VULNERABILITY OF THE NEPALESE BUILDING STOCK DURING THE 2015 GORKHA EARTHQUAKE

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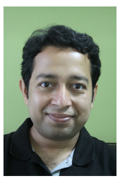

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ABSTRACT

Building fragility functions can be used to quantify the seismic vulnerability of the Nepalese building stock. In a first step the building stock is categorized into different building typologies. Fragility functions for the different building types are derived using damage probability matrices for Nepal. The Rapid Visual Damage Assessment (RVDA) database from the Nepalese Engineers' Association (NEA) is then used to update the fragility functions with damage data from the April 25, 2015 Mw 7.8 Gorkha earthquake. The obtained updated fragility functions can be used to quantify the risk of the building stock towards potential future seismic events and to analyze possible risk mitigation measures. The following study presents first preliminary results based on the processing of the RVDA database.

Keywords: vulnerability, fragility functions, Gorkha earthquake

I. INTRODUCTION

A devastating M_w 7.8 earthquake hit Nepal on April 25, 2015. The mainshock with an epicenter located approximately 80km north-west of Kathmandu in the Gorkha district, was followed by a series of aftershocks, including the M_w 7.3 aftershock on May 12 with an epicenter east of

Kathmandu, close to the border to Tibet. About 9000 people lost their lives, 22'000 got injured and more than 750,000 buildings were damaged or destroyed [1]. Many people lost their homes and were forced to move to emergency shelters. The earthquakes caused thus damage to the building stock, as well as to the different civil infrastructure systems. Residential buildings, schools, heritage structures (e.g. temples) and hospitals suffered from severe damage and a large number was irreparable destroyed. Civil infrastructure systems like the electric power supply system, the water distribution network or the cellular network were affected and their service supply capacity was sensibly reduced [2,3]. The recovery of some parts of these network could still not be achieved as of today and blackouts and shortage of service have ongoing negative impacts on the communities in Nepal. The amount of damage caused by the 2015 Nepal earthquake series is not only due to the magnitude of the mainshock and several of the aftershocks, but as well to the limited application of seismic construction standards in Nepal. The Nepalese building stock includes a large amount of buildings built using fragile and weak construction techniques, like the traditional mud mortar rubble stone houses, which can be mainly found in the more rural regions. The absence of the implementation of basic seismic refining or detailing, in combination with the bad implementation of the building code, adds to the vulnerability of the built environment in Nepal. The following study gives an introduction to the composition and the main types of buildings of the Nepalese building stock and shows preliminary results of the analysis of a damage database created by the Nepalese Engineers' Association using Rapid Visual Damage Assessment (RVDA).

II. VULNERABILITY OF THE NEPALESE BUILDING STOCK

The Nepalese building stock can be divided into different occupancy and building types, in order to account for the different construction and occupancy types [3]:

- Residential, including adobe, brick in mud, brick in cement, timber and reinforced concrete residential buildings
- Industrial, including small industries and medium/large industries
- Commercial buildings
- Critical buildings (non-commercial), including hospitals and schools

The distinction of the different occupancy and building types is necessary in order to account for the magnitude of the impact of damage to different buildings and for their varying robustness. Reinforced concrete buildings are for example often expected to be more robust than traditional mud mortar rubble stone houses, and the consequences of damage to a hospital are usually larger than those to a single family house. The seismic behavior and fragility of the different building types can be described by fragility functions.

Fragility functions express the probability of a given building type to reach a certain (or higher) damage state, as function of a given intensity measure. They can be derived in four different ways (M. Rota et al. 2007): expert judgment-based, analytical, empirical and from hybrid methods. In the following, lognormal fragility functions, expressing the damage state probability, depending on the peak ground acceleration (PGA) at the building site are computed for the different building types.

Using the damage matrices for the predominant building types in the Kathmandu Valley, provided by [4,5], and the maximum likelihood method as proposed by [6,7], lognormal fragility functions for partial damage (DS2) and complete damage (DS3) can be computed.

