Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1678

# COLLABORATIVE EFFORT TO ESTIMATE COLLAPSE FRAGILITY FOR BUILDINGS WORLDWIDE: THE WHE-PAGER PROJECT

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## ABSTRACT

The EERI WHE-USGS PAGER project is a collaborative initiative to improve the understanding and classification of the building inventory and collapse vulnerability of non-U.S. construction types worldwide. The assessment of building stock vulnerability will directly help the PAGER semi-empirical and analytical loss models to reliably estimate the casualties in the near-immediate aftermath of any destructive earthquake worldwide. Data have been collected systematically by interrogating experts to produce empirical estimates of fragility curves and numerically-based analytical models. The process of developing a consistent reference framework for collapse definitions, structures catalogue, use of experimental data existing in the literature, and correlation between the two approaches is illustrated here, followed by a discussion of the results obtained.

## Introduction

Collaboration between the U.S. Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) project and the Earthquake Engineering Research Institute (EERI) managed online World Housing Encyclopedia (WHE) has been ongoing for the past two years. The objective of this joint effort is to mobilize the expertise within the WHE contributors Roster to provide reliable estimates of the collapse fragility of the building stock by structure and occupancy type at a national level. These data then feed into the PAGER database to produce prompt assessment of earthquake casualties in the immediate aftermath of an earthquake with a magnitude greater than 5.5, on a worldwide basis. The ultimate aim of this project is to provide robust information on damage and casualties, primarily for response efforts, but also for mitigation purposes. The WHE-PAGER collaboration consists of Phase I, which constitutes compilation of empirical intensity-based building collapse fragility functions, and Phase II where analytically-based damage functions are adopted. The overall architecture of the PAGER system and the component concerning the determination and use of the structure-specific fragility curves within the loss modeling framework have been extensively reported in other publications (Wald et al. 2008).

The primary justification for worldwide data collection of fragility data for both,

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empirical and analytical approaches rests on the observation that the majority of the world's population located in seismically hazardous zones lives and works in non-engineered buildings. Furthermore, a consistent body of work that provides damage probability matrices and fragility curves for the building stocks of specific regions, based on performance observations in previous seismic events, already exists in the literature. In Europe this body of knowledge led to the development of the EMS '98 vulnerability approach (Grunthal et al. 1998).

Alternatively, initiatives by FEMA and NIBS in 1992 (Whitman et al. 1997) and parallel similar initiatives in Japan (Otani 2000), Europe (FP4 European Community Seismic vulnerability reduction program, D'Ayala et al. 1997), and elsewhere, led to a first generation of analytically-based earthquake loss-estimation methodologies. Here HAZUS represented the most standardized and readily applicable case (FEMA 2003); however, one limitation of these analytically based earthquake loss estimation methods is that these methods can be used only if for each of the typologies constituting a given building stock the following is applicable:

- an inventory and building classification by building typology does exists,
- the building typologies are designed to relatively uniform seismic standards, hence their capacity curves can be deduced either from design guidelines and overstrength relations or from experimentation on a small but representative sample,
- for a given capacity curve, thresholds of force or displacement can be identified that will correspond to specific damage states,
- existence of acceleration-displacement spectra that provides the correlation between capacity and demand displacement,
- where casualties are required, the occupancy load (no. of people) of building types for a given time of day are known, along with information on casualty rates conditioned on damage states,
- where other loss measures are required, they too can be quantitatively related to damage states.

If these conditions are verified, then it is possible to use a stochastic approach and probability distributions, such as the lognormal distribution, can be used to define fragility curves for each building typology of a given region that is exposed to a specified level of seismic hazard. The reliability of such curves is only as good as the uncertainty on any of the components of the process outlined above and hence, even if the general methodology is well established from a technical point of view, understanding its applicability and reliability at a global scale are nontrivial issues.

Within the ongoing phase of the WHE-PAGER collaboration, work focuses on two activities. The first activity is the revision of the data collected for the empirical intensity-based model and its implications for loss calculations, the development of a new data-collection protocol, an enriched structure-types list, a definition of collapse better correlated with fatalities. The second activity is the identification of critically-important non-HAZUS building types, and for these, the development of capacity and fragility curves within the analytical framework of performance-based assessment, constituting the analytical model of the PAGER project. In the process of fulfilling these two objectives, several questions needed to be addressed. These are namely clarifying the definition of collapse, updating the building class definition, correlation of vulnerability with measures of shaking, explaining the meaning and validation of performance based approach for non-engineered building types. These questions have been answered and the results obtained while pursuing them are discussed now.

## Empirical Collapse Fragility

In the initial phase of development of the empirical intensity-based model, experts provided distribution and occupancy of predominant buildings types and their fragility functions for 30+ countries. Efforts were first focused on constraining loss models for countries having substantial seismic risk. In many cases the inventory judgments were informed by local housing censuses and other public data sources. The methodology, results and analysis of the Phase I survey data along with the original contributions from experts for each country are documented in Jaiswal & Wald (2009), Porter et al. (2008), and the procedure adopted for compilation of such datasets is described through country-specific experiences by Goretti et al. (2008) and Pomonis et al (2009).

