frame is an example of the former. An example of the latter is that insurance companies by design systematically avoid insuring “bad risks”, namely buildings that are considered to be prone to damage because of perceived weaknesses or lack of adequate maintenance are simply not insured.
4. The ground motion experienced by each damaged building, in most cases, can only be estimated with a large uncertainty. For example, if at a building site at a distance R from a rupture of an earthquake of magnitude M the median value of a given IM is expected to be 0.3g, there is about 90% chance that the observed IM is anywhere between 0.1g and 0.9g, namely 1/3 and 3 times the median value. Clearly the noise due to the uncertainty on the level of ground motion is transferred to the vulnerability function.
5. Very rarely post-earthquake damage and repair cost data are collected for a number of buildings large enough to permit the development of statistically reliable (and unbiased, for the reasons stated above) vulnerability functions.
6. In many parts of the world a large population of modern buildings designed according to the latest building codes has never experienced any large earthquake that could put their performance to a serious test. Hence, damage and loss data are simply not existing.

Therefore, for all the reasons above in the large majority of cases when sufficient empirical usable data are not available, it is naturally necessary to use the other three methods to supplement or to replace the empirical approach in the development of vulnerability functions.

Judgement-based methods collect data based on the opinion and experience of a group of experts regarding the damage of different types of structures. Several studies such as ATC-13 (1985), ATC-40 (1996) and Brzev et al. (2013) can be introduced as examples of judgement-based methods. However, the reliability of judgement-based curves is questionable due to their dependence on the individual knowledge of the experts. It is practically impossible to evaluate the degree of bias potentially associated with the judgement-based source, and inherent in the expert vulnerability predictions is a consideration of local structural types, typical configurations, detailing and materials.

The analytical method uses numerical analyses, utilizing structural modelling and computer-intensive calculations (D'Ayala 2014; Kennedy and Ravindra 1984; Silva 2014a; Silva 2014b) to estimate losses for a number of representative archetype (FEMA-P695 2009) or index buildings. This approach, although not devoid of potential shortcomings (e.g., limited ability to account for human error in design or construction, to name one), can result in a reduced bias and increased reliability of the vulnerability estimates for different structures compared to those purely based on expert opinion. Hence, analytical approaches to vulnerability curve generation have become more attractive in terms of the efficiency by which data can be generated, although they have not yet been fully exploited to the limits of their potential (Kohrangi et al. 2017). Analytical methods are now the most adopted tool to develop vulnerability functions but before utilization in portfolio loss assessment they require extensive calibration as well as validation. The resulting functions are only as reliable as the mathematical models that are used to estimate the response of a structure. Hence, simplified mathematical models and analysis approaches may lead to unreliable and biased vulnerability curves.

Finally, hybrid approaches comprise a combination of any of the other three methods (Dolce et al. 2006; Kappos et al. 2006). In other words, hybrid methods attempt to compensate for the scarcity of observational data, the subjectivity of expert opinion and potential modelling simplifications and deficiencies of analytical procedures by combining data from the different sources. Commonly, hybrid vulnerability functions are obtained by updating analytical or judgement-based relationships with observational data. In most cases, however, the data deriving from the additional sources are limited in quantity and scope (ATC-40 1996).

The development of a regional model cannot be done without the contribution of experts from the local scientific community. Partnership with local governmental institutions and authorities is also an essential step to facilitate model acceptance and for potential integration with national models. Following this concept, the consortium has engaged with the local communities for building and extending awareness of risk and for enhancing the technical capacity of local experts in the use of open tools and resources (see Table 1 for the complete list of involved scientific institutions from each partner country). In this project, we first reviewed a bulk of local studies that were kindly made available to the consortium to extract the most useful one for our vulnerability analysis. A summary of the adopted studies is listed in the following section. In addition, the consortium has organized a two-day workshop with the local partners where generic as well as project-specific methods and procedures for a state of practice vulnerability analysis will be discussed.

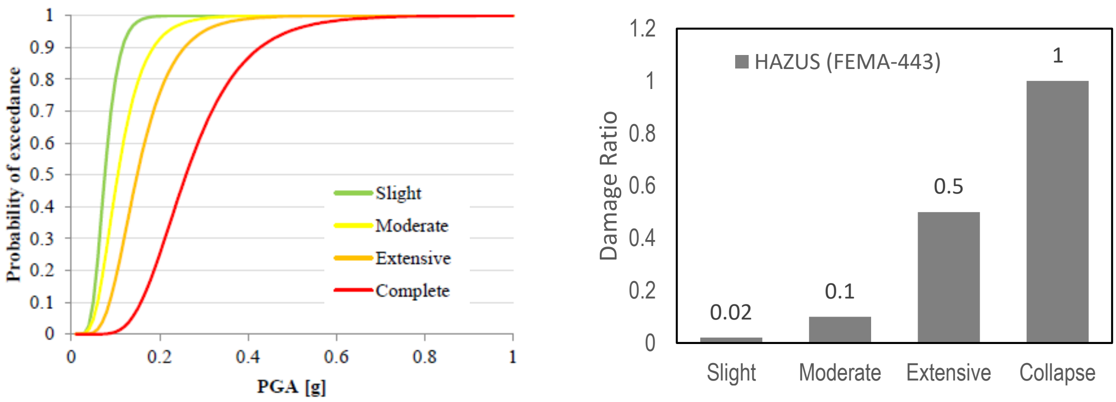
Table 1. List of partner countries of the consortium and associated scientific institutions

Country	Main Scientific Institution	Local Representative
Kazakhstan	IS - Institute of Seismology under MoES of RoK	Dr. Natalya Silacheva Dr. Baurzhan Adilkhan
Kyrgyz Republic	ISNASKR - Institute of Seismology of Kyrgyz Republic	Prof. Kanatbek Abdrakhmatov Prof. Ulugbek Begaliev
Tajikistan	IWPHE - Institute of Water Problems, Hydropower Engineering and Ecology	Prof. Zainalobudin Kobuliev
Turkmenistan	Various individual consultants	Dr. Japar Karaev
Uzbekistan	ISASUz - Institute of Seismology Uzbekistan	Prof. Vakhitkhan Ismailov

2 Concepts and Methodology

2.1 Global fragility functions

Fragility functions are commonly defined as the probability of exceeding a damage state given the ground motion intensity. These functions are assumed to show the global performance of a structure. Commonly, an Engineering Demand Parameter (EDP) such as maximum inter-story drift ratio is used to define the damage state of a building. Figure 2a shows an example of the fragility functions. In a portfolio loss assessment, at each ground motion intensity level the fragility functions are combined with consequence functions to specify the loss ratio. A consequence function specifies the expected loss ratio (i.e., the fraction of seismic losses to the total replacement cost of a building) for a given damage state. Figure 2b shows an example of a consequence function that is linked to the fragility functions shown in Figure 2a.



(a) (b)

Figure 2. (a) An example of Fragility Functions for four global damage states (slight, moderate, extensive and collapse) as a function of PGA as the ground motion IM for a hypothetical building; (b) An example of consequence function linked to the global fragility curves.

Figure 3 shows the procedure for combination of fragility functions with consequence functions for a case with Modified Mercalli Intensity. More specifically, in this example at an MMI=8.4 there is 20% chance of the building destruction, 15% chance of very heavy damages, about 30% chance of substantial damage, about 15% and 8% chance of moderate and negligible damages, respectively. For lower MMI, the chance of negligible damage is higher and as intensity increases past MMI8 the chance of destruction increases substantially.

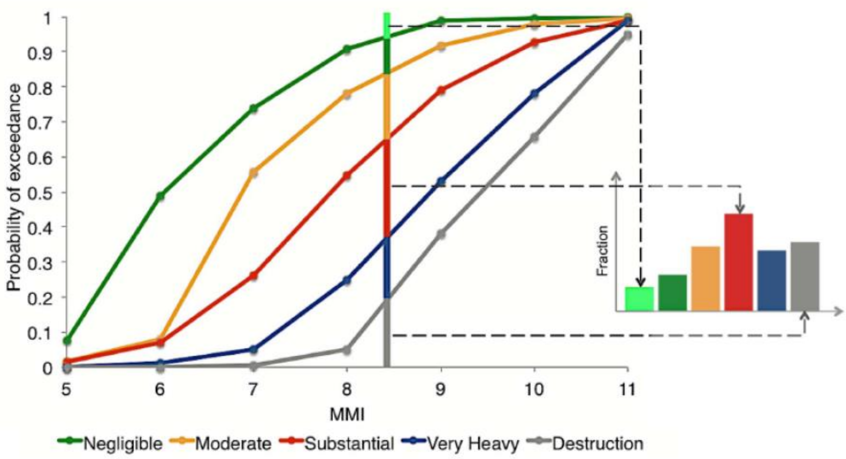


Figure 3. Schematic illustration of combining global fragility functions and associated consequence function. In this example the IM is expressed in terms of Modified Mercalli Intensity.

2.2 Consequence functions

In the last 20 years or so, several consequence models for global-response-based loss assessment have been proposed. All these models are either empirical or based on engineering judgement. Such models are commonly derived based on information regarding the repair costs claimed by the owners after the occurrence of an earthquake. A list of the most used and robust models is provided in Table 2. These are based on the studies of Di Pasquale and Goretti (2001), Durukal et al. (2006), Kappos et al. (2006), Bal et al. (2008) and HAZUS (FEMA 2003). In each case, monetary damage ratios (i.e., repair cost divided by the total replacement cost of the building) are associated with different global damage states of the building. It is interesting to note that the damage ratios proposed by Bal et al. (2008) exceeds 100%. This apparent anomaly is due to the consideration, in addition to the cost of building replacement, of also the cost of demolition and debris removal, which was estimated to be 5% of the total replacement cost for extensive damage and 4% for complete damage.

As it can be seen in Table 2, the consequence models developed for Italy, Turkey, US, and Greece, which are based on different empirical data, are indeed different. It should be noted that, all these models have different damage scales and, as discussed earlier, each damage ratio might be influenced not just by the definition of each damage state, but also by local policies. Because of the lack of available repair costs specific to the region or country of interest, on the basis of the above mentioned studies other authors have produced similar consequence functions (e.g., Chaulagain et al. (2016) for Nepalese building stock and Silva et al. (2014b) for RC buildings in Portugal). For instance, Silva (2014b) incorporated four models of Bal et al., HAZUS, Kappos et al. and Di Pasquale and Goretti (Shown in Figure 4) by taking an average between the corresponding cost ratios of the equivalent damage states in the different studies to produce the consequence function for seismic assessment of Portuguese RC buildings (i.e., Table 4).

Table 2. List of the available direct economic loss consequence functions (damage-to-loss) for global vulnerability assessment approach. Note: values 0-5 in the "damage state" column of the table represent the relative level of damage from 0 (i.e., no damage to the structure) to 5 (i.e., collapse of the structure).

Model name	Type of damage variable	Building type (Country)	Method	Damage states	General Comments
Di Pasquale and Goretti (2001)	Maximum damage to the vertical structural elements	All (Italy)	Empirical	0 (no damage) to 5 (total collapse)	▪ Damage levels are not described and there is no reference to existing damage scales. ▪ The damage scale seems to be the one used in the GNDT form used by the civil department for post-earthquake surveys in Italy. ▪ See Figure 4 for its definition.
DiPasquale-Goretti (2001)	Mean damage ratio to the entire building	All (Italy)	Empirical	0 (no damage) to 5 (total collapse)	
DiPasquale-Goretti (2001)	Mean damage to the vertical structure	All (Italy)	Empirical	0 (no damage) to 5 (total collapse)	
Durukal et al. (2006)	Replacement-cost ratio	All (Turkey)	Expert Opinion	D1 to D5 are defined on the basis of the European Macro seismic Scale – EMS'98	▪ Insurance experts were asked to give their estimations of damage levels and corresponding replacement cost ratios for eighteen cases of damage in Turkey. Their responses were analysed to yield following replacement-cost ratios which were eventually adopted in the loss estimations.
Kappos et al. (2006)	Mean damage ratio	RC & URM (Greece)	Hybrid (Empirical + Numerical)	0 (no damage) to 5 (total collapse)	▪ earthquake-damaged Greek buildings + a large number of building types are modelled and analysed (1978 Thessaloniki earthquake)
Bal et al. (2008)	Mean damage ratio	RC (Turkey)	Empirical	0 (no damage) to 5 (collapse)	▪ The cost of retrofitting applied to 231 retrofitted buildings has been obtained from a variety of sources. ▪ Main assumption: According to the Turkish code and law requirements, after an earthquake, only moderately damaged buildings are retrofitted in Turkey. Extensively and completely damaged buildings are demolished, and slightly damaged buildings are repaired.
HAZUS (FEMA 2003)	Mean damage ratio	RC (US)	Empirical	0 (no damage) to 5 (collapse)	▪ A list of all consequence functions for different occupancy types and sensitive to different EDPs are provided in Appendix B of this document.
Di Pasquale and Goretti (2001)	Damage ratio (beta distribution)	RC and URM (Italy)	Empirical	0 (no damage) to 5 (collapse)	▪ See Table 3 for the definition of beta distribution.

