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ON THE USE OF EXISTING SEISMIC FRAGILITY AND VULNERABILITY FUNCTIONS

H. Stone[(1)], D. D'Ayala[(2)], R. Gunasekera[(3)], O. Ishizawa[(4)]

[(1)] *Research Engineer, EPICentre, University College London, harriette.stone.13@ucl.ac.uk*
[(2)] *Professor of Structural Engineering, EPICentre, University College London, d.dayala@ucl.ac.uk*
[(3)] *Senior Disaster Risk Assessment and Financing Specialist, World Bank Group, rgunasekera@worldbank.org*
[(4)] *Disaster Risk Management Specialist, World Bank Group, oishizawa@worldbank.org*

Abstract

The use of existing seismic fragility and vulnerability information can provide a cheaper and faster route to completing seismic risk assessments than deriving a new set of functions, however there are many challenges with this practice, in particular an increased uncertainty in the results achieved. In addition, there is often an element of subjectivity as to which existing function to select for a new risk assessment. After demonstrating the scale of potential inaccuracies when using existing functions, this study collates the opinion of experts using a paired-comparison elicitation to ascertain what factors are more or less important for the selection of existing functions, thus testing whether the process is highly subjective or more structured, albeit sub-consciously. Results show that, for the group of experts, the selection process is statistically random. In order to give more objectivity and rigour to the selection process, a framework for selecting existing functions is suggested. This helps not only to bring traceability to the decision process, but also guides the analyst towards more accurate results.

Keywords: loss assessment; seismic vulnerability; existing functions; paired-comparison

1 Introduction

Effective seismic risk reduction requires a good understanding of the present seismic risk, as highlighted in the recently formed Sendai Framework for Disaster Risk Reduction [1]. Seismic risk is estimated using assessments of seismic hazard, exposed assets, and structural vulnerability: the latter is represented by fragility and vulnerability functions derived using seismic vulnerability assessments, for which a large number of methods exist in the literature.

The derivation of new fragility and vulnerability functions can be costly, time intensive, and requires a high level of skill and competence, thus to save resources, many seismic risk assessors, particularly in developing countries, opt to re-use existing fragility or vulnerability functions. The impact of this practice on the accuracy of seismic risk assessment results has not previously been studied, despite the prevalence of the practice particularly in the developing world. Furthermore, there is no widely-used consensus on the process for selecting existing functions for re-use, and therefore the process may be subjective and unrepeatable, and thus results from different analysts may vary significantly.

This paper aims to discuss and investigate some of the key challenges of using pre-existing functions in seismic risk assessments. Following a brief introduction to seismic fragility and vulnerability functions, this paper explores the impact on accuracy when existing functions are selected. The process of selecting which existing functions to re-use is investigated, followed by the development of a new existing functions selection framework to improve the objectivity of the process. Further challenges are then discussed on the subject, highlighting areas where further research is required.

2 Existing seismic fragility and vulnerability functions

2.1 Derivation methods

Seismic fragility and vulnerability functions are derived using one of four approaches: (1) analytical approaches use structural modelling procedures to evaluate the expected structural response, from which the damage and loss is inferred [2]; (2) empirical approaches derive a relationship between post-earthquake damage or loss data and the size of earthquake that caused it [3]; (3) expert judgement approaches utilize the opinions of a group of experts to form fragility or vulnerability functions (e.g. Jaiswal et al. [4]); and (4) hybrid approaches use a combination of two or three of the aforementioned approaches (e.g. Kappos at al. [5]).

Many different derivation methods exist in the literature [6], ranging in type of approach, complexity, assumptions, required inputs, etc. However, no seismic vulnerability assessment methods can give perfect results because of numerous aleatory and epistemic uncertainties throughout the process, and different derivation methods will result in different functions and associated uncertainties, even for the same building class. Differences arise due to variations in management of uncertainties, techniques and approaches, input requirements, etc. Generally, it is presumed that the more complex an assessment method is, the more accurate the result [7], however with the absence of a perfect result, it is difficult to test this.

2.2 Sources of existing functions

There are a large number of existing functions in the published and grey literature. Helpfully, the Global Earthquake Model (GEM) holds a database of some existing empirical and analytical functions found in literature from around the world [8]. In addition, Stone et al. [9] collected functions both from literature and grey literature that had been developed for, or used in, Central America. These two databases will be used for studies in this paper.

3 Investigating accuracy

The main concern associated with the use of existing functions is the accuracy of resulting risk assessments. To understand the impact on accuracy when existing functions are used, a set of fragility functions derived in the literature for a certain building class are compared to existing functions that could have been selected for that building class had the derivation not taken place. The building type investigated is a three-storey unreinforced masonry building class, for which fragility functions were derived by Rota et al. [10].

3.1 Results and Discussion

The results of the comparison of fragility functions for the unreinforced masonry building class are presented in Figure 1, Figure 2, Figure 3, and Figure 4, for the four damage states. The original Rota et al. [10] functions are denoted by a thicker line. Each study's description of damage states has been assumed to be similar to allow this comparison.

Figure 5 and Figure 6 show the expected state of damage of the unreinforced masonry building class at a PGA of 0.2g and 0.3g respectively, according to the different authors included in the comparison.