The parameters of the obtained fragility functions for Nepalese adobe, mud bonded, cement bonded and RC frame buildings are given in Table 1. They can be employed for the different occupancy types, taking into account information given by [8,9]. Due to the lack of available data for Nepalese timber houses, the fragility functions given for example by [10] for "wood, light frame (W1)" can be used to represent the damage probability of the timber houses.

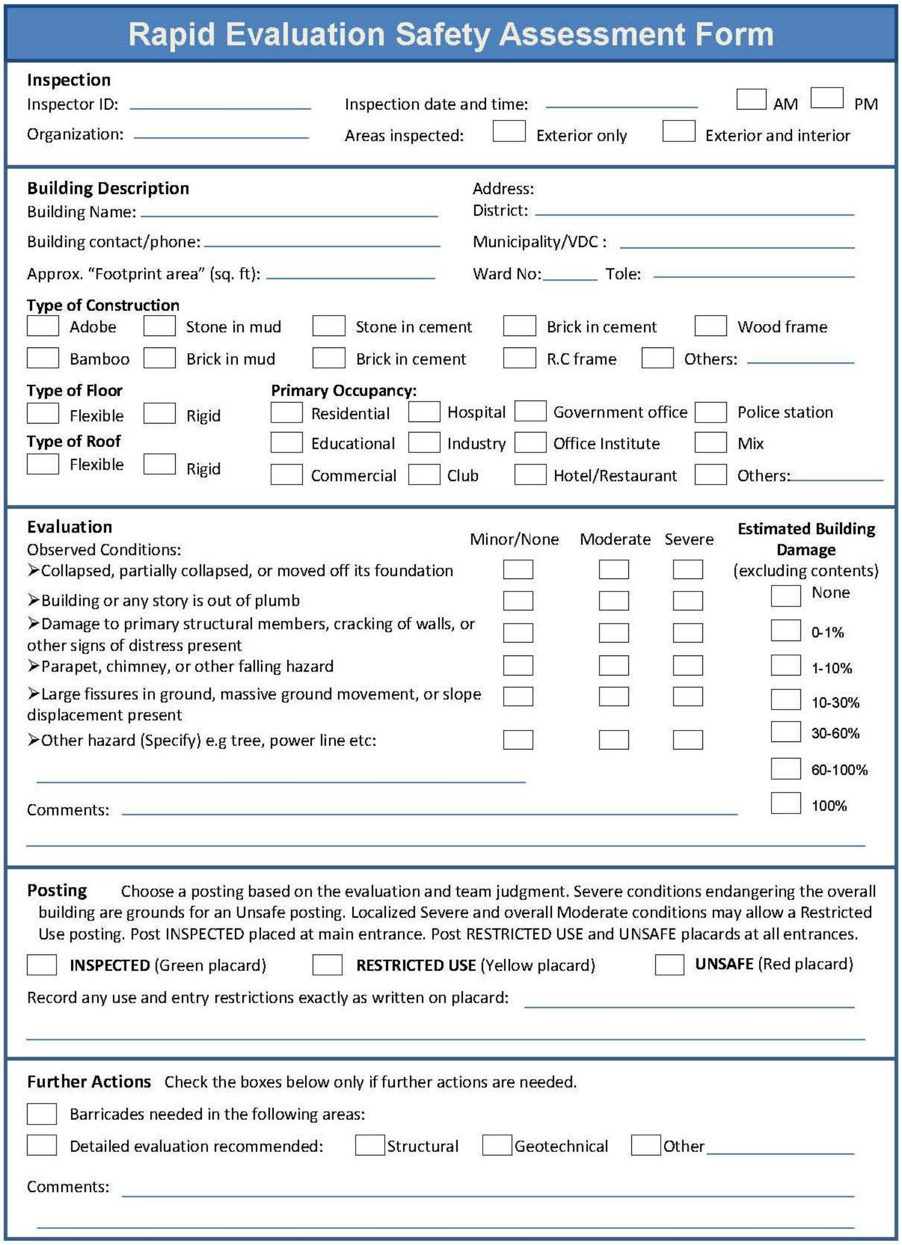
Table 1 – Used building types: lognormal fragility functions conditioned on PGA, with median λ and log standard deviation ζ, adapted from [3,11]