Table 3. Statistical values of the relative repair cost relevant to the damage levels adopted from (Goretti and Di Pasquale) (Note: μ, σ, q and r are the beta distribution parameters)

L_d	0	1	2	3	4	5
μ	0.005	0.035	0.145	0.305	0.800	0.950
σ	0.035	0.043	0.056	0.111	0.113	0.060
q	0.015	0.604	5.587	4.942	9.224	11.585
r	3.046	16.662	32.946	11.262	2.306	0.610

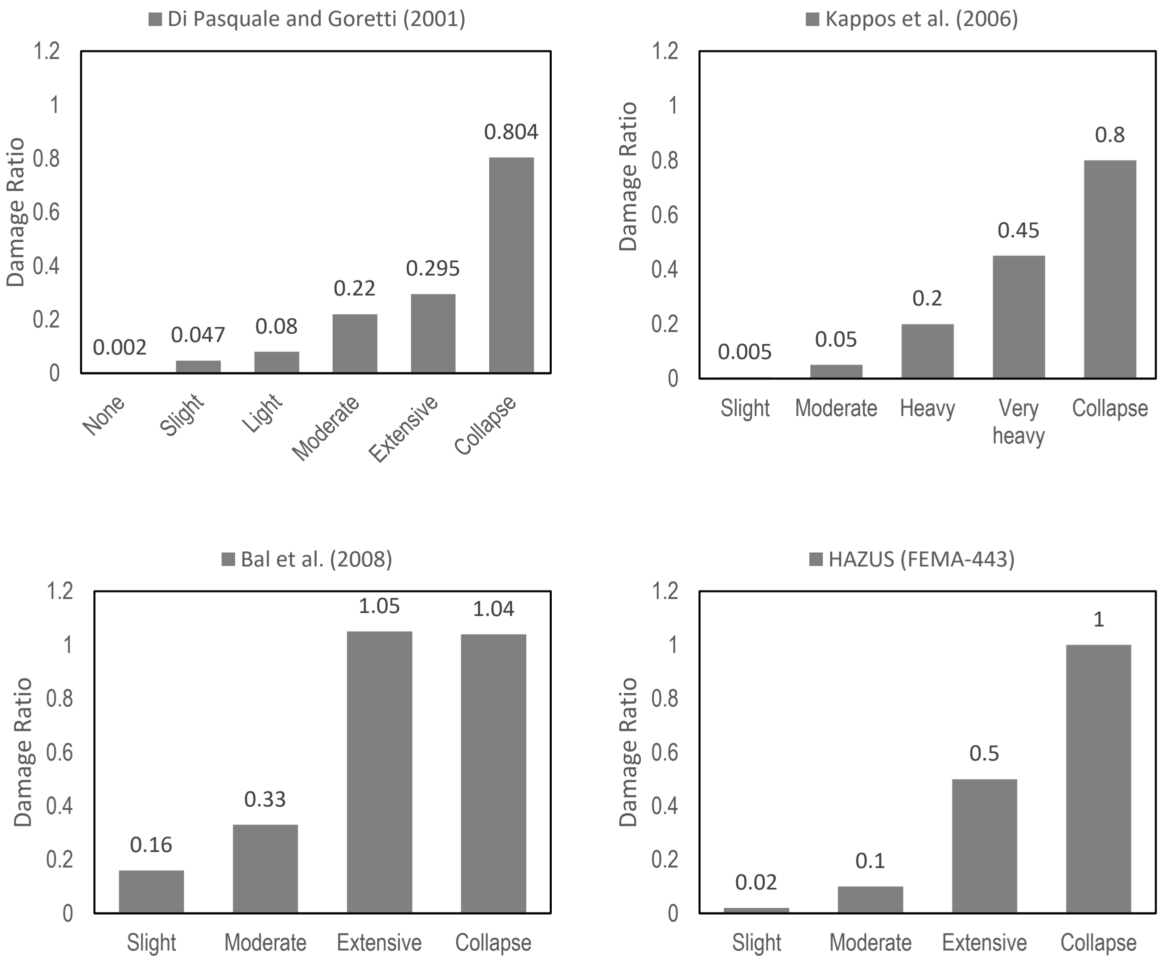


Figure 4. Comparison of the suggested consequence function mean damage ratios by Di Pasquale and Goretti (2001), Kappos et al. (2006), Bal et al. (2008) and HAZUS (FEMA 2003).

Beside the above mentioned studies that provide cost ratio estimates as a function of the building global damage level, De Martino et al. (2017) provided a preliminary relationship that correlates the damage detected by in situ inspections and the corresponding actual repair costs for damaged buildings after the 2009 L'Aquila earthquake. The damage definition in this study is based on the Italian Department of Civil Protection AeDES form described in Baggio et al. (2007) for about 50,000 buildings and focuses mainly on the residential reinforced concrete (RC) and masonry buildings damaged by the 2009 L'Aquila earthquake. The repair costs of the buildings were determined directly from the repair interventions designed and computed by practitioners engaged by owners in a post-earthquake reconstruction process (Di Ludovico et al. 2017a; Di Ludovico et al. 2017b). Even though the scope of De Martino et al. (2017) is mainly focused on helping the inspectors to make preliminary estimates of the repair cost based on quick post-earthquake surveys on residential buildings, the relationships developed in that study can also be used as a tool to estimate repair costs (as a function of the repair strategy) when performing risk assessment.

Table 4. Consequence model used in the development of the vulnerability model for the Portuguese RC building stock (Silva et al. 2014b).

Damage State	Damage Ratio	
	Mean	Coefficient of Variation
Slight	0.1	30
Moderate	0.3	20
Extensive	0.6	10
Collapse	1.0	0

3 Taxonomy

This section describes the residential, non-residential and infrastructure taxonomy classification for the central Asian countries. The residential building typology consists of six main building types with a total of 15 subtypes (Table 5) following the strategies described by Wieland et al. (2015) and more recently by Pittore et al. (2020). The taxonomy is defined according to the GED4ALL[1] mapping scheme. Herein we do not go through details of the definition of the classes and the parameters in the current document. More information about the definition of the acronyms used in the following tables can be found in the exposure modelling reports of this project (report of Task 4 - Exposure data development [2]). Several different surveys have been conducted in the Kyrgyz Republic and in Tajikistan between 2012 and 2016, for a total of around 7000 buildings remotely surveyed (Pittore et al. 2020). The surveys have been conducted by local engineers experienced in the local building practices. The surveyed buildings are then mapped to the building type. These typologies are deemed to be representative of the building stock in the region, in different proportions according to the country and the type of settlement (e.g., urban or rural).

Non-residential buildings include eight different occupancy types as listed in Table 6. The building types for this category of assets are basically made of a combination of multiple building classes listed in Table 5. Table 6 shows the fractions of different building classes for the non-residential buildings. We also consider ten classes of infrastructure for road, railways and bridges. Table 7 shows and describes these classes.

[1] https://www.hotosm.org/projects/global-exposure-database-for-all-ged4all

[2] Report of Task 4 - Exposure data development (2021) Interim technical report of exposure development, Project "Regionally consistent risk assessment for earthquakes and floods and selective landslide scenario analysis for strengthening financial resilience and accelerating risk reduction in Central Asia (SFRARR Central Asia disaster risk assessment)", coordinated by RED Risk Engineering + Development

Table 5. Summary of the taxonomy for residential buildings

EMCA typology	Sub-typology	Age	Storeys	Floor area (m²)	House-holds	Average occupancy	Taxonomy
EMCA1	URM1	1930-1960	2-4	500	1	3.8	/MUR + CLBRS + MOC/LWAL + DNO/FW + HBET:2,4 + YBET/1930,1960
	URM2		1-2				MUR+ MOCL/LWAL + DNO/FC + HBET:1,2 + YBET/1930,1960
	CM	1960-2001	1-5	2600	12	76	/MCF + MOC/LWAL + DNO/FC/HBET:1,5 + YBET/1960,2001
	RM-L		1-2			5.2	/MR + MOC/LWAL + DNO/FC/HBET:1,1 + YBET:1960,2001
	RM-M		3-4			104	/MR + MOC/LWAL + DNO/FC/HBET:3,4 + YBET:1960,2001
EMCA2	RC1	1957-2006	3-7	11000	45	152	/CR + CIP/LFM + DUC/FC/HBET:3,7 + YBET:1957,2006
	RC2	1957-2021	4-9				/CR + CIP/LDUAL + DNO/FC/HBET:4,9 + YBET:1957,2020
	RC3	1957-2021	2-5				/CR + CIP/LFINF + DNO/FC/HBET:2,5 + YBET:1957,2021
	RC4	1957-2006	4-16			190	/CR + CIP/LWAL +DNO/FC/HBET:4,16 + YBET:1957,2006
EMCA3	RCPC1	1956-1980	1-16	5000	70	152	/CR + PC/LWAL + DUC/FC/HBET:1,16 + YBET:1956,1980
	RCPC2	1980-2021	3-12				/CR + PC/LFLS + DUC/FC/HBET:3,12 + YBET:1980,2021
EMCA4	ADO	n.a.	1	100	1	5.2	/MUR + ADO/LWAL + DNO/FW/HBET:1
EMCA5	WOOD1	to present	1-2				/W/LWAL + DUC/FW/HBET:1,2 + YPRE:2021
	WOOD2	<1980	1-2	1850	1	3.8	/W+ WLI/LO + DUC/FW/HBET:1
EMCA6	STEEL	n.a.	1	2000	1		/S/LFM +DNO/FME/HBET:1

Table 6. Summary of the taxonomy for non-residential buildings. ***Note: When no data has been available (not available) "N.A" is shown for the material fractions.***

Building type	Taxonomy	Description	Material fractions
Industrial	IND_UNK+HBET:1:2	Defined as the weighted combination of the most common industrial taxonomies in post-soviet countries (see metadata for details)	33% EMCA6 + 31% EMCA1 + 25%EMCA2 + 7%EMCA3 + 3.5% EMCA5
Commercial wholesale and services	UNK/ + HBET:1,6	Commercial wholesale and services – Defined as weighted combination of the most common commercial taxonomies in post-soviet countries (see metadata for details)	36% EMCA5 + 26% EMCA1 + 37% EMCA2 + 1%EMCA3
Commercial retail	UNK/ + HBET:1,5 + YBET:1930,2021	Commercial retail – Defined as the weighted combination of the most common residential taxonomies in each country (see metadata for details)	KAZ: 26%EMCA1, 35% EMCA4, 28% EMCA5, 9% EMCA6 KYR: 31%EMCA1, 67% EMCA4 TAJ: 25% EMCA1, 72%EMCA4 UZB: 84% EMCA1, 9% EMCA4 TUR: 35% EMCA1, 57% EMCA4
Hospitals	UNK + HBET:1,16 + YBET:1956,2021	Hospitals – Defined as the weighted combination of EMCA2 and EMCA3 typologies	50% EMCA2 and 50% EMCA3
Clinics	UNK/ + HBET:1,5 + YBET:1930,2021	Clinics – Defined as weighted combination of most common residential taxonomies in each country (see metadata for details)	KAZ: 26%EMCA1, 35% EMCA4, 28% EMCA5, 9% EMCA6 KYR: 31%EMCA1, 67% EMCA4, TAJ: 25% EMCA1, 72%EMCA4 UZB: TUR: 35% EMCA1, 57% EMCA4
Other healthcare facilities	UNK/ + HBET:1,5 + YBET:1930,2021	Other healthcare facilities (dentist, doctor, pharmacy) – Defined as weighted combination of most common residential taxonomies in each country (see metadata for details)	KAZ: 26%EMCA1, 35% EMCA4, 28% EMCA5, 9% EMCA6 KYR: 31%EMCA1, 67% EMCA4, TAJ: 25% EMCA1, 72%EMCA4 UZB: N.A TUR: 35% EMCA1, 57% EMCA4
Urban schools	SCHOOL_URB_UNK + YBET:1960,2021	Material: weighted sum of the most common school typologies in Kyrgyz Republic	59% EMCA1, 10% EMCA3, 31% EMCA4
Rural schools	SCHOOL_RUR_UNK + YBET:1960,2021	Rural schools – Defined as the weighted sum of the most common school typologies in Kyrgyz Republic	50% EMCA2 and 50% EMCA3

Table 7. Summary of the taxonomy for infrastructures

Type	Taxonomy	Description
Road network	RDN+MO	Motorway: restricted access major divided highway (i.e., freeway), normally with 2 or more running lanes plus emergency hard shoulder
	RDN+TR	Trunk: the most important roads in a country's system that aren't motorways (not necessarily be a divided highway)
	RDN+PR	Primary: the next most important roads in a country's system (often link larger towns)
	RDN+SE	Secondary: the next most important roads in a country's system (often link towns)
	RDN+TE	Tertiary: the next most important roads in a country's system (often link smaller towns and villages)
Railway network	RLW+LR	Light rail: a higher-standard tram system, normally in its own right-of-way. Often reaches a considerable length (tens of kilometer)
	RLW+MR	Monorail: a single-rail railway
	RLW+RL	Rail: full sized passenger or freight trains in the standard gauge for the country or state
Bridges	RDN+BR	Road bridges: most of them constituted by RC and steel, more than 85% constructed between 1960 and 1990
	RLW+BR	Railway bridges: large majority constituted of RC, most of them with length<25m

4 Residential buildings

4.1 Available relevant fragility and vulnerability studies

Many international and local studies have been collected during the project. In particular, the local partners of the Consortium have gathered multiple local references that provide information about the earthquake fragility of buildings in the region. We reviewed such studies about the fragility and vulnerability analysis of the most common structural types in central Asia and considered them to generate a regional harmonized vulnerability model for this study. A short description of these references is provided hereafter. These studies are herein categorized into five main groups: (i) SRKR16; (ii) SERA; (iii) International Literature; (iv) GLOSI, and (v) local studies. We herein explored these studies and described how they were used to derive a final set of vulnerability curves for each one of the residential classes listed in Table 5. In the following subsections a short description for each group is provided.

4.1.1 World Bank funded project for Kyrgyzstan republic (SRKR16)

This study (World-Bank 2016) is based on a World Bank funded project to develop building fragility functions to be used for seismic risk assessment in the Kyrgyzstan Republic (here after called SRKR16). The fragility functions are provided for the EMCA building typologies, which are defined based on the building material and construction methodologies employed in central Asian countries. The building classes and the final fragility function parameters of this study, in terms of the mean and logarithmic standard deviation for five damage states, are listed in Table 8. Note that, the building classes listed in Table 8 are mapped with their corresponding ones in our residential taxonomy classes (see Table 5). Given the generality of these functions, this study states that they can be used for residential buildings, schools, hospitals, fire stations, etc. The study follows a vulnerability index approach, which is a hybrid of the empirical and expert-judgement-based methods. In this study, the SYNER-G approach (Pitilakis et al. 2014) was applied to the Kyrgyz building stock using a classification of building types that is consistent with the building environment in the country. In order to convert these fragility functions to vulnerability, we have used the consequence function proposed by Kappos et al. (2006). Note that Kappos et al. (2006) provides ranges of damage ratio for each damage states, although herein we used the central values of such ranges: 0.005, 0.05, 0.2, 0.45 and 0.8 damage ratios for slight, moderate, heavy, very heavy, and collapse damage states, respectively. This is done to avoid considering a too large uncertainty in the final vulnerability model that is already built considering a large database of different studies and consequently a large uncertainty due to the variety of sources.

It should be emphasized that no specific data about consequences are available for the Central Asia context, thus it was necessary to select adequate and applicable functions from literature to derive vulnerability functions from the fragility models available. The Kappos consequence function was selected since it is defined according the EMS98 damage scale and such scale has been used to derive most of the fragility models considered in our study. This consequence function has been often used in other places of the world. For instance, SYNER-G vulnerability database, which includes also the Eastern European countries, uses Kappos consequence functions among others. If in the future consequence data specific for the Central Asia context would become available, it will be possible to overcome this assumption and leverage all the data collected and the methodology adopted in this study to derive an updated vulnerability model.

Table 8. Fragility parameters in terms of PGA reported and used SRKR16. Note: the EMCA numbers are the ones used SRKR16 and not the ones used in the current study.