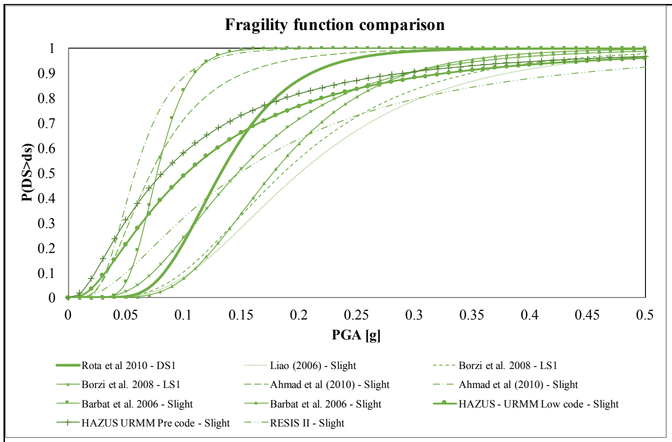

Figure 1 – Comparing results for an unreinforced masonry building class by Rota et al. [10] – first damage state

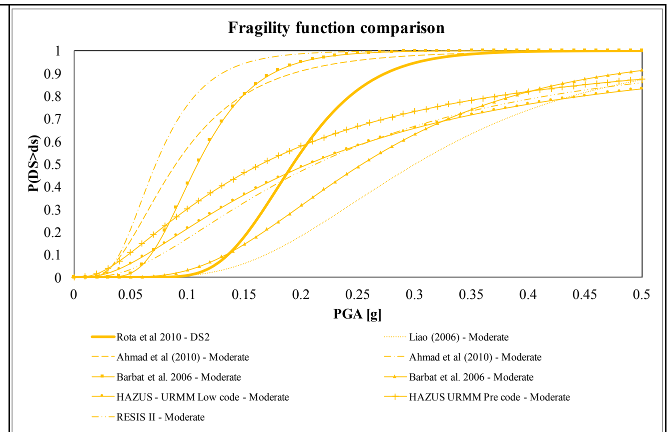

Figure 2 – Comparing results for an unreinforced masonry building class by Rota et al. [10] – second damage state

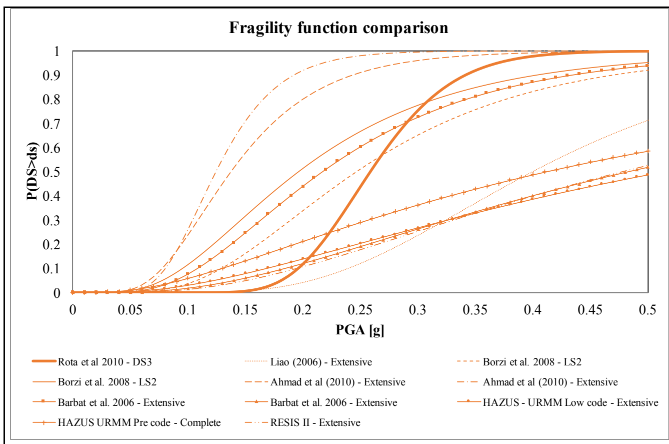

Figure 3 – Comparing results for an unreinforced masonry building class by Rota et al. [10] – third damage state

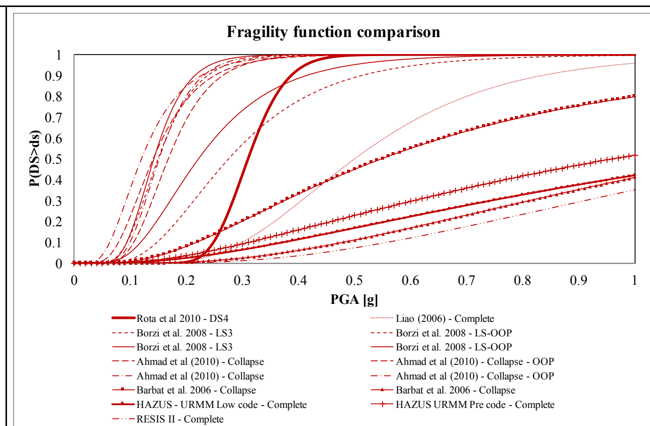

Figure 4 – Comparing results for an unreinforced masonry building class by Rota et al. [10] – fourth damage state

The results show a range of functions from the databases derived for similar building types. The vast differences in results achieved by different authors is stark and immediately raises concerns about the accuracy of adopting existing functions for new uses. Of course, it must be noted that the original functions may be inaccurate themselves, however, the relative difference between all functions is a major concern. There are a number of possible reasons for the observed differences; these will be discussed here.