The vulnerability definition in Phase I survey was limited to the collapse probability for each structure type, given a specified shaking level. Structure types were assigned with the WHE construction classes (see http://www.world-housing.net/) and the shaking intensity levels were expressed in modified Mercalli intensity (MMI) as well as peak ground acceleration (PGA). Results have been analyzed for similar structure types and were compared in terms of vulnerability curves among different countries.

Expert feedback and data review led to an update of the data collection method, which ensured better consistency from country to country and limited the need for data post-processing. As the collection of empirically based data was rolled out to more nations worldwide modifications were introduced to address these shortcomings.

## New Structural Types Catalogue (PAGER-STR)

From the collected data emerged that not only was the catalogue of WHE construction types insufficient to cover all entries, many of the experts own specified building types had validity and applicability which transcended the boundary of a single country. Moreover, the description provided in the WHE construction type catalogue does not always univocally indicate the specific characteristics which qualify the seismic vulnerability or resilience of a given typology. A comparative study was conducted of construction typology catalogues available in the literature relevant to the PAGER aims. Specific sources included ATC (1985), HAZUS-MH (FEMA 2003), EMS-98 (Grünthal 1998), and Coburn and Spence (2002). A new catalogue was compiled structured logically from very generic broad building types, applicable when no detailed information is available, to specific subcategories, able to identify a type and its seismic behavior univocally. Currently the PAGER-STR has in excess of 100 structures types, and is organized in two description tiers, where each subcategories is identified by a succinct description of the vertical structure providing earthquake resistance, the type of horizontal structure, and the height of the building (Jaiswal and Wald, in progress). Some other vulnerability affecting parameters, such as year of construction (hence code generation compliance) are applied as modifying factors to the reference fragility curve. The PAGER-STR is validated by mapping all typologies that were submitted by the experts, and by ensuring that buildings from different countries with similar structure types and comparable vulnerabilities fell into the same PAGER-STR categories and sub-categories (Jaiswal and Wald 2009). It is also confirmed that the description for each building subcategory is specific enough so that there would be little ambiguity in class assignment. The list, available at WHE-PAGER project website (http://pager.world-housing.net/data-available/construction-types), is not exhaustive. It will be revised as data from new countries with different construction technologies are contributed and further refinements of the descriptions are also possible. Given its open logic tree structure, subcategories can be introduced where particular seismic relevant construction details emerge that directly affect the fragility of a regional type. A further validation of the PAGER-STR catalogue was performed by using these classes as reference for the first trial development of the analytical data discussed in the following section.

**PGA and Macroseismic Intensity Ranges**

An issue that emerged from the experts' feedback is the perceived limited validity of the correlation between MMI intensity levels and PGA from a global viewpoint, as it was originally presented in the survey form. As several empirical correlation curves exist for the conversion of PGA to intensity this suggests that either regional difference for these correlations exist, or these correlations are based on limited data ranges within each region, compounded perhaps by variable intensities assignments. Worldwide there is little direct evidence for the correlation between the level of damage, or probability of collapse, and the PGA. Therefore, the PGA ranges were removed in favor of a correlation table with the most common macroseismic intensity scales such as MMI, European Macroseismic Scale (EMS) and Medvediav Sponheur Karnik (MSK) scale. Most published analyses suggest a one-to-one equivalence of these three scales in the range of interest, between degree VI and IX. Experts can indicate the intensity scale that is relevant to their collapse probability assessment.

**Definition of Collapse and Collapse Probability Ranges**

The definition of collapse in earthquake engineering is dependent on the nature of the structure, the scope of the study and the method of analysis used in the study. A more comprehensive review of definitions of collapse that are commonly used in literature and their implication for the computation of casualty probability curves is provided in Jaiswal et al. (in prep). In the initial phase of the WHE-PAGER project, the definition of collapse contained in HAZUS-MH was offered to the experts as a source of reference. HAZUS-MH provides a procedure to estimate the collapse proportion of the total square footage of a structure type using a complete damage state fragility curve and a factor $P_c$, where $P_c$ represents the fraction of building area that collapses among structures that have experienced the complete structural damage state (FEMA 2003).

In EMS'98, the collapse state is associated to specific damage grades and for each shaking intensity level, the probability of a particular vulnerability class experiencing collapse damage state is provided. The EMS'98 collapse definition is limited to European observations and is applicable specifically to the European building stock; however, the consistency among EMS'98, MSK, and MMI, make such definitions sufficiently general to be applicable for the scope of the Empirical Intensity-based model of the WHE-PAGER project at a global scale. In order to clarify what is intended by collapse in this context, specifically concerning causation of casualties, definitions were proposed for each structural typology, focusing on the elements whose failure leads to partial or total collapse of the building (and thus casualties). EMS '98 provides collapse probability ranges for a given vulnerability class for each level of intensity. Although EMS '98 groups structures of different typologies into the same vulnerability classes, it is possible to disaggregate such definitions and assign collapse rates to each structure type for a given intensity. This was done for each PAGER–STR tier 1 generic classes, predefining the expected proportion of collapses estimated using structure-dependent descriptions of damage within EMS intensity scale. These ranges can be used as guidance by experts completing the survey for the empirical intensity-based model to understand the expected behavior of structure types pertaining to the same PAGER-STR class. This is particularly relevant in countries where there is limited evidence of damage due to past earthquakes, yet the building stock has substantial vulnerability. The ranges are included in Table 1.