No.	Acronym	EMCA Number	Description	DS 1		DS 2		DS 3		DS 4		DS 5	
				μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
1	SRKR-1.1	1.1	Unreinforced masonry with	0.08	0.21	0.11	0.21	0.15	0.21	0.21	0.21	0.33	0.21
2	SRKR-1.2	1.2	Unreinforced masonry with	0.10	0.23	0.13	0.23	0.19	0.23	0.27	0.23	0.42	0.23
3	SRKR-1.3	1.3	Reinforced or confined	0.17	0.25	0.26	0.25	0.38	0.25	0.56	0.25	0.86	0.25
4	SRKR-1.4	1.4	Reinforced or confined	0.17	0.25	0.26	0.25	0.38	0.25	0.56	0.25	0.86	0.25
5	SRKR-2.1	2.1	Monolithic concrete frames	0.15	0.25	0.24	0.25	0.35	0.25	0.5	0.25	0.78	0.25
6	SRKR-2.2	2.2	Dual frame and wall	0.17	0.25	0.27	0.25	0.39	0.25	0.57	0.25	0.88	0.25
7	SRKR-2.3	2.3	Monolithic frames with brick infill	0.12	0.24	0.18	0.24	0.26	0.24	0.38	0.24	0.58	0.24
8	SRKR-2.4	2.4	Monolithic concrete walls with flat slabs	0.2	0.26	0.31	0.26	0.45	0.26	0.65	0.26	1.01	0.26
9	SRKR-3.1	3.1	Large panel walls with monolithic panel joints	0.21	0.26	0.33	0.26	0.49	0.26	0.71	0.26	1.1	0.26
10	SRKR-3.2	3.2	Large panel walls with welded plate connections	0.24	0.26	0.38	0.26	0.56	0.26	0.82	0.26	1.28	0.26
11	SRKR-3.3	3.3	Flat slab	0.1	0.23	0.15	0.23	0.21	0.23	0.3	0.23	0.47	0.23
12	SRKR-3.4	3.4	Frame with cruciform and linear beam elements	0.17	0.25	0.26	0.25	0.38	0.25	0.56	0.25	0.86	0.25
13	SRKR-4.1	4.1	Adobe structures	0.07	0.19	0.1	0.19	0.12	0.19	0.16	0.19	0.24	0.19
14	SRKR-5.1	5.1	Wooden structures	0.12	0.24	0.17	0.24	0.25	0.24	0.37	0.24	0.57	0.24
15	SRKR-6.1	6.1	Steel structures	0.34	0.26	0.54	0.26	0.79	0.26	1.16	0.26	1.87	0.26

4.1.2 SERA

A large database of fragility and vulnerability curves including 511 different building classes was recently generated within the framework of SERA project. The vulnerability models developed within this study will be one of the inputs to the European seismic risk model. It should be noted that in this study while generating fragility and vulnerability functions, information about Eastern Europe countries have also been considered. Given the similarities between the construction practice in such counties and that in the Central Asian countries considered here, we decided to include SERA as one of the sources in our calculations.

SERA's methodology builds upon an extensive review of existing fragility and vulnerability models and is based on a robust framework that accounts for and propagates all the sources of uncertainty affecting the problem, including the building-to-building variability, the uncertainty about the record-to-record variability (relevant for the curves derived via an analytical approach that uses nonlinear dynamic analysis of structures subject to ground motion records) and the uncertainty about the damage states. The robustness of the framework is also set by a systematic validation. In SERA, four attributes were selected for the consistent definition of building classes across Europe: (i) Main construction material (reinforced concrete, unreinforced masonry, reinforced/confined masonry, adobe, steel, timber); (ii) Lateral load-resisting system, LLRS (infilled frame, moment frame, wall, dual frame-wall system, flat slab/plate or waffle slab, post and beam); (iii) Number of stories; and (iv) Ductility level (non-ductile, low, moderate and high ductility). The main attributes used in SERA to define the residential masonry and reinforced concrete buildings are listed in Table 9 and Table 10, respectively.

Table 9. Main attributes used for definition of residential masonry buildings within SERA framework

Typology (MTYPE)	Masonry unit (Block)	Number of stories (H)	Ductility Level (DC)
• Unreinforced masonry (MUR) • Reinforced masonry (MR) • Confined masonry (MCF)	• Adobe (ADO) • Fire clay unit, unknown type • solid bricks (CL99) • Fire clay solid bricks (CLBRS) • Stone, unknown technology (S99) • Regular cut stone (STDRE) • Rubble stone (STRUB) • Concrete blocks (CB)	• H:1 to 2 (L) • H:3 to 5 (M) • H:6 to 7 (H) • H:8+ (Ta)	• Non-ductile (DNO) • Low Ductility (DUL) • Medium Ductility (DUM) • High Ductility (DUH)

Table 10. Main attributes used for definition of residential RC buildings within SERA framework

Lateral Load resisting system (LLRS)	Number of stories (H)	Ductility Level (DUC)
• RC frame buildings (LFM) • RC frame buildings with infill walls (LFINF) • RC wall buildings (LWAL) • RC wall-frame dual buildings (LDUAL) • RC buildings with flat/waffle/ribbed slabs (LFLS) • RC buildings with flat/waffle/ribbed slabs with infill walls (LFLSINF)	• H:1 • H:2 • H:3-5 • H:6+	• DUL • DUM • DUH

4.1.3 *Local studies*

The local partners of the Consortium have made a considerable effort to collect multiple studies about the fragility and vulnerability of typical buildings in their country and to provide useful information on the topic. We have thoroughly reviewed all this material, and a summary of the most relevant references are listed in this section. These local studies are then used for calibrating our proposed vulnerability functions.

4.1.3.1 Turkmenistan

The 4th Annex of the document "Construction in seismic areas. Part 1: Residential, public and industrial buildings and structures" issued by the ministry of construction in Turkmenistan, provides valuable information regarding the vulnerability of existing buildings. The first part of the Annex describes the classification of existing building types based on the material of structures, structural type, and earthquake-resistant design. The building structures located in earthquake-prone areas are classified into different taxonomy classes according to their seismic vulnerability. Table 11 describes the different typologies (left) and the distribution of damage grades for each typology (right) according to MSK-64. The tables are to be used for the structural design of new buildings and damage assessment of buildings in terms of MSK-64 scale. Furthermore, the tables might be used when selecting measures for strengthening existing buildings. The building classes listed in Table 11 have been mapped with their corresponding classes in our building taxonomy (see Table 5) to leverage the information provided for the development of the final vulnerability model. The mapping has been done considering the typologies of building material, lateral load resisting system, the building class height and age ranges.

Table 11 provides the data to construct fragility curves for the different typologies and Table 12 defines the damage states. It defines fragility curves in terms of macroseismic intensity (MSK). In order to convert the macroseismic intensity to peak ground acceleration (PGA), an IGMCE (Intensity to ground motion conversion equation) has to be used. We used three different conversion equations to account for the epistemic uncertainty associated with a conversion from macroseismic intensity to a ground motion parameter. For more information see report of Task 4 - Exposure data development of the current project. In particular we considered those proposed by Faenza and Michelini (2010), Murphy & O'Brien (1977) and Margottini et al. (1992), which are shown in Equation (1), (2) and (3).

$$I_{MCS} = 1.68 + 2.58 * log_{10}PGA \quad (1)$$

$$log_{10}PGA = 0.25 * I_{MMI} + 0.25 \quad (2)$$

$$log_{10}PGA = 0.18 * I_{MSK} + 0.85 \quad (3)$$

In order to convert the fragility functions to vulnerability curves, we have used the consequence function proposed by Kappos et al. (2006) with 0.005, 0.05, 0.2, 0.45 and 0.8 for five damage states ranging from 1 to 5. Please refer to section 4.1.1 for a detailed explanation on the reason why this consequence function was preferred herein.

Table 11. Classification of building types in Turkmenistan-Construction in seismic areas according to the National Seismic Code

Type	Description
1	Buildings with adobe or mud brick, or rubble stone walls without strengthening with wooden framework, including: a) buildings with a heavy earthen roof; b) buildings with a light wooden roof. (Without seismic considerations)
2	Buildings with adobe walls, reinforced with a wooden framework coupled to the foundation. (Without seismic considerations)
3	Buildings with masonry walls of standard bricks, stone or blocks on cement or mixed mortar, made without antiseismic protection, including: a) buildings with wooden floors; b) buildings with prefabricated reinforced concrete floors. (Without seismic considerations).
4	Buildings with masonry walls of standard bricks, stone, blocks on cement or mixed mortar, made with antiseismic strengthenings such as masonry reinforcement, reinforced concrete belts and RC inclusions without full framing. Buildings with external masonry walls and internal RC or metal frames (posts). (Design seismic intensity level 7, 8, 9).
5	Buildings with walls of complex construction, where RC belts and posts constitute a full frame and are concreted in masonry slots which are open at least on two sides. Large-panel buildings with non-cast-in-place joints. (Design seismic intensity level 7, 8, 9).
6	Prefabricated and monolithic RC frame buildings with not earthquake-resistant infill walls. (Design seismic intensity level 7, 8, 9).
7	Frame-braced prefabricated and monolithic reinforced concrete buildings. (Design seismic intensity level 7, 8, 9).
8	Large-panel buildings with cast-in-place concrete joints. Monolithic reinforced concrete buildings constructed in climbing formwork. (Design seismic intensity level 7, 8, 9).
9	Steel-framed buildings with lightweight walls. (Design seismic intensity level 7, 8, 9).

Table 12. Definition of damage grades

Building type	Distribution (%) of damage grades (MSK-64)					
	0	1	2	3	4	5
Intensity VI						
1.a	0	10	50	37,5	2	0,5
1.б	0	37,5	50	10	2	0,5
2	10	50	37,5	2	0,5	0
3.a	37,5	50	10	2	0,5	0
3.б	50	37,5	10	2	0,5	0
4(7)	87,5	10	2	0,5	0	0
5(7), 4(8)	97,5	2	0,5	0	0	0
6(7), 5(8), 4(9)	97,5	2	0,5	0	0	0
7(7), 6(8), 5(9)	99,5	0,5	0	0	0	0
8(7), 7(8), 6(9)	99,5	0,5	0	0	0	0
9(7), 8(8), 7(9)	99,5	0,5	0	0	0	0
9(8), 8(9)	99,5	0,5	0	0	0	0
9(9)	99,5	0,5	0	0	0	0
Intensity VII						
1.a	0	0,5	10	50	37,5	2
1.б	0	0,5	37,5	50	10	2
2	0	10	50	37,5	2	0,5
3.a	0	37,5	50	10	2	0,5
3.б	0	50	37,5	10	2	0,5
4(7)	37,5	50	10	2	0,5	0
5(7), 4(8)	87,5	10	2	0,5	0	0
6(7), 5(8), 4(9)	87,5	10	2	0,5	0	0
7(7), 6(8), 5(9)	97,5	2	0,5	0	0	0
8(7), 7(8), 6(9)	97,5	2	0,5	0	0	0
9(7), 8(8), 7(9)	99,5	0,5	0	0	0	0
9(8), 8(9)	99,5	0,5	0	0	0	0
9(9)	99,5	0,5	0	0	0	0
Intensity VIII						
1.a	0	0	0	30	50	20
1.б	0	0	0,5	37,5	50	12
2	0	0,5	10	50	37,5	2
3.a	0	0,5	37,5	50	10	2
3.б	0	0,5	50	37,5	10	2
4(7)	0	37,5	50	10	2	0,5
5(7), 4(8)	37,5	50	10	2	0,5	0
6(7), 5(8), 4(9)	50	37,5	10	2	0,5	0
7(7), 6(8), 5(9)	60	37,5	2	0,5	0	0
8(7), 7(8), 6(9)	87,5	10	2	0,5	0	0
9(7), 8(8), 7(9)	97,5	2	0,5	0	0	0
9(8), 8(9)	99,5	0,5	0	0	0	0
9(9)	99,5	0,5	0	0	0	0
Intensity IX						
1.a	0	0	0	0,5	37,5	62
1.б	0	0	0	0,5	50	49,5
2	0	0	0	30	50	20
3.a	0	0	0,5	37,5	50	12
3.б	0	0	0,5	50	37,5	12
4(7)	0	0,5	37,5	50	10	2
5(7), 4(8)	0	37,5	50	10	2	0,5
6(7), 5(8), 4(9)	0	50	37,5	10	2	0,5
7(7), 6(8), 5(9)	37,5	50	10	2	0,5	0
8(7), 7(8), 6(9)	50	37,5	10	2	0,5	0
9(7), 8(8), 7(9)	87,5	10	2	0,5	0	0
9(8), 8(9)	97,5	2	0,5	0	0	0
9(9)	99,5	0,5	0	0	0	0
Intensity higher than IX						
1.a	0	0	0	0	0,5	99,5
1.б	0	0	0	0	0,5	99,5
2	0	0	0	0,5	20	79,5
3.a	0	0	0	0,5	37,5	62
3.б	0	0	0	0,5	50	49,5
4(7)	0	0	0,5	37,5	50	12
5(7), 4(8)	0	0,5	37,5	50	10	2
6(7), 5(8), 4(9)	0	0,5	50	37,5	10	2
7(7), 6(8), 5(9)	0	10	50	37,5	2	0,5
8(7), 7(8), 6(9)	0	37,5	50	10	2	0,5
9(7), 8(8), 7(9)	37,5	50	10	2	0,5	0
9(8), 8(9)	50	37,5	10	2	0,5	0
9(9)	87,5	10	2	0,5	0	0

Damage grades:
0-no damage, 1-slight damage, 2-moderate damage, 3-heavy damage, 4-destruction, 5-collapse

4.1.3.2 Kyrgyz Republic

The document issued by the local partners in the Kyrgyz Republic provides information from one study carried by the State Seismic Resistance and Design Institute of Kyrgyz Republic concerning the earthquake vulnerability assessment of different building typologies in country. The scope of that study was to compare structural schemes of buildings in the Kyrgyz Republic according to MSK-64 and EMS-98 and to assess the seismic resistance of existing buildings. A vulnerability curve, already defined in terms of percentage of damage expected in the building for a given level of macroseismic intensity, is assigned to each building class based on EMS-98 scheme. (Figure 5). The building classes listed in Table 13 have been mapped with the corresponding classes in our building taxonomy (see Table 5) to leverage the information provided for the development of the final vulnerability model. The mapping has been done considering the typologies of building material, lateral load resisting system, the building class height and age ranges. We follow the same procedure as described in Section 4.1.3.1 to convert the macroseismic intensity to PGA.