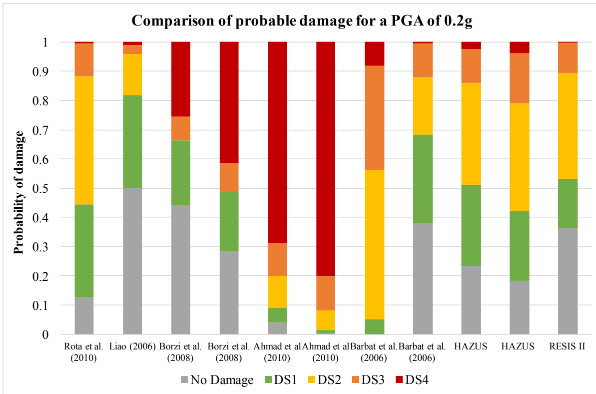

Figure 5 – Comparing probable damage of the URM class from different authors for a PGA of 0.2g

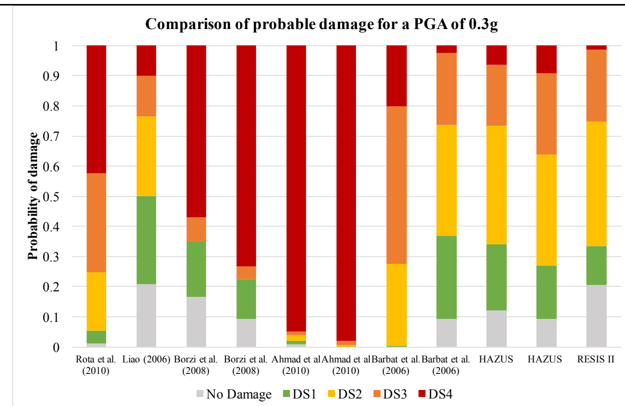

Figure 6 – Comparing probable damage of the URM class from different authors for a PGA of 0.3g

Firstly, masonry is a construction material that can vary vastly, from hollow concrete blocks with cement mortar, to rubble stone in weak mud mortar, and these materials may behave very differently in earthquakes and have widely ranging strengths and stiffness, but all are classes, at the highest level, as masonry. Although functions that most closely resembled the tuff stone masonry units in the original building class [10] were selected, there may still be tangible differences in the behaviour of the different masonry building types compared. Additionally, the defined damage states for each study may not correspond exactly, whether standard definitions (e.g. HAZUS, EMS-98) or a custom scale have been used. Also, some studies delineate between the design level of the building class, however these may not translate well between different countries with different building codes. Similarly, some studies derive different fragility functions for different building heights and some authors may group buildings by height in different ways (e.g. low-rise, medium-rise, and high-rise) and these groupings may not correlate to the height classification systems of other studies, or those that consider specific numbers of storeys. There are also major differences in methodology used by different authors for deriving each set of functions. The range of methods employ differing assumptions and techniques, incorporate different uncertainties, and use different inputs which can range significantly depending on country, urban or rural setting, level of development, and building regulation levels, amongst others.

Additionally, differences may arise from the way the functions have have been compared in this study, in particular, the translation of fragility functions from different intensity measures (IMs). The original study [10] derived results in peak ground acceleration (PGA), thus any functions that use other IMs such as spectral acceleration (Sa), or spectral displacement (Sd) had to undergo a transformation to allow comparison in PGA. To enable this, the fundamental period was either taken the study concerned, or assumed according to the similar buildings results, and a value of 2.5 was assumed for the PGA/Sa relationship, as is given by most code spectra for the fundamental periods observed.

All of these factors may account for the differences observed between original and existing functions. The variation can be associated with either differences between the actual buildings being studied by authors (building variation), or differences arising from different methods of modelling and deriving fragility functions (derivation variation). As every building in the world is unique (at the most detailed level), and every derivation technique non-perfect, there will never be a perfect existing function available to select and use; instead the aim of this practice should be to achieve the best results possible, with the present limitations.

Depending on the existing fragility functions selected, the expected damage ranges significantly for example:

- For a PGA of 0.2g, either 50% of buildings are expected to have no damage, or 80% buildings are near collapse (see Figure 5)
- For a PGA of 0.3g either 50% of buildings are expected to have no damage or low levels of damage, or nearly all buildings are near collapse (see Figure 6)

This disparity is large, and would lead to significant inaccuracies in the final risk results, the extent of which would depend on various factors, in particular the exposure profile. In reality, analysts would exercise some judgement to adopt what are thought to be the best functions and hence perhaps reduce these inaccuracies. However, this raises a different concern: does the selection of existing functions vary between analysts?

4 Investigating the selection of existing functions

The process of selecting which functions to use is currently undertaken according to the client's or analyst's priorities, biases, or heuristics, however despite being individually subjective, overall it may be the case that experts have clear priorities or determined ways, albeit possibly subconscious, for choosing between functions. On the other hand, the process might be random, with different experts making different selections, leading to significantly different results in seismic risk assessments. To investigate a paired-comparison elicitation is completed to determine the way that expert analysts select functions. Following discussions with experts in the field, eleven attributes or characteristics of the functions were identified that may impact on selection: they are explained in Table 1.