Building type		**Typology**	**Fragility function DS2**		**Fragility function DS3**	
			λ	ζ	λ	ζ
Residential	Adobe	AH	-1.183	1.094	-1.187	1.095
	Brick in mud	BM	-0.970	0.950	-0.830	0.967
	Brick in cement	BC	-1.026	0.947	-0.284	0.827
	Reinforced concrete	RC3	-0.582	0.932	0.078	1.114
	Timber [13]	TH	-1.079	0.640	-0.051	0.640
Industrial	Small industries	BC	-1.026	0.947	-0.284	0.827
	Medium/large industries	RC4	-0.808	0.810	-0.197	0.989
Commercial		RC3	-0.582	0.932	0.078	1.114
Critical	Hospitals	BC	-1.026	0.947	-0.284	0.827
	Schools	BM	-0.350	1.467	-0.883	0.861

The accuracy of the risk quantification of the building stock of a given community, using fragility functions, is however limited by several factors. First of all, it is often not possible to obtain exact exposure data. The exact structure, in terms of the number of buildings, and their exact location is often not known. Secondly, the fragility functions, provided in literature, are often mean fragility functions, obtained for several realizations of the evaluation of the robustness for a given building type. Additionally, the fragility functions proposed above are representative for aggregated classes of buildings. The single buildings may present a more or less pronounced variance in their seismic performances, depending, for example, on the quality of workmanship or the quality of the used building materials. Often no fragility functions taking into account all regional characteristics of a certain building type are available and, therefore, need to be substituted in a risk assessment by fragility functions for building types representing similar characteristics from other regions. The fragility functions used from [10] for timber houses might for example slightly overestimate the seismic performance of timber houses in Nepal, as they are derived for low seismic code timber houses in the United States. In order to decrease the epistemic uncertainty to a minimal degree, an individual fragility function for every single building would be needed.

III. UPDATING THE FRAGILITY FUNCTIONS USING THE NEA RVDA DATABASE

Updating (prior) fragility functions from literature with data, obtained from earthquake damage (e.g. through RVDA), can thus help to better represent the behavior of the buildings in a certain region, district or city, when subjected to seismic load and, thus, to take local parameters better into account. To update the fragility functions presented previously (Table 1), the RVDA database, assembled by the NEA after the April 25, 2015 Gorkha earthquake, is used. The RVDA, done by the NEA immediately after the earthquake, provided the trained evaluators with a paper form, permitting to determine the safety of buildings in the areas affected by the disaster. The form is divided into 5 different parts (Figure 1). The first part provides general information on the inspection, including information about the inspector, the inspection date and time, as well as the type of the assessment (exterior only or interior and exterior). The second part contains a description of the building, including its location, type of construction, type of floor and roof and occupancy type. However, no information about the building height (number of floors) and the date of construction are collected. The third part comprises the evaluation of the damage of the building. The damage was first rated using 6 criteria on a 3-level damage scale (minor/none, moderate, severe damage). The conditions include, for example, the degree of collapse of the building or damage to primary structural members. The overall building damage is then finally judged on a scale from 0-100%, corresponding to no damage (0%) and complete damage (100%), respectively. The building is then labelled according to the damage evaluation (green / yellow / red placard), signaling if the use of the building is safe and unrestricted, or unsafe and, therefore, (partially or completely) restricted. Recommendations for future actions could be included in the assessment.