Table 13. Classification of different typologies in EMS-98 in the Kyrgyz Republic (Note: The classification of the existing buildings is performed according to the degree of seismic resistance according to SN KR 22-01:2018)

№	Class	Structural scheme of the building	Building class by EMS-98
1	1.1	Large-panel buildings with monolithic butt joints of wall panels between themselves and floor slabs. TP-series 105	E
2	1.2	Buildings with steel frames and hinged wall panels	E
3	1.3	Buildings with load-bearing walls of monolithic reinforced concrete, erected in volumetric-rearrange or large-panel formwork	E
4	1.4	Buildings with monolithic reinforced concrete cores of rigidity, monolithic or precast concrete frame of construction	E
5	1.5	One-story buildings with reinforced concrete frames and hinged wall panels	E
6	2.1	Large-panel buildings with butt joints of wall panels and floor slabs on welding of embedded parts	E
7	2.2	Buildings with precast concrete frame of linear elements and butt joints of longitudinal reinforcement on the bathroom welding. Wall fencing – hinged wall panels	D
8	2.3	Buildings with load-bearing walls of monolithic reinforced concrete, erected in sliding formwork	D
9	3.1	One-, two-story buildings with reinforced concrete frame and wall-filling of brickwork in the frame plane, designed after 1957	D
10	3.2	Multi-story frame reinforced concrete buildings with wall fencing of brickwork in the plane of the frame, designed after 1957	D
11	3.3	One-, two-story buildings with reinforced concrete frame and wall-filling of brickwork in the frame plane, designed before 1957	C
12	3.4	Multi-story frame reinforced concrete buildings with brick wall fencing in the frame plane, designed before 1957	C
13	4.1	Buildings with wooden frames and wall-filling of reeds	C
14	4.2	Prefabricated wooden panel buildings	D
15	4.3	Wooden chopped buildings	E
16	5.1.	Frame reinforced concrete buildings with self-supporting brickwork walls, designed after 1957	C
17	5.2.	Frame reinforced concrete buildings with self-supporting walls, designed before 1957	C
18	6.1	Buildings with load-bearing walls of brickwork with reinforced concrete inclusions (complex structures) and monolithic reinforced concrete floors	D

№	Class	Structural scheme of the building	Building class by EMS-98
19	6.2	Buildings with load-bearing walls of brickwork with reinforced concrete inclusions (complex structures) and precast concrete floors	C, D
20	6.3	Buildings with load-bearing walls of brickwork and monolithic reinforced concrete floors, designed after 1957	C
21	6.4	Buildings with load-bearing brick walls and precast concrete floors designed after 1957	C
22	6.5	Buildings with load-bearing walls of brickwork and monolithic reinforced concrete floors, designed before 1957	B
23	6.6	Buildings with load-bearing walls of brickwork and precast concrete floors, designed before 1957	B
24	6.7	Buildings with external load-bearing walls of brickwork and internal reinforced concrete frame (incomplete frame)	C
25	6.8	Multi-story buildings with first flexible floor	B
26	7.1	One-story buildings with load-bearing walls of brickwork and wooden beamed floors	B
27	7.2	Buildings with a height of two or more floors with load-bearing walls of brickwork and wooden floors	B
28	8	Buildings with load-bearing walls made of adobe or raw brick	A

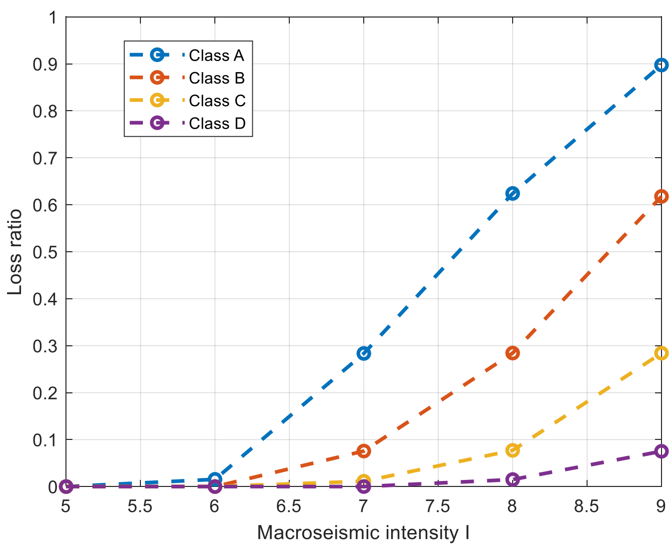


Figure 5. Vulnerability curves-Kyrgyz Republic provided by the local partners. Legend: different lines in the figure refer to the different classes of A, B, C and D. ***Note: The curve for class E was almost always zero for the range of intensities considered in the plot and hence was discarded for improving clarity of the chart.***

4.1.3.3 Uzbekistan

The document contains valuable information derived from an international research project (NATO Science for Peace project) carried out between 2000-2004 to assess and reduce the seismic risk in Uzbekistan. The objectives of that research project were mainly to assess the seismic hazard, estimate the expected losses from earthquake events, and find ways to mitigate those losses. The document provides a vulnerability classification for a list of building typologies. Those building typologies were matched across taxonomies by comparing the main attributes of each typology. The building typologies in Table 14 have been mapped with their corresponding ones in our building taxonomy (see Table 5) in terms of construction material, number of stories and seismic design level as described in section 4.1.3.1.

In that study two approaches for generation of fragility curves are undertaken. In the first approach, fragility curves are generated based on macroseismic intensity while in the he second approach (the one we considered as a reference in our study) creates fragility curves based on the capacity spectrum method (CSM). Table 14 contains information on the parameters of the fragility curves based on Spectral displacement that are provided for different typologies in that study.

The fragility functions available in this reference were harmonized with the others first of all by converting the intensity measure definition. The spectral displacements were turned into spectral accelerations depending on the period of each structure by using $S_a = \omega^2 \times S_d$ that relates pseudo spectral acceleration (Sa) and pseudo spectral displacement (Sd) through natural frequency (ω). Then the spectral acceleration was converted into PGA using the ground motion prediction equation (GMPE) from Akkar and Bommer (2010) and constructing a spectral shape considering the plausible magnitudes and distances most contributing to the hazard in the region.

Table 14. Fragility curves for different typologies in Uzbekistan-Local reference

Building type	Slight		Moderate		Extensive		Full	
	Sd [cm]	β	Sd [cm]	β	Sd [cm]	β	Sd [cm]	β
1 -2-storey, clay, built before 1948	0.675	0.99	1.35	1.05	2.03	1.10	2.70	1.08
1-2-storey, built before 1966 mainly of raw brick	0.675	0.99	1.35	1.05	1.69	1.10	2.03	1.08
1-2-storey, brick, built after 1966	0.675	0.99	1.35	1.05	2.03	1.10	2.70	1.08
2-storey, brick multi-section	1.406	0.99	2.81	1.05	4.22	1.10	5.63	1.08
4-5-storey brick, built before 1966	2.531	0.90	5.06	0.95	8.10	1.00	11.14	0.98
4-5-storey, brick, with anti-seismic measures	3.544	0.70	7.09	0.74	10.13	0.86	12.15	0.98
4-5-storey, large-panel	4.050	0.70	8.10	0.74	14.18	0.86	25.31	0.98
9-storey, large-panel	6.143	0.70	12.29	0.81	20.48	0.89	32.76	0.98
9-12-storey, frame-panel	7.020	0.70	17.55	0.74	26.33	0.86	43.88	0.98
Volumetric block	4.050	0.70	8.10	0.74	14.18	0.86	25.31	0.98
16-storey, monolithic frame	17.28	0.66	28.80	0.66	57.60	0.76	115.20	0.91

4.1.4 *Other studies (literature)*

Herein we also use several studies from the international literature (Ahmad et al. 2011; Karantoni et al. 2011; Kostov et al. 2004; Lagomarsino and Cattari 2014) that are relevant for the study area. In addition to the above-mentioned studies, we considered a World Bank funded project (MottMacDonald 2020) that provides input to the seismic risk analysis of multi-family buildings in the Europe and Central Asia region. Within this report a set of fragility and vulnerability functions for large-panel multi-family buildings (LPBs) in Bulgaria are presented. These functions are the result of an investigation of the seismic performance of this building type by means of full-scale non-linear finite element models with LS-Dyna. In this study, the fragility functions for more than 11 different structural configurations, building heights and layouts are provided. This study further combines the fragility curves with a proposed consequence function in terms of direct loss ratios of 0.05, 0.15, 0.45, 1.00 and 1.00 corresponding with the DS1 to DS5.

4.1.5 GLOSI

To enhance the library of the vulnerability functions of the residential and non-residential buildings, already established vulnerability functions from GLOSI (Global Library of School Infrastructure) were used in this study. The GLOSI is a global repository of evidence-based knowledge and data about school infrastructure. It includes a global catalog of school building types, vulnerability information, and solutions to improve the safety and resilience of school infrastructure. Among the vulnerability functions in the GLOSI database, we have considered only those relevant to the local context. Some examples of the typologies used in the current study are illustrated in Figure 6 and Figure 7. Since GLOSI provides the final vulnerability curve for each typology in terms of PGA, there was no need to convert the intensity measure (IM).

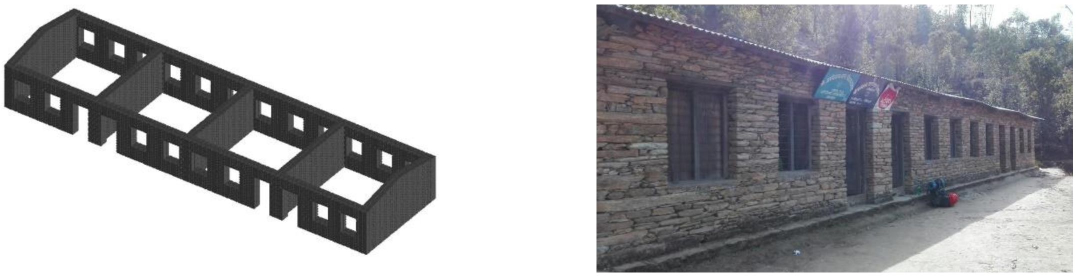


Figure 6. Dry stone masonry (UCM-URM1 Low-rise with low seismic design)-GLOSI

Figure 7. Rectangular block in Cement Mortar Masonry (UCM-URM 7 mid-rise with low seismic design)-GLOSI

4.2 Proposed vulnerability functions for residential buildings

To derive the final regional vulnerability curves for each residential building class of the taxonomy, the vulnerability functions retrieved from the available studies are mapped to each single class as described in the section above. Table 15 lists the studies that correspond to the 15 residential building classes. The functions from the different references were harmonized to the same intensity measure, peak ground acceleration, and when fragility curves were reported, the functions were combined with an appropriate consequence function, compatible with the damage scale assumed in the original reference. The harmonization allowed to make a direct comparison of the information provided in the different references considered.

Figure 8 to Figure 22 show the comparison of the functions obtained from the different data sources along with the statistics extracted from them and the vulnerability functions proposed in this vulnerability study. Figure 23 shows the comparison among the functions obtained for each building class in the taxonomy. Note that in these Figures, the thin dotted lines represent the individual study of a cluster (e.g., "Local: TKM") while the thicker solid lines show the mean of the group. The same colour was used for both for better presentation of the results.

We made a statistical analysis of all the functions collected and mapped to each building class of the taxonomy to determine the mean vulnerability and the associated uncertainty for a given level of intensity measure. A summary of the procedure is briefly listed below:

1- For each cluster of the curves (e.g., SERA) and for a given building class (e.g., EMCA1-URM1), multiple curves might have been available. To avoid overweighting one reference with more available curves than others, we first computed the average of all functions in a cluster (i.e., belonging to the same reference or typology of references) as the representative of the cluster for that class. Such average function of the cluster was computed averaging the damage ratios corresponding to each intensity measure level. For instance, from SERA reference it was possible to extract six functions for EMCA1-URM1 taxonomy class (green dotted thin lines in Figure 8). The average of these six functions (green tick solid line in Figure 8) was computed and considered as the representative function for the SERA reference.
2- In the second step, for each taxonomy, we computed the mean and dispersion of the representatives of the clusters for a given PGA value. This gives us an idea about the central value of all the available data points. For instance, as shown in Figure 8, for EMCA1-URM1, six clusters corresponding with SERA, SRKR16, Literature, Local: TKM, Local: KGZ and Local: UZB have been available. The mean of these six data points is shown by the dotted black lines in Figure 8. At this stage, when computing the mean, all the functions were equally weighted.
3- A parametric lognormal function is then defined for each of the vulnerability class. As discussed in point 5 below, these functions are then calibrated to be used as the final vulnerability function to use in the regional seismic risk assessment. The parametric vulnerability curves (before calibrations) are shown by blue solid lines in Figure 8 to Figure 22. Table 16 shows the parameters of the vulnerability curves in terms of log-normal median and standard deviation. We defined these parameters by keeping the curves close enough to the mean of the references computed assuming equal weights for all the studies. The only exception is the case of "EMCA: URM1", where the function extracted from "GLOSI" was providing too conservative loss ratios compared to other references. In this case the team decided, based on expert judgement, to exclude such reference from the set when defining the parametric curve to ensure consistency among the vulnerability curves of different building classes. This might be related to the different analytical methodologies and assumption used in GLOSI. On the other hand, we should emphasize that the functions proposed by local studies are mainly relevant for the new buildings designed based on the latest seismic design codes rather than the existing buildings in those countries and thus resulting in larger estimates of building capacities compared to the other studies considered here.
4- Uncertainty is also determined for each vulnerability function computed above. A coefficient of variation (CoV) is provided in the final database for the discrete mean loss ratios and IM level. At each IM value, the CoV is computed by dividing the standard deviation by the mean LRs of the data. This CoVs, together with the mean values, can be considered to define the

parameters of a Beta distribution ranging between 0 and 1 to describe the uncertainty in damage assessment corresponding to each IM level.

5- Almost all the studies that we considered here are based on analytical methodologies. As such, thanks to their physical basis, they allow a reduction in the uncertainty to a minimum. However, a certain level of uncertainty might still exist, and it is good practice when implementing a risk model to adjust the vulnerability curves based on comparisons between observed losses and modelled losses (either in probabilistic terms, e.g., exceedance probability curves, or on an event basis). More details regarding this calibration are presented in the Task 6 Report (Earthquake and flood risk assessment). Here the resulting, calibrated vulnerability curves are presented. The final vulnerability curves after calibration can be obtained using the log-normal distribution parameters listed in Table 16 together with the calibration parameters shown in the last two columns of this table, obtaining the following equation

$$Loss\ Ratio = Lognormal(alfa + X, beta) * SF$$

Table 15. List of studies used for definition of vulnerability curves for the residential buildings

NO.	EMCA MACRO-TYPOLOGY	EMCA SUB-CLASS	RELEVANT STUDIES
1	EMCA1	URM1	▪ SRKR16-1.1 ▪ SERA: (MUR)-(H2-H4)-(DNO) ▪ Literature: Ahmad et al. (2011) and Karantoni et al. (2011) ▪ Local: TKM, KGZ, UZB ▪ GLOSI: UCM-URM7_MR_LD
2		URM2	▪ SRKR16-1.2 ▪ SERA: (MUR)-(H1-H2)-(DNO) ▪ Literature: Karantoni et al. (2011) ▪ GLOSI: UCM-URM1_LR_LD
3		CM	▪ SRKR16-1.3 ▪ SERA: (MCF)-(CB)-(DUL) ▪ Literature: Kostov et al. (2004) ▪ Local: TKM, KGZ
4		RM-L	▪ SRKR16-1.4 ▪ Literature: Kostov et al. (2004) ▪ SERA: (MR)-(H1) ▪ Local: TKM, UZB
5		RM-M	▪ SRKR16-1.4 ▪ SERA: (MR)-(H2-H3) ▪ Local: UZB
6	EMCA2	RC1	▪ SRKR16-2.1 ▪ SERA: (CR)-(LFM)-(H3-H7)-(DUL) ▪ Local: KGZ
7		RC2	▪ SRKR16-2.2 ▪ SERA: (CR)-(LDUAL)-(H4-H9)-(DUL) ▪ Local: KGZ
8		RC3	▪ SRKR16-2.3 ▪ SERA: (CR)-(LFINF)-(H2-H5)-(DUL) ▪ Local: TKM, UZB
9		RC4	▪ WB-2016: SRKR16-2.4 ▪ SERA: (CR)-(LWAL)-(H4-H11)-(DUL)

10	EMCA3	RCPC1	▪ SRKR16-, SRKR-3.4 ▪ Local: TKM, KGZ, UZB
11		RCPC2	▪ SRKR16-3.1, SRKR-3.2 ▪ Local: TKM, KGZ, UZB
12	EMCA4	ADO	▪ SRKR16-4.1 ▪ SERA: (MUR)-(ADO) ▪ GLOSI: LBM_A_LR_LD ▪ Local: TKM, KGZ
13	EMCA5	WOOD1	▪ SRKR16-5.1 ▪ Local: KGZ
14		WOOD2	▪ SRKR16-5.1 ▪ Local: KGZ
15	EMCA6	STEEL	▪ SRKR16-6.1 ▪ Local: TKM

Figure 8 to Figure 22 show the comparison of the functions obtained from the different data sources along with the statistics extracted from them and the vulnerability functions proposed in this vulnerability study before calibration. Figure 23, however, shows the comparison among the functions obtained for each building class in the taxonomy after the calibration is performed. Figure 24 compares the vulnerability curves before and after calibration.