Table 1 – Potential influences on an analyst's selection of existing functions

Characteristic or attribute of influence	**Description**
Authenticity of function	The function you have obtained is authentic and could not have been altered by others
Mean and standard deviation	The mean and standard deviation values of the function appear, from your experience, to be reasonable
Gives expected loss results vs. other studies	When the function is used to calculate loss, the value achieved is comparable to other comparable studies
Credibility of authors/source	The functions have been developed by a credible author or organisation
Derivation method used	The general methodology and techniques used to derive the function are reasonable
Derived for a proximate location	The vulnerability calculations have been done for a location comparable to the new location
Gives expected loss results vs. your judgement	When the function is used to calculate loss, the value achieved is as your experience would expect
Uncertainty reported/considered	Uncertainty in the function has been considered and reported appropriately
Popularity or 'track-record' of function	The function has been used on numerous occasions for risk assessments
Quality of inputs used	The quality of inputs, such as building typologies, intensity measures and damage states, used in the development of the function is reasonable
Relevance of inputs used	The building typologies, intensity measure and damage states associated with the function are reasonably relevant to the new study

4.1 Method

The relative preferences of the attributes in Table 1 are tested using a paired-comparison [11], [12]. The technique elicits a ranking of the eleven characteristics in Table 1 in order of importance to a selection decision. Instead of simply ranking the characteristics into a list (which is not deemed to give good results with more than five or six items), pairs of items are compared and ranked using a matrix, until all possible combinations have been considered. Two different matrix arrangements are used to allow any biases towards items placed in different positions in the matrix to be identified. A software programme called UNIBalance [12], [13] is then used to determine the overall rankings, any circular triads (i.e. when experts have ranked A>B, B>C, and C>A), and the statistical agreement between participants.

Experts were selected if they have recently published in the field, attended a GEM seismic vulnerability course held at UCL in November 2014, or if they attended a World Bank seismic vulnerability workshop held in Managua in March 2014. Experts were elicited in two different ways: (1) at a session at the GEM course, and (2) through email. Video instructions were provided in English and Spanish to enable participation of Spanish speakers, and to improve the quality of responses from all email participants. Information was also collected about the experts themselves to enable investigations into any patterns of opinions due to geography, or experience levels. One hundred and twenty-five participants were targeted, and fifty-five full responses were received which exceeded the minimum number of participants, recommended as between ten and thirty. Each individual expert's results were statistically tested to avoid the inclusion of any results that were more likely to have been completed by randomly filling in the matrix, i.e. any results with a p-value of over 0.1 (achieved as a consequence of a high number of circular triads). Only one participant's results were disregarded.

As is standard practice with this technique, UNIBalance is used to perform probabilistic inversion to score and rank the expert's opinions of the eleven characteristics.

4.2 Results and Discussion

Overall, the group's responses achieved a combined p-value of zero, indicating that the participants completed the paired-comparison exercise successfully, i.e. as instructed. The probabilistic inversion results are shown in Figure 7, and despite some preference appearing in the scoring, the standard deviations show that it cannot, with any acceptable statistical probability, be concluded that any attribute is preferred by the group above another. This study therefore shows that the process of selecting existing functions is, for the group of elicited experts, unsystematic and subjective.

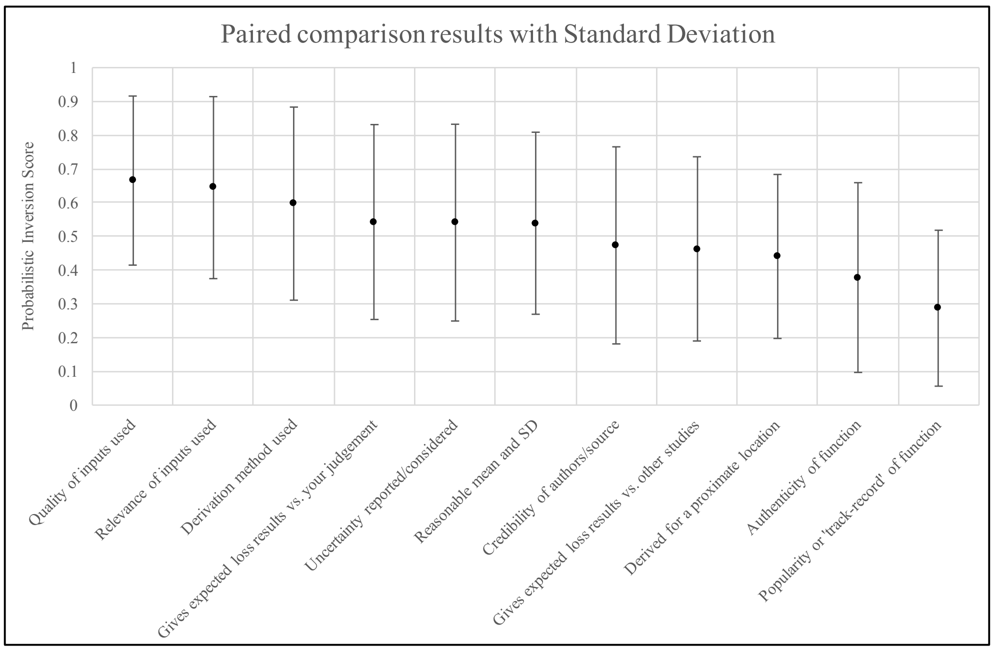

Figure 7 – Paired-comparison probabilistic inversion results with standard deviations

Additional analysis shows that there are no significant differences in preferences if the data are split by geography, experience level, data collection method, or matrix version: the results are presented in Figure 8, Figure 9, Figure 10, and Figure 11 respectively.

In reality, this subjectivity in the selection of existing functions could lead to significantly different risk results depending on the analyst, which may lead to ineffective DRR strategies. This finding shows the importance of more rigourous and repeatable methods to select existing functions, such as [14], which will be discussed next.