Rapid Evaluation Safety Assessment Form

Inspection

Inspector ID: ______ Inspection date and time: ______ ☐ AM ☐ PM

Organization: ______ Areas inspected: ☐ Exterior only ☐ Exterior and interior

Building Description

Building Name: ______ Address:

District: ______

Building contact/phone: ______ Municipality/VDC : ______

Approx. "Footprint area" (sq. ft): ______ Ward No: ______ Tole: ______

Type of Construction

☐ Adobe ☐ Stone in mud ☐ Stone in cement ☐ Brick in cement ☐ Wood frame

☐ Bamboo ☐ Brick in mud ☐ Brick in cement ☐ R.C frame ☐ Others: ______

Type of Floor

☐ Flexible ☐ Rigid

Type of Roof

☐ Flexible ☐ Rigid

Primary Occupancy:

☐ Residential ☐ Hospital ☐ Government office ☐ Police station

☐ Educational ☐ Industry ☐ Office Institute ☐ Mix

☐ Commercial ☐ Club ☐ Hotel/Restaurant ☐ Others: ______

Evaluation

Observed Conditions:	Minor/None	Moderate	Severe
➢Collapsed, partially collapsed, or moved off its foundation	☐	☐	☐
➢Building or any story is out of plumb	☐	☐	☐
➢Damage to primary structural members, cracking of walls, or other signs of distress present	☐	☐	☐
➢Parapet, chimney, or other falling hazard	☐	☐	☐
➢Large fissures in ground, massive ground movement, or slope displacement present	☐	☐	☐
➢Other hazard (Specify) e.g tree, power line etc:	☐	☐	☐

Estimated Building Damage (excluding contents)

☐ None
☐ 0-1%
☐ 1-10%
☐ 10-30%
☐ 30-60%
☐ 60-100%
☐ 100%

Comments: ______

Posting Choose a posting based on the evaluation and team judgment. Severe conditions endangering the overall building are grounds for an Unsafe posting. Localized Severe and overall Moderate conditions may allow a Restricted Use posting. Post INSPECTED placed at main entrance. Post RESTRICTED USE and UNSAFE placards at all entrances.

☐ **INSPECTED** (Green placard) ☐ **RESTRICTED USE** (Yellow placard) ☐ **UNSAFE** (Red placard)

Record any use and entry restrictions exactly as written on placard: ______

Further Actions Check the boxes below only if further actions are needed.

☐ Barricades needed in the following areas:

☐ Detailed evaluation recommended: ☐ Structural ☐ Geotechnical ☐ Other ______

Comments: ______

Figure 1: Rapid evaluation safety assessment form [12]

More than 40'000 buildings have been evaluated after the earthquake, using the presented form. The paper forms were then manually digitalized by the NEA. In order to use the damage data in the database, a pre-processing was necessary [11]. Accuracy of spelling and data entry need to be verified and corrected, where necessary. Incomplete datasets are discarded (e.g. missing information about the construction type). In a first step, the correct spelling and assignment of the districts needs to be verified, in order to assign the correct PGA values to the different building locations. The database contains damage data from the following districts and municipalities (yellow shaded in Figure 2): Banepa (municipality in Kavrepalanchok), Bhaktapur, Chitwan, Dhading, Dolakha, Gorkha, Kathmandu, Kavre, Kavrepalanchok, Lalitpur, Lamjung, Makwanpur, Nuwakot, Sindhupalchok, Tanahun and Tokha (municipality in Kathmandu).

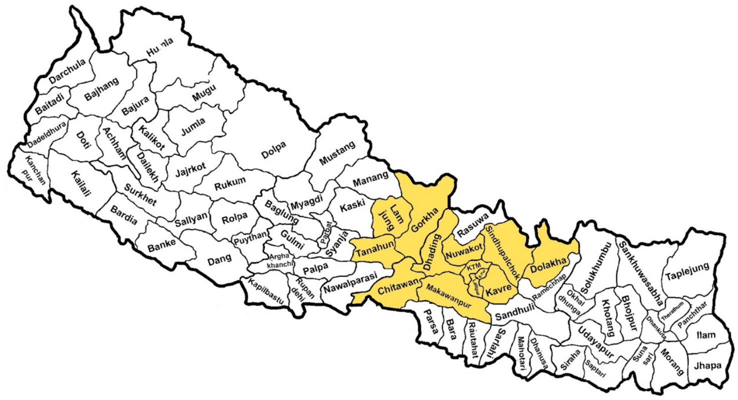


Figure 2: Districts of Nepal with RVDA data available (yellow shaded) (underlying map from [13])

In a subsequent step, the buildings are categorized into the different building typologies, as used in Table 1. This step is necessary in order to compare the derived fragility functions to the observed damage data from the earthquake. In total five building types are used for the updating: adobe, brick/stone in mud, brick in cement, RC frame and wood frame.