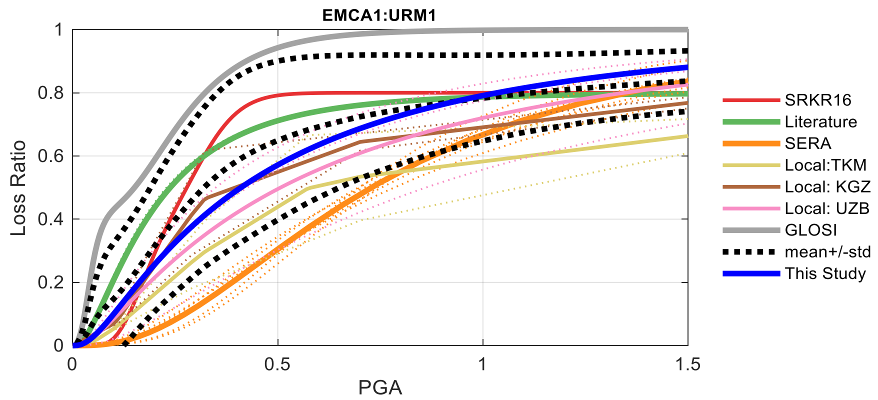


Figure 8. Comparison between the vulnerability functions of different studies for residential building class EMCA1: URM1. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

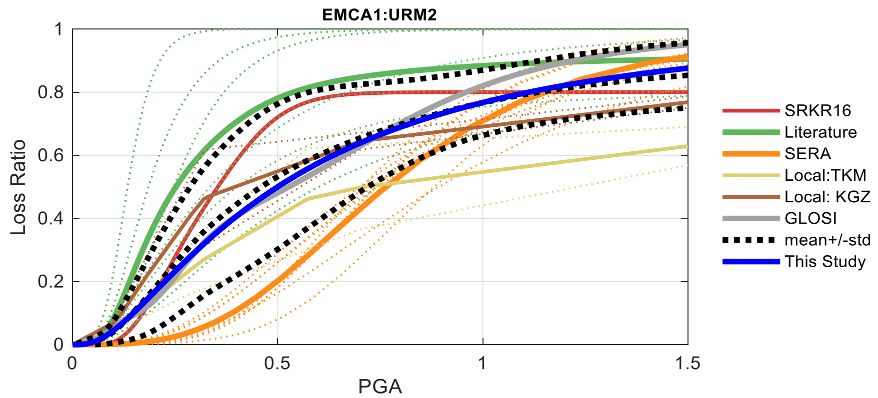


Figure 9. Comparison between the vulnerability functions of different studies for residential building class EMCA2: URM2. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

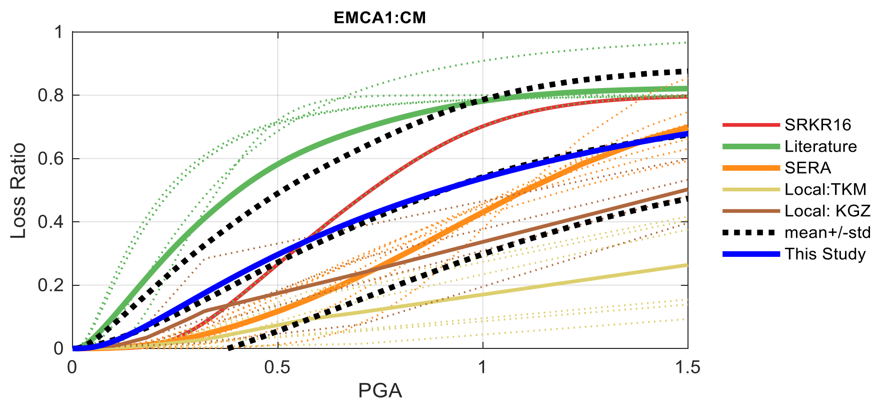


Figure 10. Comparison between the vulnerability functions of different studies for residential building class EMCA1: CM. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

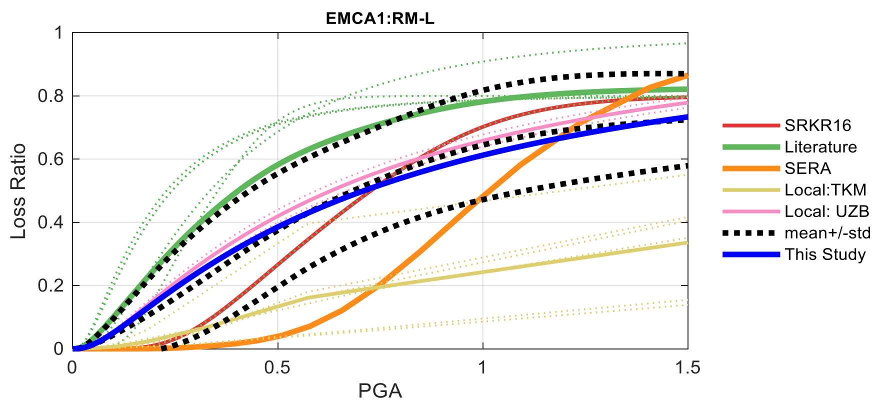


Figure 11. Comparison between the vulnerability functions of different studies for residential building class EMCA1: RM-L. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

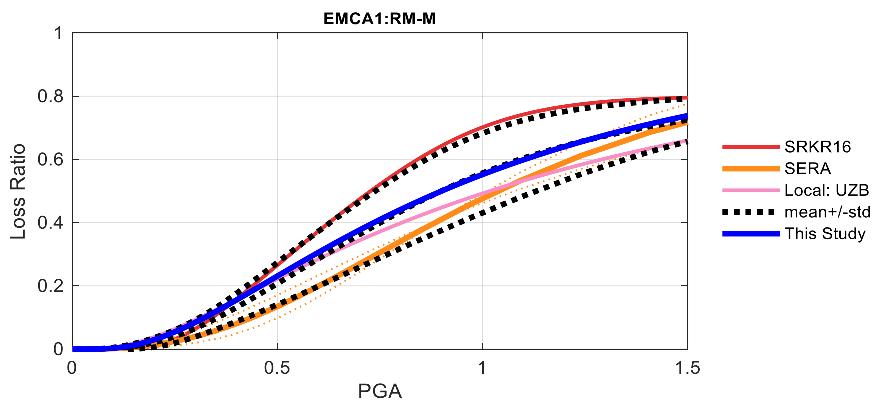


Figure 12. Comparison between the vulnerability functions of different studies for residential building class EMCA1: RM-M. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

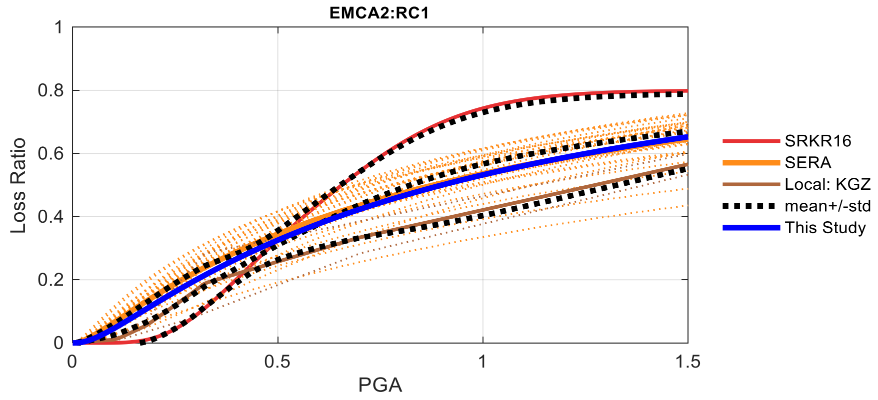


Figure 13. Comparison between the vulnerability functions of different studies for residential building class EMCA2: RC1. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

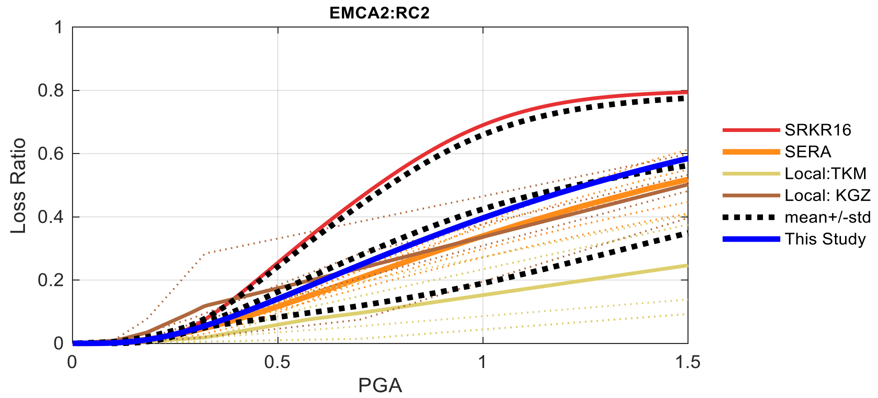


Figure 14. Comparison between the vulnerability functions of different studies for residential building class EMCA2: RC2. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

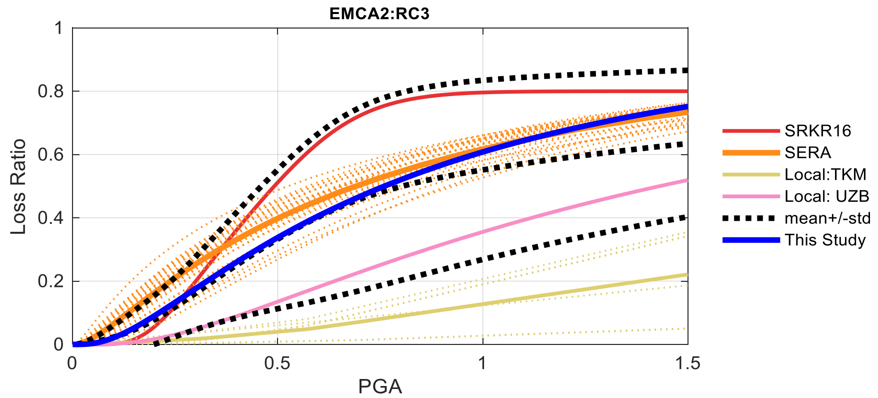


Figure 15. Comparison between the vulnerability functions of different studies for residential building class EMCA2: RC3. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

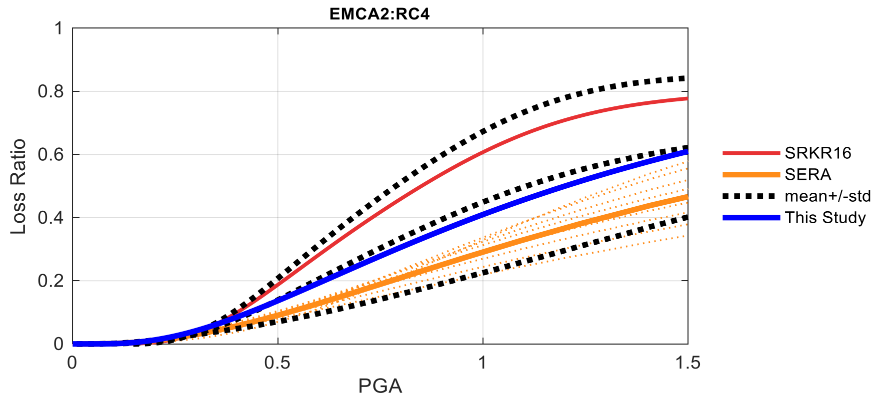


Figure 16. Comparison between the vulnerability functions of different studies for residential building class EMCA2: RC4. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

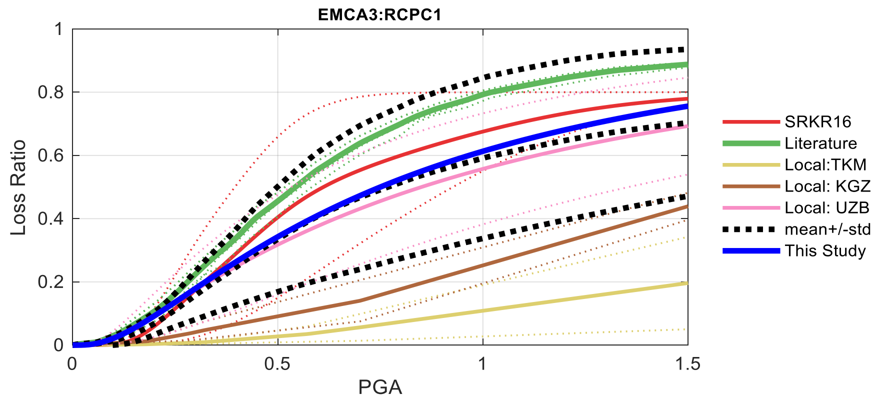


Figure 17. Comparison between the vulnerability functions of different studies for residential building class EMCA3: RCPC1. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

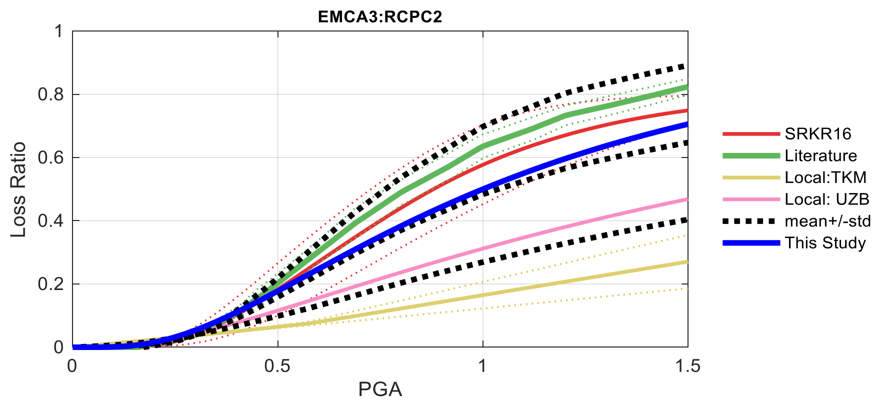


Figure 18. Comparison between the vulnerability functions of different studies for residential building class EMCA3: RCPC2. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