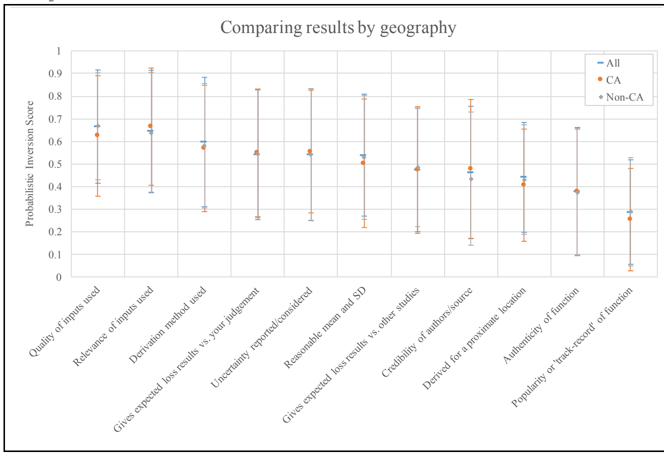

Figure 8 – Comparing results for Central American experts against experts from the rest of the world

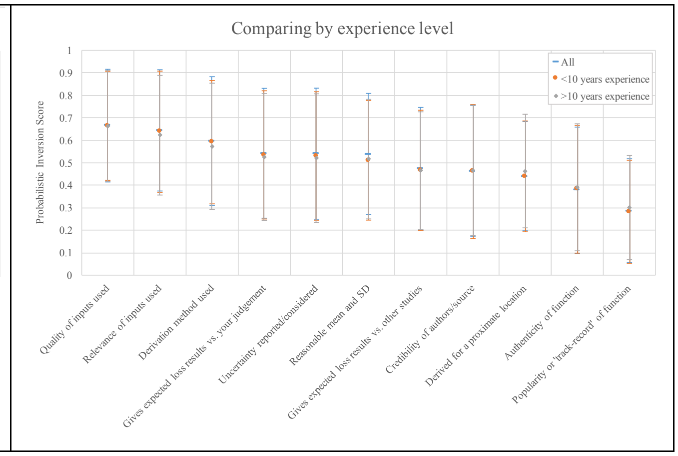

Figure 9 – Comparing results for less and more experienced experts

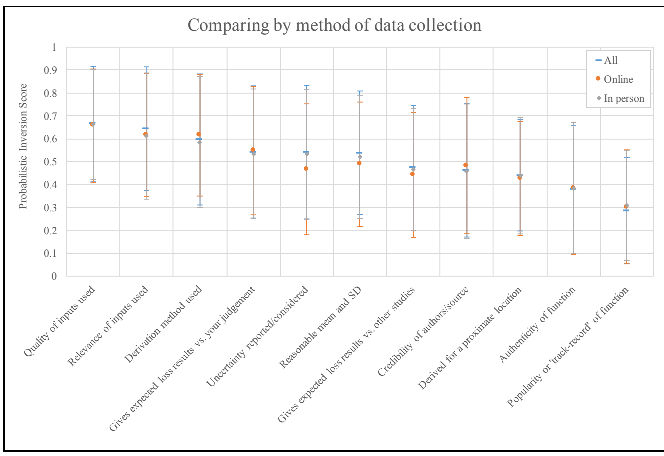

Figure 10 – Comparing results by method of data collection

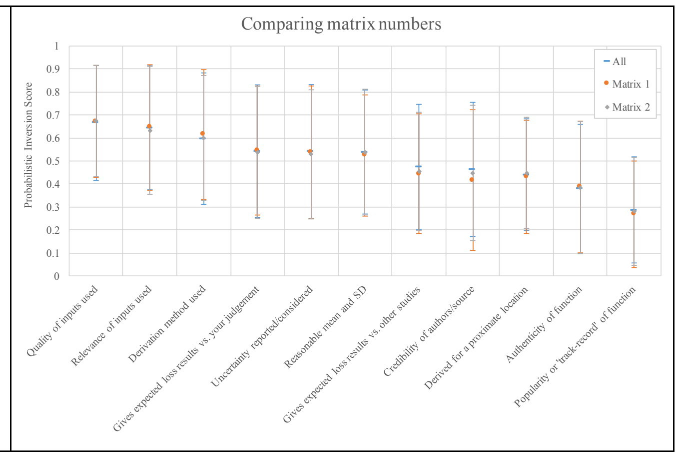

Figure 11 – Comparing results by matrix version number

5 A strategy for objective selection of existing functions

The GEM existing functions selection framework [14] is based on the rating of the overall quality of a function and its relevance to the new study area. The overall quality is based on the quality of inputs, the rationality of derivation procedures, and the document quality. The relevance is concerned with how representative damage states, building classes, and ground motion intensity measurements are of the new study. Each branch is rated as low, moderate, or high, and scored as 1, 2, or 3 respectively. The branches are equally weighted (or otherwise if desired) and the total scores are summed, with the highest scores revealing the proposed functions for selection. A method for combining multiple highly ranked functions is given, using a simple averaging method [14].

This framework focuses on functions with good background information about their derivation, yet it is difficult to use with functions that lack data, i.e. those from grey literature or non-published functions. With this is mind a new, more simplified framework, has been developed and is presented here.