The assessment of damage, as proposed by the form, leads to some difficulties in the processing of the data: the qualitative evaluation of the damage, using the 6 proposed criteria, is not always coherent with the quantification of the total building damage (i.e. buildings presenting no damage using the proposed criteria were classified in overall as severely damaged and vice-versa). For many buildings, no total damage evaluation was assigned by the evaluator. To assign a damage state, the following procedure is used (Table 2) [11]: 1) if an estimated building damage is assigned, it is used to assign the damage state to the building. 2) If no estimated building damage is provided, the damage state is assigned to the building, according the evaluation of the 6 damage criteria.

Table 2: Assignment of DS according to the RVDA, adapted from [11]

Damage according to 6 damage criteria	Estimated building damage	Assigned DS
5 or more criteria rated as minor	None / 0-1%	DS1 (no/minor damage)
2-4 criteria rated as moderate	1-10%	DS2 (partial/moderate damage)
	10-30%	
	30-60%	
3 or more criteria rated as severe	60-100%	DS3 (severe/complete damage)
	100%	

A PGA value, according to the USGS Shake Map [14], is assigned to the different buildings. The PGA is assigned on a district level. This is done, due to two reasons: the building location data out of the assessment forms is very rough and the low quality of cartographic information of Nepal does not allow a more exact localization without tremendous effort. The second reason is the limited resolution of the available Shake Map for the April 25, 2015 Gorkha Earthquake (Figure 3).

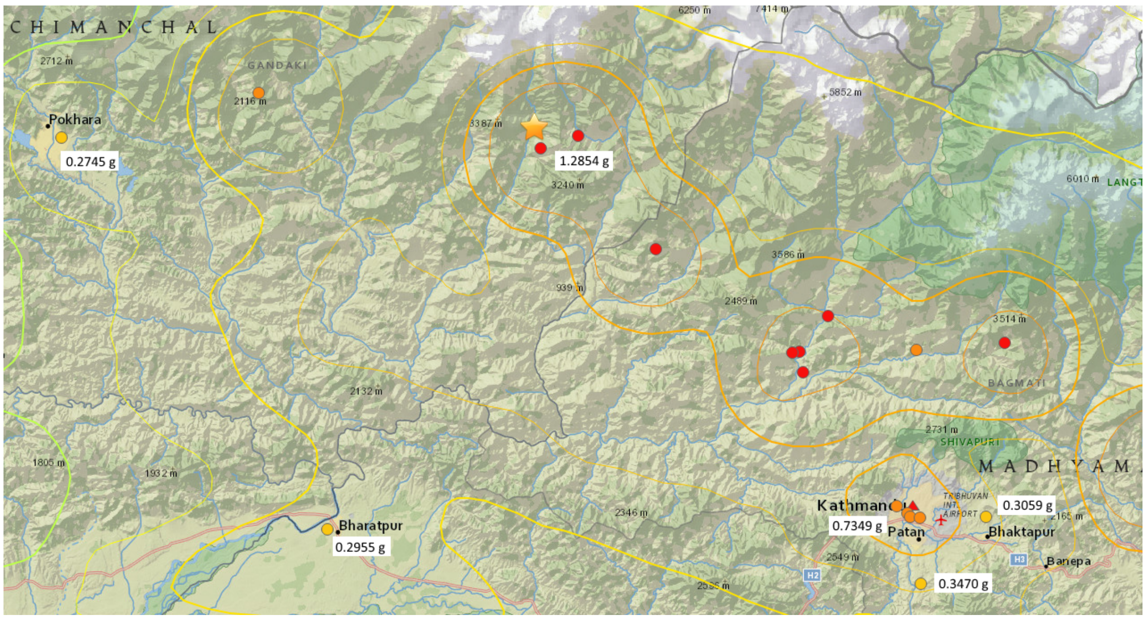


Figure 3: Shake Map of the April 25, 2015 April Gorkha earthquake [14]