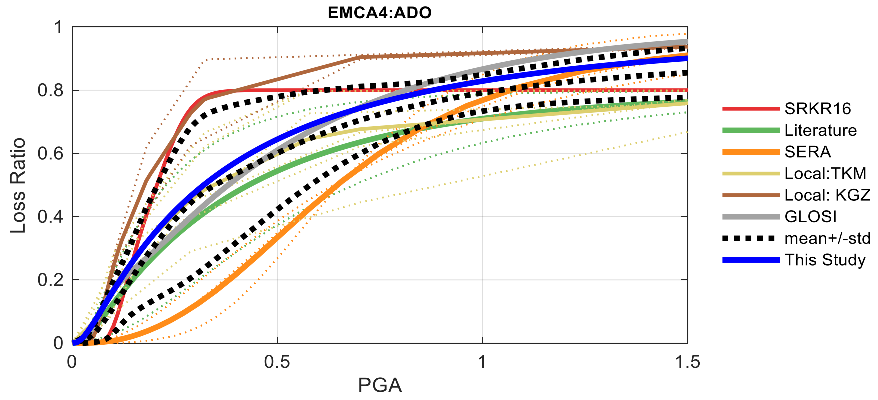


Figure 19. Comparison between the vulnerability functions of different studies for residential building class EMCA4: ADO. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

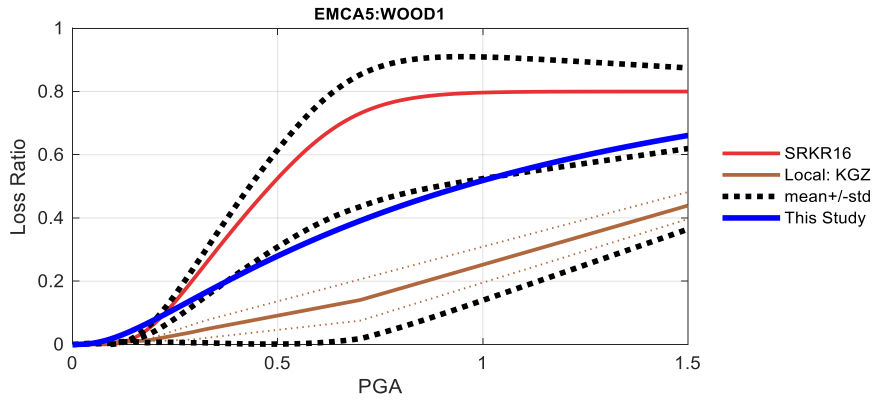


Figure 20. Comparison between the vulnerability functions of different studies for residential building class EMCA5: WOOD1. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

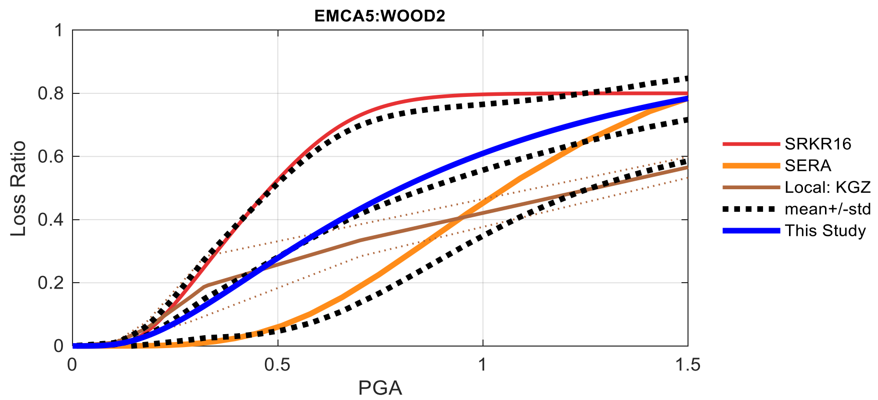


Figure 21. Comparison between the vulnerability functions of different studies for residential building class EMCA5: WOOD2. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

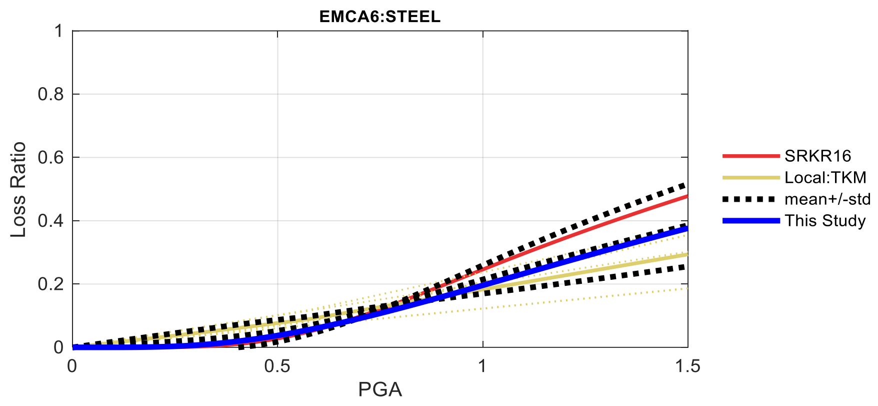


Figure 22. Comparison between the vulnerability functions of different studies for residential building class EMCA5: STEEL. ***Note: the thin dotted lines represent the individual study of a group while the thicker solid lines show the mean of the group. The same colour was used for both in the figure. The blue line shows the parametric vulnerability function before calibration.***

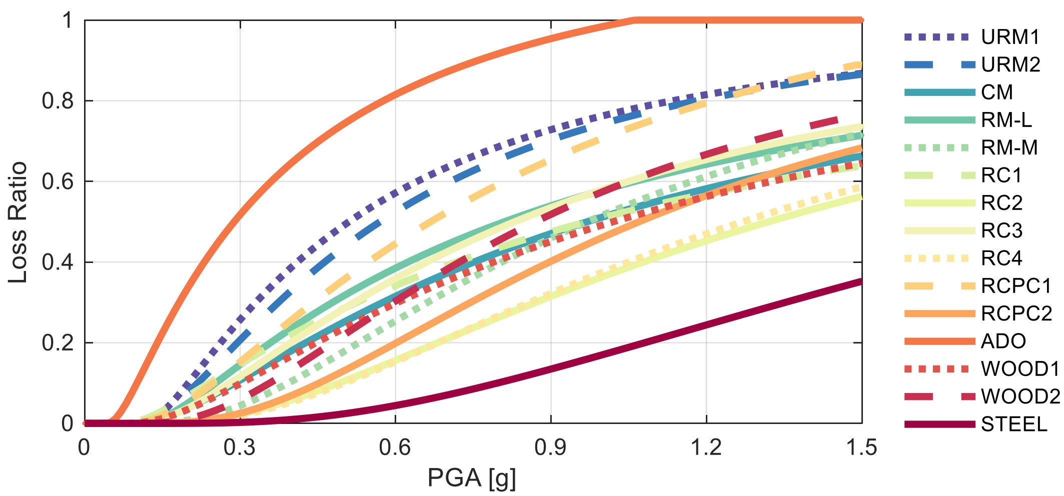


Figure 23. Comparison of the proposed vulnerability functions for different classes of residential buildings after calibration

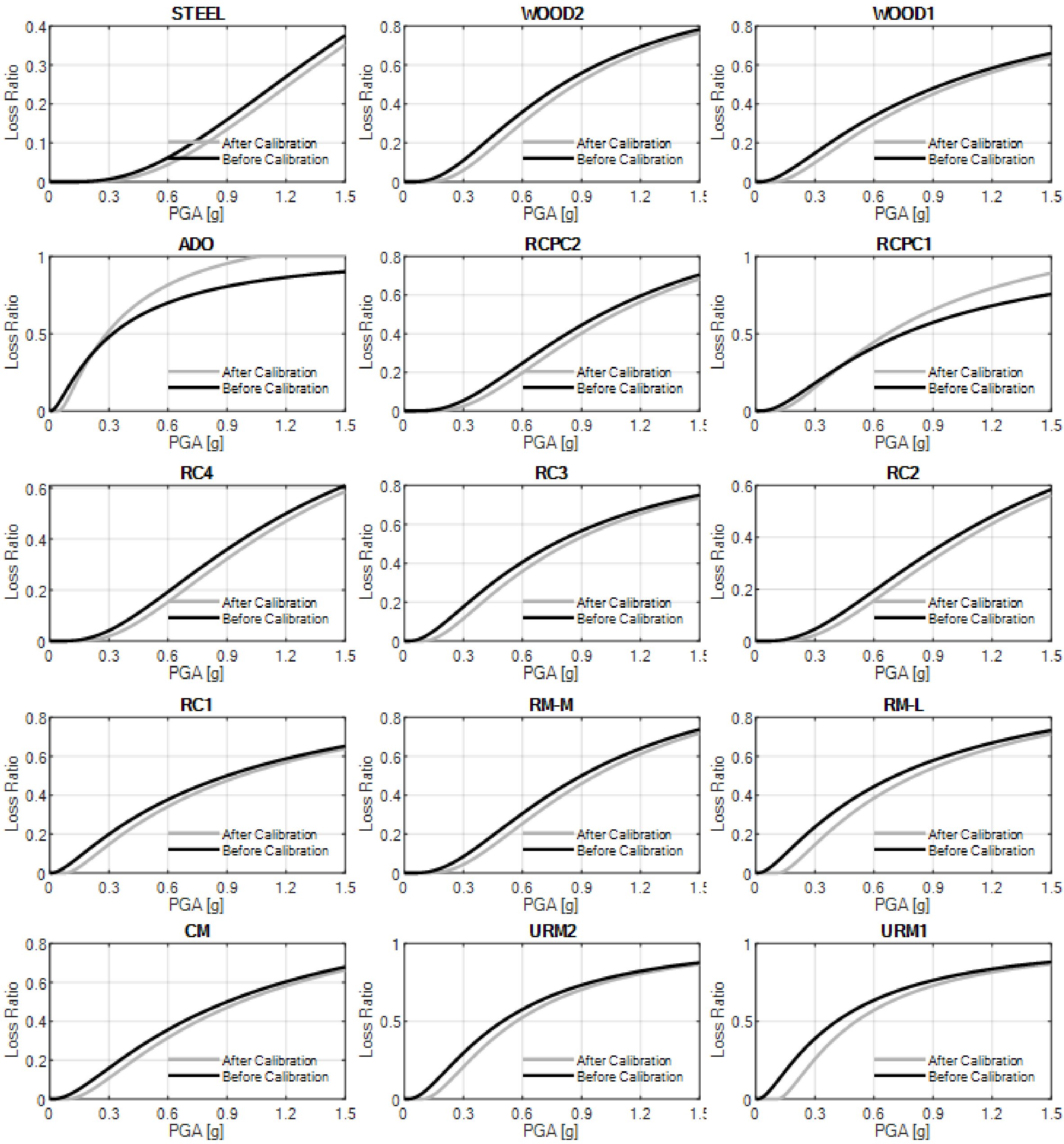


Figure 24. Comparison of the proposed vulnerability functions before and after calibration for different classes of residential buildings.

Table 16. Summary of the final parametric vulnerability functions for the residential building classes. ***Note that the Log-normal parameters represent the vulnerability curves before calibration. The final vulnerability curves are obtained using the "alfa+X" as the median of the log-normal distribution and then by scaling the Loss ratios using SF.***

No.	Class	Sub-class	Description	Log-normal parameters (no calibration)		Calibration parameters	
				alfa	beta	X	SF
1	EMCA1	URM1	Unreinforced masonry	0.41	1.10	0.10	1.0
2		URM2	Unreinforced masonry concrete floors	0.50	0.95	0.07	1.0
3		CM	Confined masonry	0.90	1.10	0.07	1.0
4		RM-L	Reinforced masonry, low rise	0.71	1.20	0.10	1.0
5		RM-M	Reinforced masonry, medium rise	0.90	0.80	0.07	1.0
6	EMCA2	RC1	RC (reinforced concrete) frame without ERD	0.90	1.30	0.07	1.0
7		RC2	RC (reinforced concrete) frame with moderate ERD	1.25	0.85	0.07	1.0
8		RC3	RC (reinforced concrete) frame with high level of ERD	0.76	1.00	0.07	1.0
9		RC4	RC (reinforced concrete) walls without ERD	1.20	0.80	0.07	1.0
10	EMCA3	RCPC1	RC (reinforced concrete) walls with moderate level of ERD	0.75	1.00	0.06	1.2
11		RCPC2	RC (reinforced concrete) walls with high level of ERD	1.00	0.75	0.07	1.0
12	EMCA4	ADO	Adobe	0.32	1.20	0.04	1.2
13	EMCA5	WOOD1	Timber structure, load-bearing braced frames	0.95	1.10	0.07	1.0
14		WOOD2	Timber structure, wooden frame and mud infill	0.80	0.80	0.07	1.0
15	EMCA6	STEEL	Steel structure	1.90	0.75	0.07	1.0

5 Non-residential buildings

Given the lack of specific vulnerability information/references for non-residential buildings and the similarities among residential and non-residential building typologies, the vulnerability functions for the non-residential buildings were generated using the final calibrated functions derived for residential building in the previous section. For each non-residential building class listed in Table 6, we considered a weighted average of the residential vulnerability functions based on the building fractions identified in the exposure modelling component for each different building occupancy type (shown in Table 6). It should be noted that as in Table 6 for some cases the building fractions are different in different countries. In order to derive a unique model applicable for the entire region, we further used a weighted average based on the population of the countries to combine these functions. Weighted average curves are computed averaging the loss ratio values corresponding to each IM level, thus the final curves for non-residential are non-parametric functions. An uncertainty is also determined for the non-residential vulnerability curves combining the uncertainties determined for residential functions. In particular, the standard deviation of the combined function is determined for each IM level considering the uncertainties of all the functions averaged corresponding to such IM level, and the weights adopted. Figure 25 shows the final non-residential buildings' vulnerability curves after calibration while in Figure 26 the vulnerability curves before and after the calibration are compared.