5.1 Proposed framework for selection

This new framework is designed for use with all functions, including those for which information is lacking. In these data-poor cases it is difficult to rate functions from high to low, as is done in the GEM framework, because there is little information available to judge whether functions are of high or low quality or relevance. However, it is possible to rank functions, as comparison is only needed between the functions at hand. Thus, the framework proposed here requires the ranking of functions with regard to various characteristics or attributes to ascertain which function is best suited for use in the new seismic risk assessment.

The framework is based on two steps, designed to capture as much inherent and known information about the functions as possible. The first step ranks the functions using attributes that are often well known, even in data poor situations. The second step involves plotting the functions on the same graph, plotting an average curve, and then ranking the curves on a distance from the average. The framework does require some subjective judgements, but these are guided as far as practicable. The framework is explained in detail below.

Step 1: Ranking of quality and relevance

In the first step, the functions are ranked according to the different characteristics or attributes given in Table 2. From previous research it is observed that these attributes are often known about functions, even if the studies are poorly documented [15]. Each attribute and the proposed ranking process are described in detail below.

Table 2 - Attributes to be ranked in the proposed framework

Quality	Authenticity
	Credibility
	IM
	Size of building class

Relevance	Age
	Building class similarity
	IM similarity
	Locality
	Matched damage states

Quality 1: Authenticity

This attribute concerns the authenticity of a function, i.e. is the function as the authors intended it, or has it been altered. The authenticity of a function is judged by the authenticity of the study in which it was derived and can be measured as High, Moderate, or Low, according to the framework developed in Stone et al. [15]. The ranking of functions for authenticity will result in a maximum of three levels (1^{st}, 2^{nd}, or 3^{rd}), and it is likely that multiple curves will be ranked equally at each of these levels.

Quality 2: Credibility

This attribute concerns the credibility of a function which is judged by assessing the credibility of the study in which it was derived. It can be measured as High, Moderate, or Low, according to the framework developed in Stone et al. [15]. The ranking of functions for credibility will result in a maximum of three levels (1^{st}, 2^{nd}, or 3^{rd}), and it is likely that multiple curves will be ranked equally at each of these levels.

Quality 3: Intensity measure

The intensity measure (IM) used gives a good indication of the quality of earthquake demand information used in the function derivation process. Published research and the GEM framework suggests that IMs be ranked into four groups, see Table 3 [16]-[18]. As above, it is possible that multiple functions will be ranked as equal.

Quality 4: Size of building class

Large building classes, that attempt to capture the behaviour of a large group of varying building types, are less likely to yield accurate results, as the range in potential buildings that are represented by one curve is very large. Therefore, functions are ranked according to the size of the building class. It is also imperative that a building class defines the buildings that it concerns well. An example is given in Table 4 to guide how the functions should be ranked.

Relevance 1: Age

Older functions are likely to have been derived using aged empirical data or modelled on older types of construction, and therefore are likely to be less relevant to a new seismic risk assessment. This might not always be the case, so groupings of 10 years are suggested, assuming that between decades there are more likely to be pronounced differences in relevance. So, functions should be grouped into age brackets of 10 years. Within these brackets functions are ranked equally, and then the groups are ranked from newest to oldest.

Relevance 2: Building class similarity

The similarity between the building class of the candidate functions and the building class that the function needs to represent in the proposed study is important. Therefore, for this ranking exercise, the functions should be ranked according to the similarity between the number and the description of the building class of each function and the building class in the new study – the more similar, the higher a function should be ranked.

Table 3 - Ranking of IMs

Higher			**Lower**
Advanced IMs	Spectral IMs	Scalar IMs	Discrete IMs
e.g. S^c_a, IM_{CR}, IM_{SR}	*e.g.* $S_a(T_1)$, $S_d(T_1)$	*e.g. PGA, PGD*	*e.g MMI, EMS-98*

Table 4 - Ranking of size of building class

Higher		**Lower**
Well defined, smaller building classification		Very broad, or poorly defined, building classifications
e.g. Medium-rise, low-code, RC frame with masonry block infill; low-rise unreinforced concrete block masonry with timber diaphragms	*e.g. RC frame with infill; low rise unreinforced masonry*	*e.g. Concrete, Masonry*

Relevance 3: IM similarity

It is likely that hazard information using a particular intensity measure has been obtained for the new study, e.g. hazard maps with PGA, or spectral acceleration. Therefore, it is likely that a function that already uses the needed intensity measure will give better results than a function that needs to be translated between different IMs.. Therefore, the functions should be ranked according to whether the IM matches that of the one that is needed, and then by how easily the IM can be translated to the needed IM, as demonstrated in Table 5.

Table 5 - Similarity of IMs

Higher			**Lower**
e.g. Assume needed IM is $S_a(T_1)$			
$S_a(T_1)$	$S_d(T_1)$	*PGA*	*MMI*

Relevance 4: Locality

If a function is derived for a nearby city or country, it may be fair to assume that the building design, construction materials, building practices, etc., might be more similar than if the function was derived for a country further away. Similarly, the seismic demand information used in the derivation process of a closer study might be more relevant to the seismo-tectonic setting of the new study. Therefore, candidate functions should be ranked according to the distance between the location they were originally derived and the new study's location.