In the first evaluation presented hereafter, a preliminary version of the database is used, as the complete database containing all evaluated buildings was not yet available. This version of the database contains originally a total of 37’416 buildings. 2’389 datasets could however not be categorized into one of the 5 building types. For 9’265 buildings, no intensity measure and no damage not be assigned, due to incomplete data. 73.5% of the initial database are usable for the subsequent updating of the fragility functions [11]. Figure 4 shows the distribution of the damage states for the different PGA levels for RC frame buildings, obtained from the RVDA database. Similar plots can be generated for the other building types.

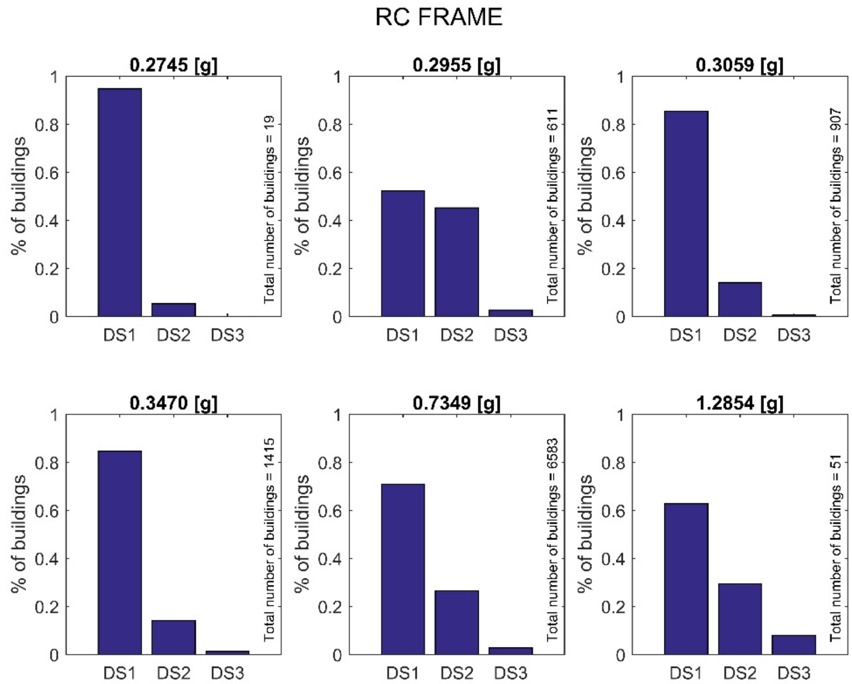


Figure 4: Distribution of the assigned DS, using the NEA RVDA database [11]

The obtained database is used to update the prior fragility functions (Table 1) employing Bayesian updating. The likelihood of the empirical data is multiplied with the prior distribution to obtain the target distribution. To find the parameters of this curve, a lognormal distribution is assumed and shifted to fit the target distribution [15]. The used data points, the prior and the updated fragility curves are shown for RC frame buildings (Figure 5) and brick in mud buildings (Figure 6). The blue line corresponds to the prior fragility curve as presented in Table x, the crosses to the data points and the orange line to the updated fragility function. The parameters of the updated fragility functions are given in Table 3.