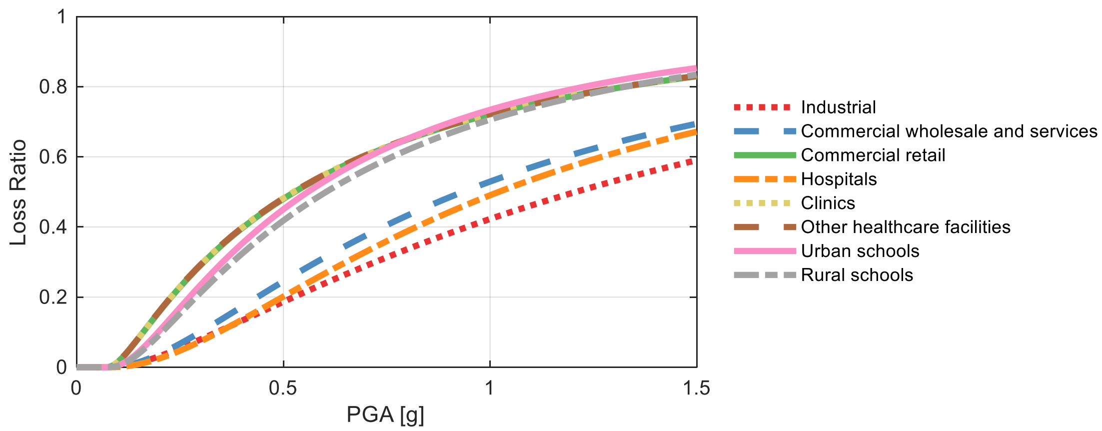


Figure 25. Comparison between the proposed vulnerability functions among different classes of the non-residential buildings after calibration

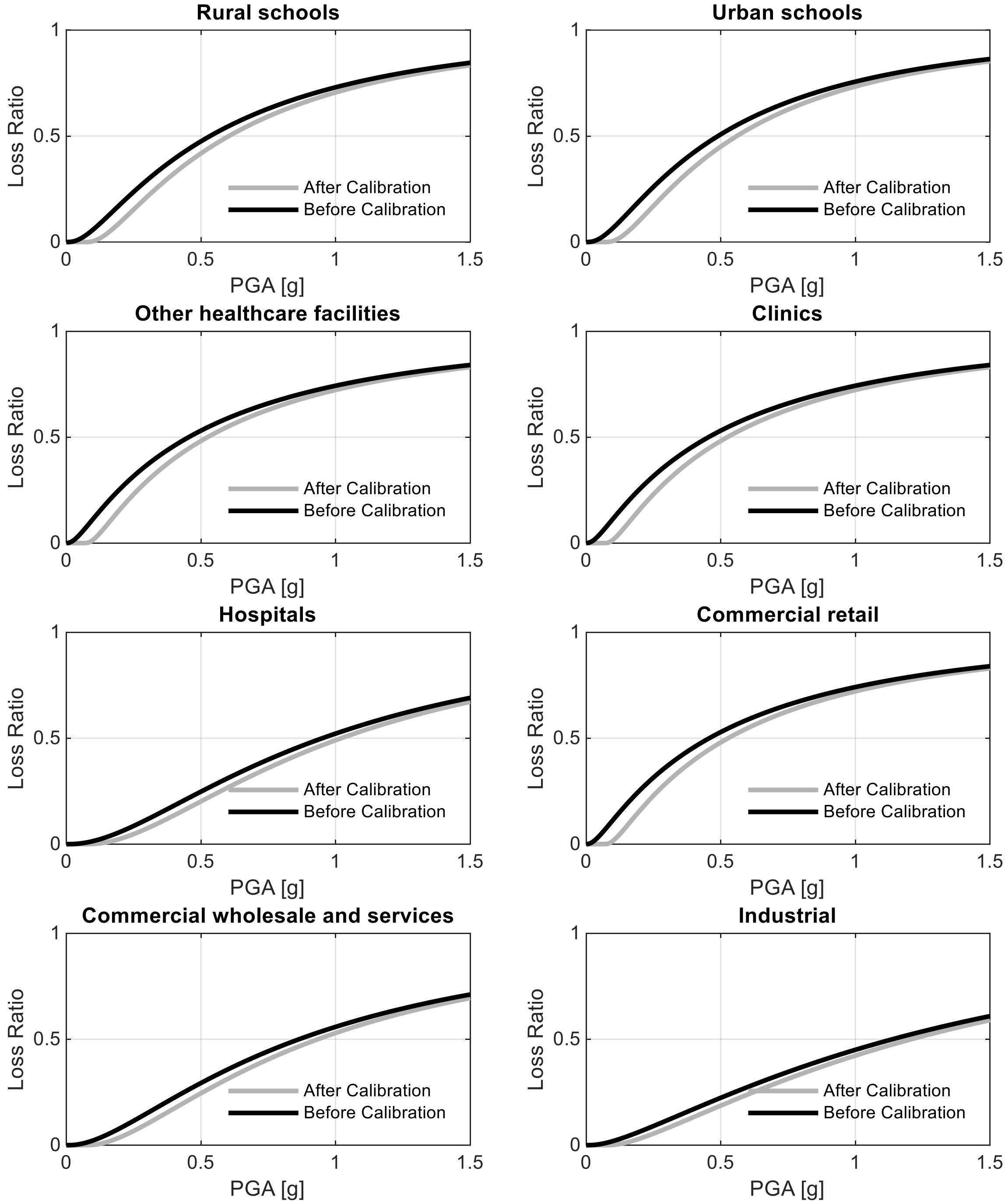


Figure 26. Comparison between the proposed vulnerability functions among different classes of the non-residential buildings before and after calibration.

6 Infrastructure

Herein we use the established fragility curves from HAZUS (FEMA, 2003) to assess the vulnerability of the transportation system. It should be noted that similar approach was also used in a previous project for Kyrgyz republic in the framework of SRKR16 project (World-Bank 2016). Note that no specific data about the road vulnerability were available from the local context. Although, in general roads and infrastructure most of the times are constructed by international companies and they are built following international standards, so it is reasonable to not expect a huge difference in construction practice and consequently in earthquake vulnerability between Central Asia and US. The roads in Central Asia could be expected to be slightly more vulnerable than in the US, but it's not possible a priori to establish by how much, for this reason we kept the HAZUS functions in this study. This assumption could lead to a slight underestimation of the losses in the final risk estimates, although given the low vulnerability of the roads compared to the other analysed assets within the scope this study, this is not expected to significantly influence the final overall assessment.

The highway transportation system is comprised mainly of two main damageable components, namely roads and bridges. Past earthquakes damage has shown that bridges are vulnerable to ground shaking and ground failure, while roads are mainly affected by ground failure (See HAZUS). Roadways are classified into two main categories, major and urban roads. Major roads include roads with more than 4 lanes, while urban roads comprise 2 lanes. The fragilities of the roadways are given in Table 17 in terms of permanent ground deformation (PGD). Since the intensity measure (IM) that is expected to be used for the risk calculations in the project is peak ground acceleration (PGA), the PGD was converted to PGA. The conversion was performed using the lateral spreading displacement relationship described in HAZUS (Figure 27). This trilinear relationship estimates the PGD in terms of the ratio PGA/PGA(t). The term PGA(t) refers to the threshold PGA corresponding to zero probability of liquefaction according to the associated susceptibility category. By inverting this trilinear relationship, we estimate the PGA for a given PGD. Because here the aim was to define a vulnerability model applicable to the whole region and the areas potentially susceptible to liquefaction are usually not too large, here we assumed a "low susceptibility" category based on HAZUS definitions. Such assumption could be revised in case the provided functions would be adopted for site specific studies. In that case, a specific susceptibility analysis may be required.

Highway bridges in HAZUS are classified into different classes based on different structural characteristics. For the purpose of this study, and since the bridges were constructed between 1960 and 1990, the fragilities of the HWB1 and HWB3 classes were selected. Table 18 lists the median values of the fragility curves, while the dispersion is set to 0.6 for the ground shaking and 0.2 for the ground failure.

For the main damageable components of the railway network (tracks/roadbeds, bridges), the approach in HAZUS is similar to that used for the components of the highway transportation system. Fragility functions for tracks/roadbeds are similar to those of major roads, while fragility curves for rail bridges are the same as those presented for single-span highway bridges. Table 19 shows the damage ratios (repair cost normalized by replacement cost) for the damageable components of the highway system.

Table 17. Fragility functions for Roadways adopted from HAZUS

Components	Damage State	Median (in)	β
Major Road	Slight	12	0.7
	Moderate	24	0.7
	Extensive/Complete	60	0.7
Urban Road	Slight	6	0.7
	Moderate	12	0.7
	Extensive/Complete	24	0.7

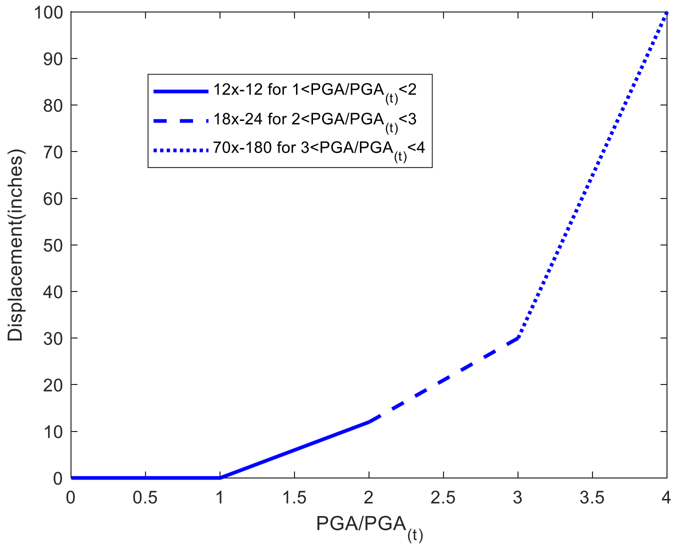


Figure 27. Lateral spreading displacement relationship- HAZUS

Table 18. Fragility function median values for highway bridges-HAZUS

Class	Sa [1.0 sec in g's] for Damage Functions due to Ground Shaking				PGD [inches] for Damage Functions due to Ground Failure			
	Slight	Moderate	Extensive	Complete	Slight	Moderate	Extensive	Complete
HWB1	0.4	0.5	0.7	0.9	3.9	3.9	3.9	13.8
HWB2	0.6	0.9	1.1	1.7	3.9	3.9	3.9	13.8
HWB3	0.8	1	1.2	1.7	3.9	3.9	3.9	13.8
HWB4	0.8	1	1.2	1.7	3.9	3.9	3.9	13.8

Table 19. Damage ratios for highway system components

Classification	Damage State	Best Estimate Damage Ratio	Range of Damage Ratios
Roadways	Slight	0.05	0.01 to 0.15
	Moderate	0.20	0.15 to 0.40
	Extensive/Complete	0.70	0.40 to 1.00
Tunnel's Lining	Slight	0.01	0.01 to 0.15
	Moderate	0.30	0.15 to 0.40
	Extensive	0.70	0.40 to 0.80
	Complete	1.00	0.80 to 1.00
Bridges	Slight	0.03	0.01 to 0.03
	Moderate	0.08	0.02 to 0.15
	Extensive	0.25	0.10 to 0.40
	Complete	1.00	0.30 to 1.00

Figure 28 shows the comparison of the final vulnerability functions considered for the infrastructure. Same vulnerability functions are used for different road or railway classes identified by the exposure taxonomy. In particular, the HAZUS function for major roads was assigned to motorway, trunk, and primary road classes (i.e., RDN+MO, RDN+TR, and RDN+PR), the function for secondary roads was assigned to secondary and tertiary roads (i.e., RDN+SE, and RDN+TE), and the function for railways was assigned to light rail, monorail and rail (i.e., RLW+LR, RLW+MR, and RLW+RL). It should be noted that in HAZUS the curves for major roads and for railways are coincident.

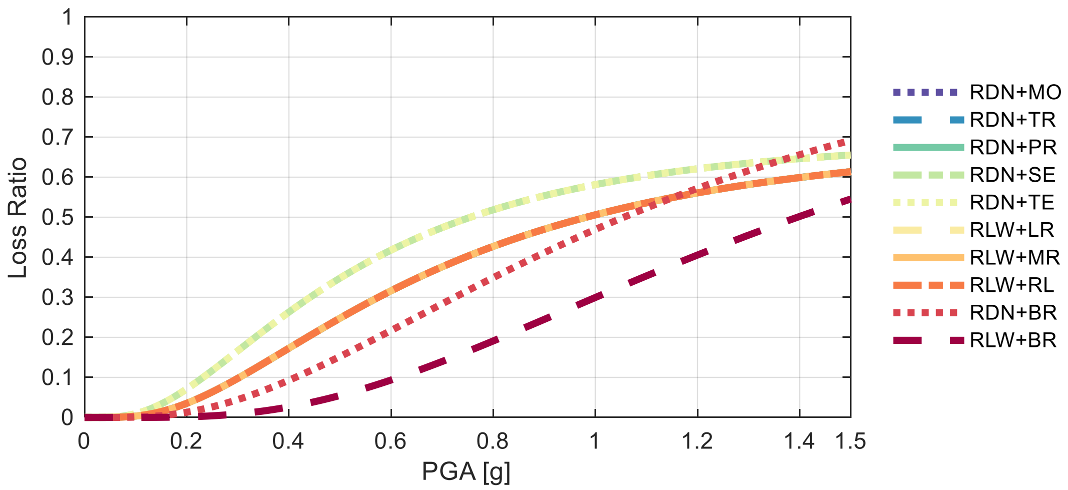


Figure 28. Comparison between different vulnerability functions considered for the infrastructure. The chart includes two groups of coincident curves: Group 1='RDN+MO', 'RDN+TR', 'RDN+PR', 'RLW+LR', 'RLW+MR', and 'RLW+RL' and Group 2='RDN+SE' and 'RDN+TE' that have the same vulnerability curve as discussed above.

7 Human loss

During an earthquake the chaotic disruption and physical damage cause loss of life or injuries in many different ways, such as building collapse, machinery accidents, and heart attacks among other causes. Some earthquakes trigger secondary effects, such as landslides, mudflows and fires, which can also cause casualties. Herein we estimate the mean number of casualties as a function of the level of building damage. In other words, we assumed that the number of casualties is expressed as a fraction of the total number of people exposed in the building, namely the so-called mean fatality ratios. A list of the consequence functions based on different studies for the fatality rates as a function of the damage level of buildings is shown in Table 20. In this study we selected the fatality rates provided by HAZUS (FEMA, 2003) and we combined them with the collapse fragility functions proposed in SRKR16 to define the human loss functions.

The fatality consequence model proposed by HAZUS was selected since it is the most recent among the ones analyzed and it provides rates applicable to all building typologies. Such fatality rates were combined with the fragility functions extracted from SRKR16 since this was the only local reference providing fragility functions rather than directly vulnerability curves. Moreover, this study was the only cluster that had a coverage of all building typologies. The vulnerability model derived according to the depicted methodology will be capable to predict the fatalities as function of the number of occupants of the buildings and of the peak ground acceleration. Note that the human loss vulnerability curves derived according to the above procedure has been eventually calibrated during the risk assessment phase (Task 6 – Earthquake and Flood risk assessment) based on the comparison between modelled losses and losses reported for historical events. Figure 29 shows the final human loss curves for each class of the residential building. Figure 30 shows the comparison between the vulnerability curves to assess economic loss and fatalities for building class EMCA1: URM1. Comparisons like this one were made for all building classes to ensure compatibility between the human loss and direct economic loss vulnerability models. In Figure 31 the human loss vulnerability functions before and after calibration are compared for all the residential classes.

Table 20. Literature review of engineering studies of earthquake fatalities in RC frame structures. The probability of fatality is equivalent to the fraction of building occupants at the time of the earthquake who do not survive.