Relevance 5: Damage state similarity

It is important to select a function for which the number and descriptions of damage states match as closely as possible those required for the new study. Therefore, candidate functions need to be ranked according to how well the number and descriptions of damage states match the required damage states for the new study.

Overall attributes ranking

By adding up the scores from each quality ranking exercise, an overall score will be calculated, which can then be used to give each functions an overall quality ranking. The same will then be done for the relevance rankings. Ties, and therefore equal overall quality and relevance rankings are expected.

Step 2: Similarity ranking

The second step of the framework involves ranking the similarity of the candidate functions to an average curve. Firstly, the candidate functions are plotted with the average curve. If there are less than eight functions, it is recommended that additional functions for a similar building class be taken from the existing sources [7], [8] and plotted alongside the candidate curves. These additional functions may then be included as candidate functions, if appropriate. As functions will be plotted using the IM required by the new study, the additional functions may need to be translated into the correct IM, for which conversion equations are available [19] or by the standard engineering equations, making an assumption for the fundamental period and a spectral conversion factor (between acceleration and spectral acceleration) where necessary.

The ranking of the functions is based on their overall deviation from the average curve. This can be found by calculating the distance of each function from the average at each IM value, and summing the distances.

Overall ranking

Functions are ranked overall by summing the scores achieved for quality, relevance, and similarity. Equal rankings are possible. If a single function is ranked first overall, then it is, by this framework, and relative to the other candidate functions, considered to be most suitable for selection. If there is a tie for the top ranking, or if it is preferred that the average of a number of highly ranked functions be used, then the average curve can be calculated for the highly ranked functions, and that used as the function in the new study.

It is suggested that once functions have been selected for the range of building typologies present in the exposure portfolio, that a common-sense comparison is carried out on the set of functions, to ensure that there are no obvious issues. Additionally, improvements could be made to the selected functions using empirical data, or additional expert judgement input if available, however this not been investigated here.

5.2 Testing the proposed framework for selection

Using the proposed selection framework, the functions in Figure 12, Figure 13, Figure 14, and Figure 15 are proposed for the URM case presented above in Figure 1, Figure 2, Figure 3, and Figure 4. The functions selected using the framework match the original functions relatively well, particularly the top ranked curves.

Figure 16 and Figure 17 indicate the damage expected at PGAs of 0.2g and 0.3g respectively for the original function and the selected functions. The damage states are fairly well matched, particularly in comparison with the range observed in Figure 5 and Figure 6. The results are very rarely more than one damage state away from the original result, which is a marked improvement. These findings indicate that, on the whole, more accurate results would be achieved if the proposed framework were used by an analyst when selecting existing functions for use in a seismic risk assessment.

Analysts need to be aware of the implications of using existing functions, and be able to clearly communicate these with decision makers. This practice is far from ideal, and still derivation of new functions will offer much better results, however if resource is limited this gives another option. Additionally, this might be a good way to deliver a rapid ‘first pass’ prior to more substantial analysis, or for use in the aftermath of a large earthquake where results could help in the emergency response.