Table 3 –Updated lognormal fragility functions conditioned on PGA, with median λ and log standard deviation ζ, adapted from [11]

Building type		**Typology**	**Fragility function DS2**		**Fragility function DS3**	
			λ	ζ	λ	ζ
Residential	Adobe	AH	-2.246	1.370	0.030	1.926
	Brick in mud	BM	-2.148	1.993	0.558	1.994
	Brick in cement	BC	-0.128	1.976	0.687	0.799
	Reinforced concrete	RC3	0.655	1.973	0.687	0.580
	Timber [13]	TH	-2.035	1.765	0.143	1.706

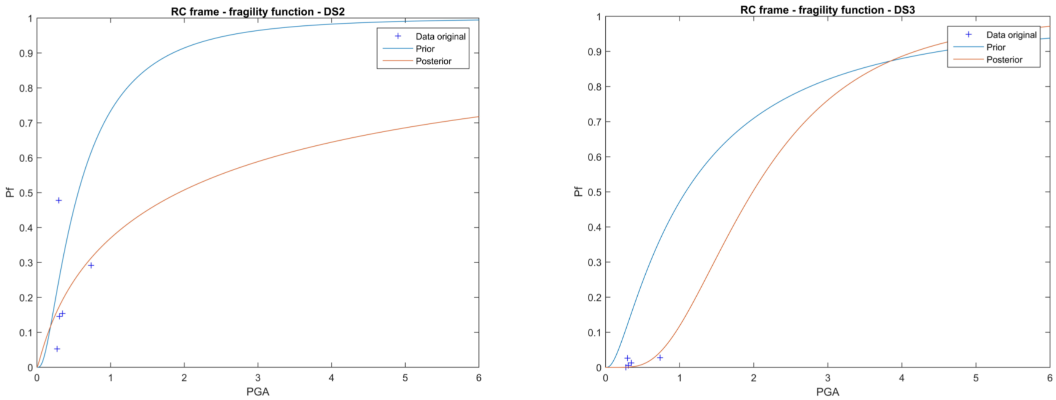


Figure 5: DS2 and DS3 fragility functions (prior and updated) and damage data from the RVDA database for RC frame buildings [11]

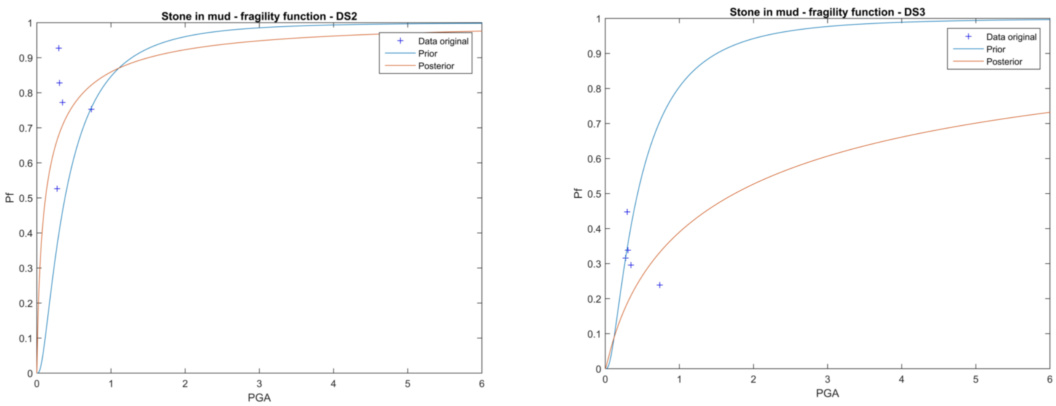


Figure 6: DS2 and DS3 fragility functions (prior and updated) and damage data from the RVDA database for brick in mid buildings [11]

IV. CONCLUSIONS

First preliminary results of the analysis of the RVDA database collected by the NEA and preliminary updated fragility functions are presented. The updated fragility curves, using the RVDA database collected, result in curves with lower damage probabilities than the prior ones. The overall damage of the building stock might therefore be lower as could be initially expected, using existing damage probability matrices. The collected data could however be enhanced by reducing ambiguity, or by collecting additional data, like for example the building height, the local soil type, or by obtaining more precise location data. This would allow a more coherent classification of the buildings into building types and could improve the overall vulnerability assessment. The proposed fragility functions can be employed to quantify the risk of the Nepalese built environment towards potential future earthquakes.

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