Author	Building Characteristics	Structural Damage States	Probability of Fatality Given the Damage State	Methodology
ATC-13 (1985)	All constructions, except light steel and wood frame	Moderate	0.0001	Expert judgement
		heavy	0.001	
		major	0.01	
		destroyed	0.2	
Coburn et al. (2002)	RC frame buildings	Collapse, Severity depending on the volumetric reduction	0.31 to 0.49	Study of collapse volume in RC structures in Mexico City,

				Bucharest, Armenia and Greece.
FEMA (2003)	All buildings (this example: RC moment frames).	Extensive damage Complete damage (no collapse) Complete damage (collapse)	0.00001 0.0001 0.1	Expert judgement
Shoaf et al. (2005)	Non-Ductile RC frame buildings	Partial Collapse Total Collapse	0.0015 0.11 0.13 (mid-rise RC frames) 0.16 (upper floors of mid-rise RC frames)	Survey following 1999 Izmit earthquake

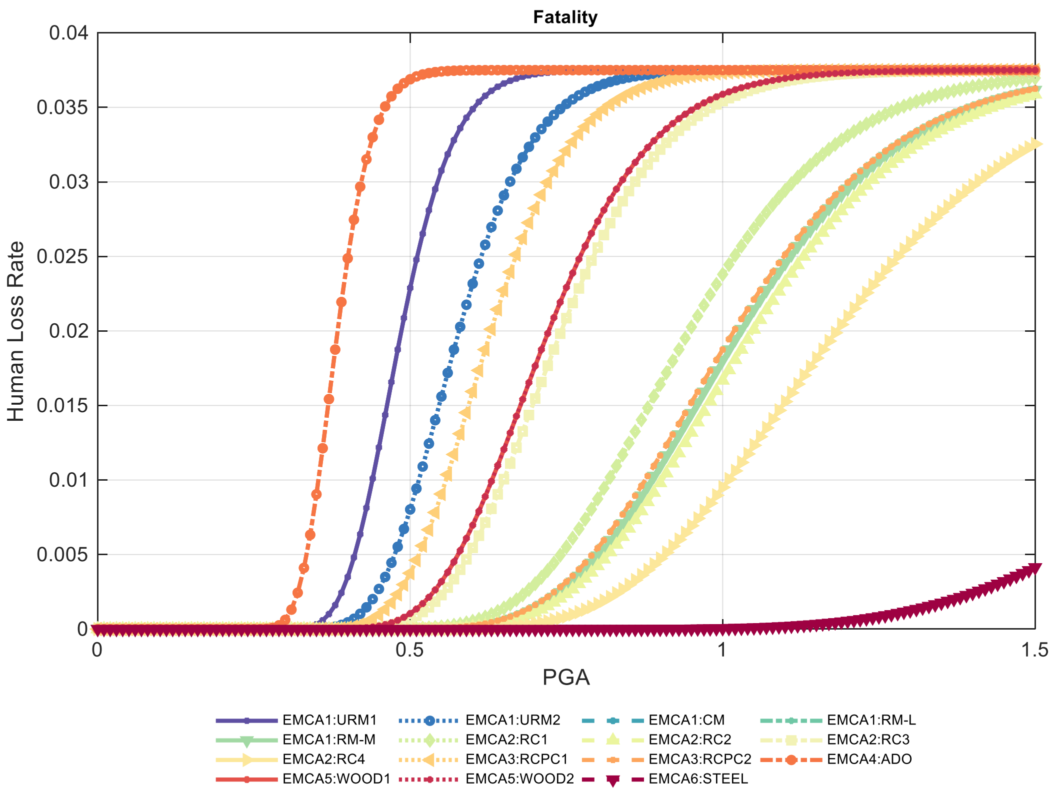


Figure 29. Human loss vulnerability functions for the residential buildings.

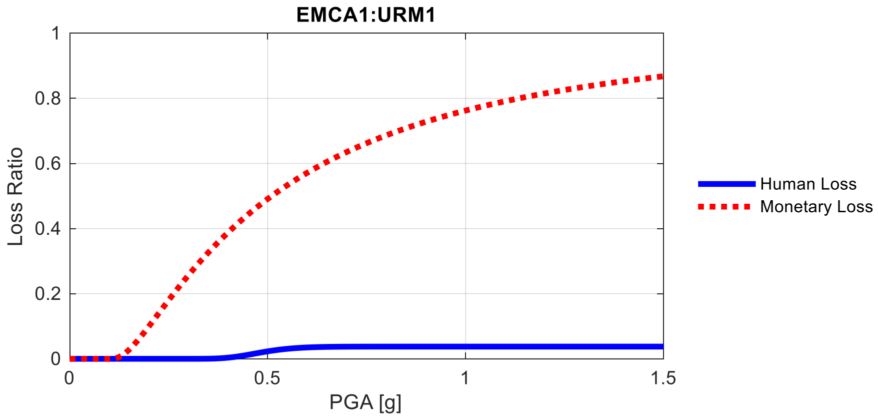
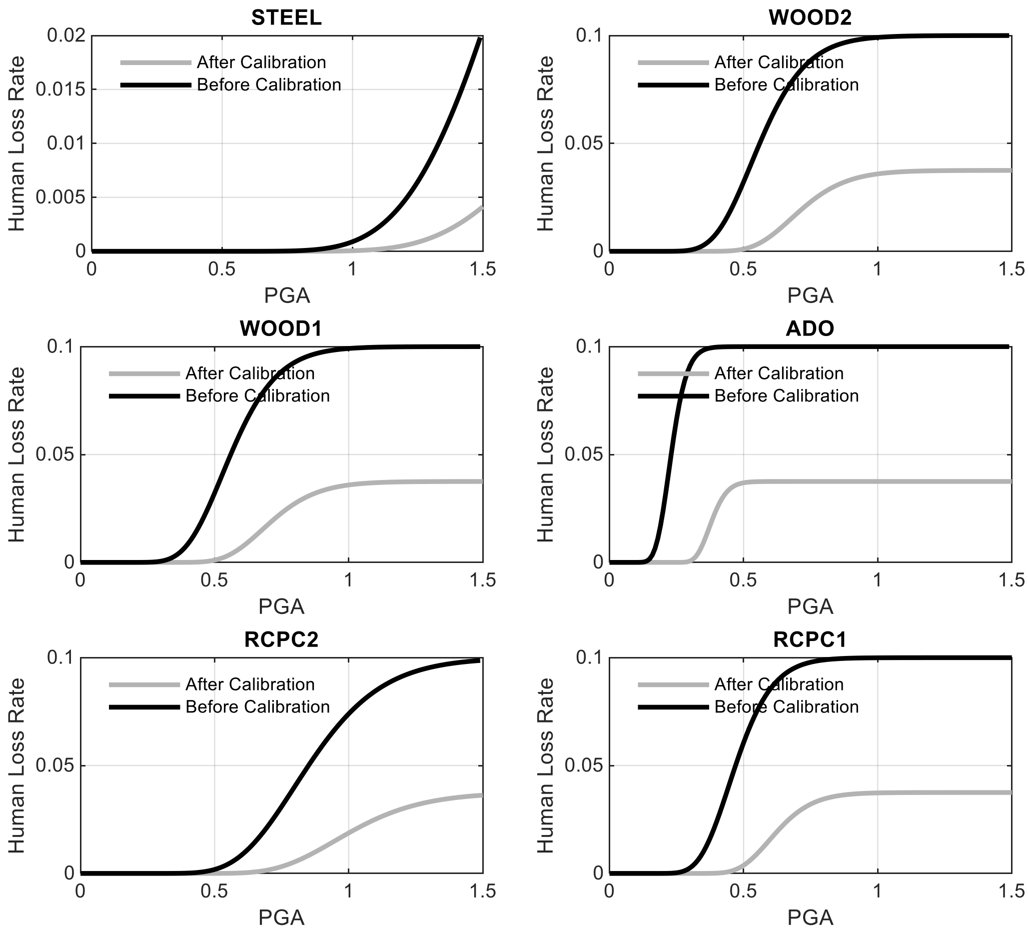


Figure 30. Comparison between human loss and monetary loss vulnerability functions for "EMCA1: URM1" residential building class after calibration.



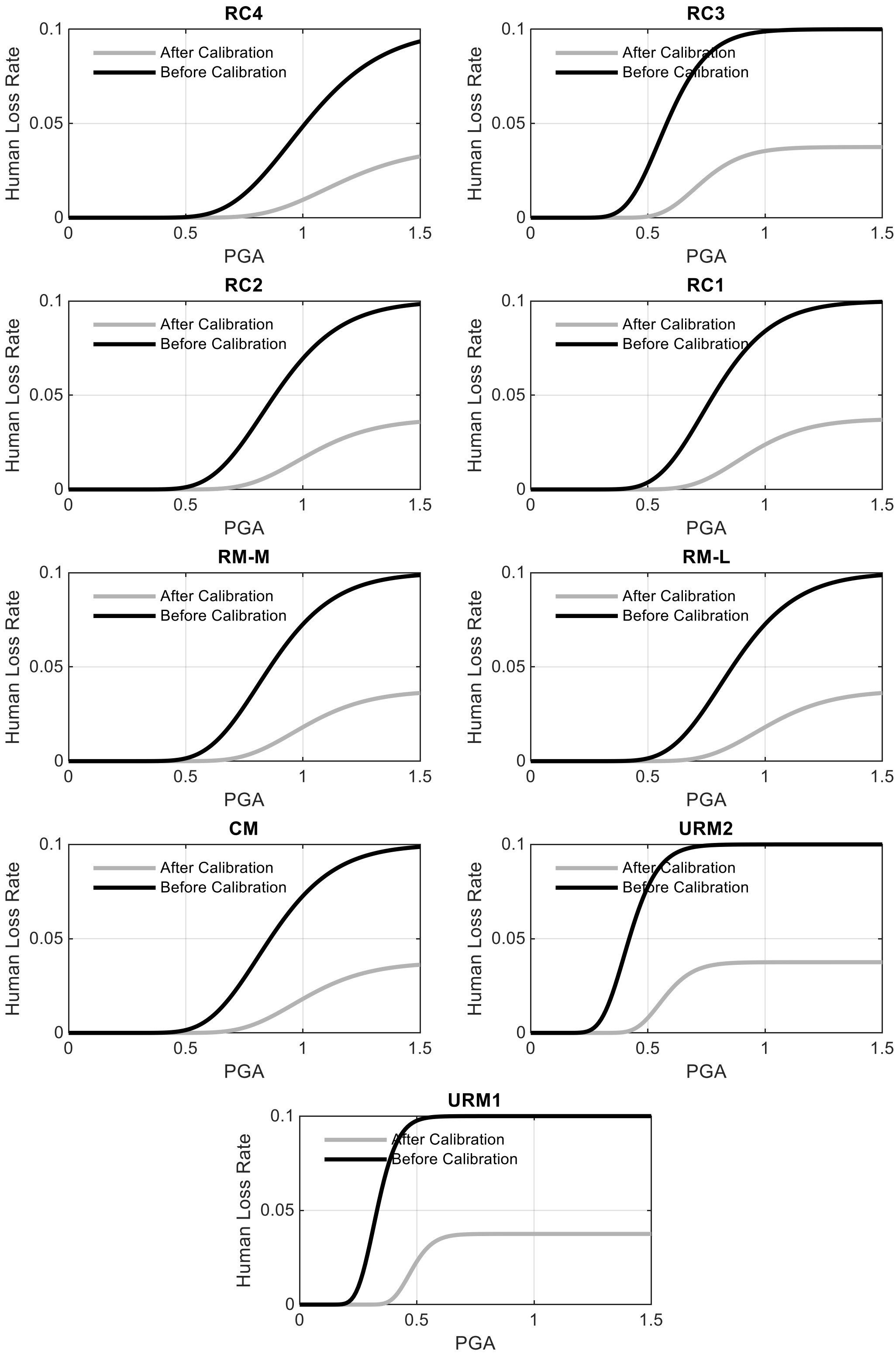


Figure 31. Comparison between human loss vulnerability functions for all residential building classes before and after calibration.

8 Conclusion

The main scope of this study was to derive sets of vulnerability functions to be used for seismic risk assessment of residential buildings, non-residential buildings, and infrastructure in Central Asia. We collected and reviewed multiple sets of existing fragility and vulnerability functions from various references relevant for the region, including local studies, international literature and World Bank projects previously developed in the region. Such analysis allowed to create a large database of vulnerability functions that were classified in accordance with the taxonomy used in our exposure model. These functions were further harmonized and processed, and a single class-specific function was extracted to capture the mean and variation in the database compiled.

For the first time in Central Asia context, the methodology adopted and presented in this report allowed deriving a new model applicable for the entire region leveraging the most recent international research outcomes and the local observations and expertise. Moreover, the approach adopted allows to consider the uncertainty associated with the evaluation of the damage due to the different approaches that could be adopted to define the vulnerability (i.e., the variability among the studies analyzed).

The approach adopted is anyhow affected by some limitations, mainly due to lack of some local data, in particular for some of the countries covered by the model. This lack of data was partially overcome by the development of a regional model and considering the similarities in construction practice in the whole area. Although if in the future more data and information would become available for the entire region and particularly for some countries, the model could benefit from their inclusion in the overall framework. More local studies could be developed in the following years targeting the assessment of vulnerability of specific asset typologies, maybe leveraging post event data coming from different past events occurred in the overall region and combining them with analytical studies to differentiate among specific structural typologies. The development of such studies will be particularly needed for infrastructure and non-residential buildings and for the definition of local consequence functions.

The sets of vulnerability functions obtained in this study will be used in the following tasks of the technical assistance to perform the earthquake risk assessment of the region and will be available for any further regional study that may be needed in future applications. In order to ensure full compatibility with the other components of the project the final vulnerability model was defined considering the taxonomy considered for the development of the different exposure layers. In particular, when on the exposure side it was not possible to differentiate among building classes given the lack of spatial data about their geographic distribution, average vulnerability functions were derived leveraging the information collected by the exposure team in terms of country-level building type distributions. Consistency with other modules was also ensured using an intensity measure at the same time compatible with the hazard model derived in the project and sufficiently general to be usable also in other future local or international efforts.

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Appendix A - List of acronyms

ATC: Applied Technology Council

CM: Confined Masonry

CSM: Capacity Spectrum Method

EDP: Engineering Demand Parameter

EMCA: Earthquake Model of Central Asia

EMS: European Macroseismic Scale

FEMA: Federal Emergency Management Agency

GLOSI: Global Library of School Infrastructure

GMPE: Ground Motion Prediction Equation

GNDT: Gruppo Nazionale per la Difesa dai Terremoti

IGMCE: Intensity to Ground Motion Conversion Equation

IM: Intensity Measure

IS: Institute of Seismology

ISASUZ: Institute of Seismology of the Academy of Science of Uzbekistan

ISNASKR: Institute of Seismology of Kyrgyz Republic

IWPHE: Institute of Water Problems, Hydropower Engineering and Ecology

KGZ: Kyrgyz Republic

LLRS: Lateral Load-Resisting System

MMI: Modified Mercalli Intensity

MSK: Medvedev-Sponheuer-Karnik

NATO: North Atlantic Treaty Organization

PGA: Peak Ground Acceleration

PGD: Permanent Ground Deformation

RED: Risk Engineering + Development

RC: Reinforced Concrete

RM: Reinforced Masonry

SERA: European Seismic Risk Assessment

SFRARR: Strengthening Financial Resilience and Accelerating Risk Reduction in Central Asia

TKM: Turkmenistan

URM: Unreinforced Masonry

US: United States

UZB: Uzbekistan