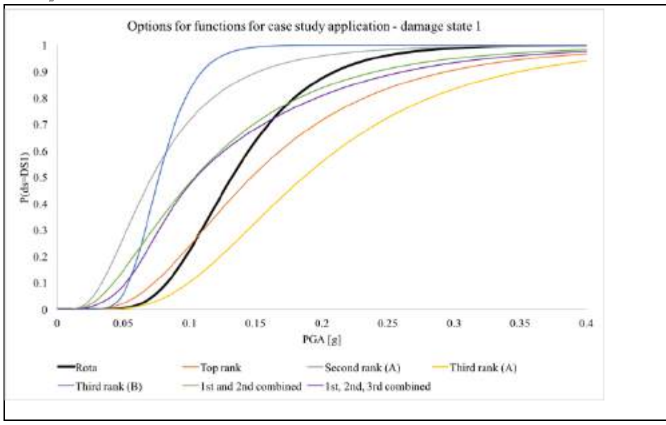

Figure 12 – Comparing existing function options – first damage state

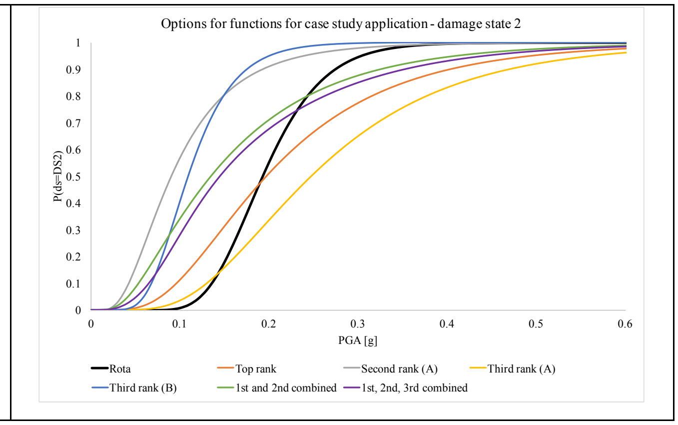

Figure 13 – Comparing existing function options – second damage state

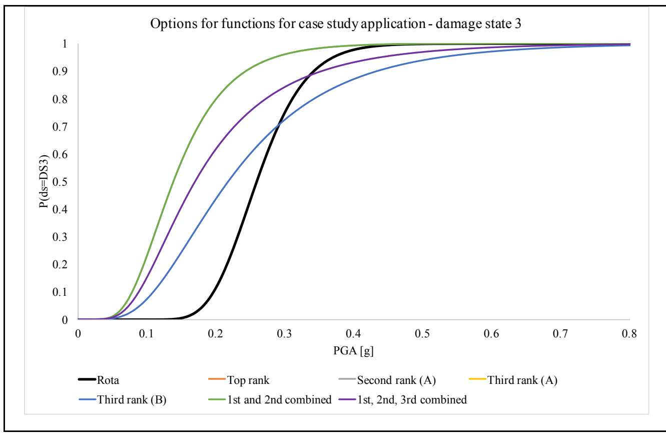

Figure 14 – Comparing existing function options – third damage state

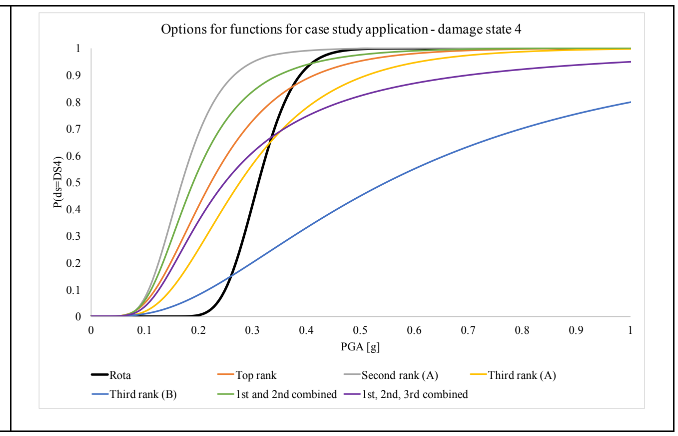

Figure 15 – Comparing existing function options – fourth damage state

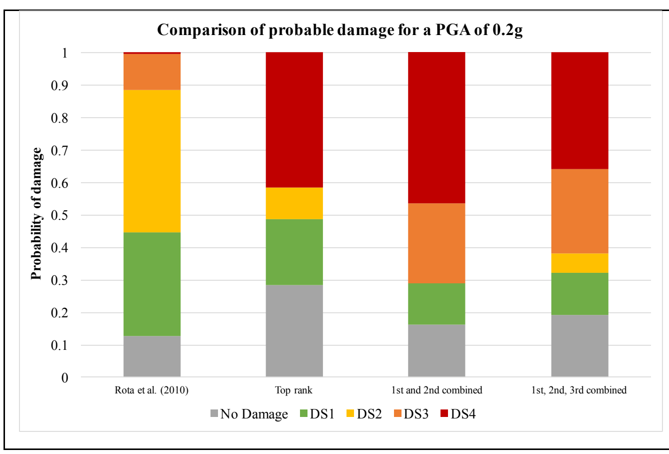

Figure 16 – Comparing probable damage of the URM class from the selected functions for a PGA of 0.2g

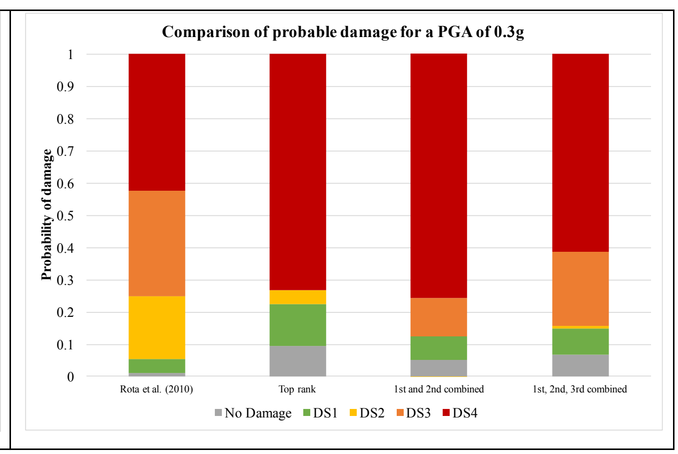

Figure 17 – Comparing probable damage of URM class from selected functions for PGA of 0.3g

6 Conclusions

This paper has offered some initial investigation and discussion on the use of existing seismic fragility and vulnerability functions. Firstly, the impact on the accuracy of seismic risk assessments has been shown to be potentially large, with significant differences in expected damage depending on the function selected. In turn, the results form a seismic risk assessment could be affected.

Secondly, the process of selecting existing functions is shown to be largely subjective and differs significantly between experts. This indicates that results would vary depending on the analyst used. This adds another dimension to inaccuracies in the results. Therefore, to add some rigour to the selection process, a framework is proposed which is based on ranking existing functions based on basic characteristics. This framework is shown to select good existing functions for use, which results in less inaccuracy in the damage predictions.

The use of existing functions should be done with a high level of consideration. Although there are financial benefits in the risk assessment process, there are potential wider pitfalls associated with the use of inaccurate results to develop DRR strategies. This is a very difficult balance to strike.

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