Table 1. Expected range of collapse probability (combination of EMS-98 Grade 4 and 5 damage states) as a function of EMS shaking intensities for various structure types.

| Structure Type | EMS Class | EMS Most Likely Vul. Class | Probability of Collapse at Intensity | | | |
|---|---|---|---|---|---|---|
| | | | VI | VII | VIII | IX |
| Rubble stone, field stone | M1 | A | 0 % | 0 to 5 % | 2.5 to 32 % | 21.25 to 70 % |
| Adobe (earth brick) | M2 | A | 0 % | 0 to 3.8 % | 1.9 to 25 % | 17 to 61 % |
| Simple stone (dressed) | M3 | B | 0 % | 0 to 0.3 % | 0.13 to 6.5 % | 3.5 to 34 % |
| Massive stone | M4 | C | 0 % | 0 % | 0 to 1.3 % | 0.6 to 12 % |
| Unreinforced brick | M5 | B | 0 % | 0 to 0.3 % | 0.13 to 6.1 % | 3.3 to 33 % |
| Unreinforced brick with RC floor | M6 | C | 0 % | 0 % | 0 to 1.3 % | 0.6 to 12 % |
| Reinforced or confined masonry (assuming 5 % in B, 50 % in C and 45 % in D) | M7 | D | 0 % | 0 % | 0 to 0.3 % | 0.1 to 4 % |
| Reinforced concrete frame without ERD | RC1 | C | 0 % | 0 to 0.3 % | 0.13 to 2.6 % | 1.6 to 13.4 % |
| Reinforced concrete frame with moderate ERD | RC2 | D | 0 % | 0 % | 0 to 0.25 % | 0.15 to 2.6 % |
| Reinforced concrete frame with high ERD | RC3 | E | 0 % | 0 % | 0 % | 0 to 0.25 % |
| Reinforced concrete shear walls without ERD | RC4 | C | 0 % | 0 % | 0 to 0.25 % | 0.13 to 5.1 % |
| Reinforced concrete shear walls with moderate ERD | RC5 | D | 0 % | 0 % | 0 % | 0 to 0.25 % |
| Reinforced concrete shear walls with high ERD | RC6 | E | 0 % | 0 % | 0 % | 0 % |
| Steel frame (all type) | S | E | 0 % | 0 % | 0 to 0.5 % | 0.25 to 4.5 % |
| Timber structures (all type as per EMS 98) | W | D | 0 % | 0 % | 0 to 0.25 % | 0.13 to 2.6 % |
| Timber structures (high ERD) | WA | - | 0 % | 0 % | 0 % | 0 % |
| Timber structures (medium ERD) | WB | - | 0 % | 0 % | 0 to 0.25 % | 0.13 to 2.6 % |
| Timber structures (low ERD) | WC | - | 0 % | 0 to 0.3 % | 0.13 to 5 % | 3 to 27 % |

The provision of such definitions allows a more explicit approach for including the effects of secondary parameters affecting vulnerability in specific regions. For instance an expert can provide a range which is altered with respect to the reference range by: a) shifting the expected range beyond the predefined limit, b) widening or narrowing the predefined limits, or c) doing both. Justification can be provided relating, for instance, to a) higher proportions of buildings with vertical/horizontal irregularities (buildings on slopes or buildings with irregular plans), b) different proportions of presence or absence of soft story, c) prevalent code era, d) known structural deficiencies (ductile detailing practice, significant changes in the code provisions during revisions, etc.) or resiliencies. These alterations can be further substantiated by experimental data, published literature, or statistics on performance during past earthquakes. This flexibility is critical for regions with building stocks significantly different from Europe's, to the extent that some generic building types might be altogether missing from the EMS'98 catalogue. This is certainly the case for timber structures. The EMS'98 has only one generic timber type without a detailed description of the reference typology. Substantial differences exist in seismic performance of wooden structures in several countries outside Europe (for instance Japanese traditional types, as opposed to light timber frames in the U.S.). For this reason the wooden EMS'98 typology has been subdivided in 3 subcategories characterized by different seismic performance. To define the ranges shown in Table 1 the fuzzy definition of Few, Many, and Most provided in EMS'98, were translated into probability ranges assuming that 25% of buildings in Damage Grade 4 would be in a state of partial collapse causing casualties, besides the full proportion of buildings in Damage Grade 5, and hence included in the overall estimate. The correlation between the fuzzy definition and the assumed probability in WHE-PAGER is shown in Table 2.

Table 2: Conversion of Fuzzy classes into probabilistic ranges.

| Description | Quantity (Grade 5) | Quantity (Grade 4) |
|---|---|---|
| Few | 0 to 15-20 % | 0 to 5 % |
| Many | 10-15 to 50-60 % | 2.5 to 15 % |
| Most | 50-60 to 100% | 12.5 to 25 % |

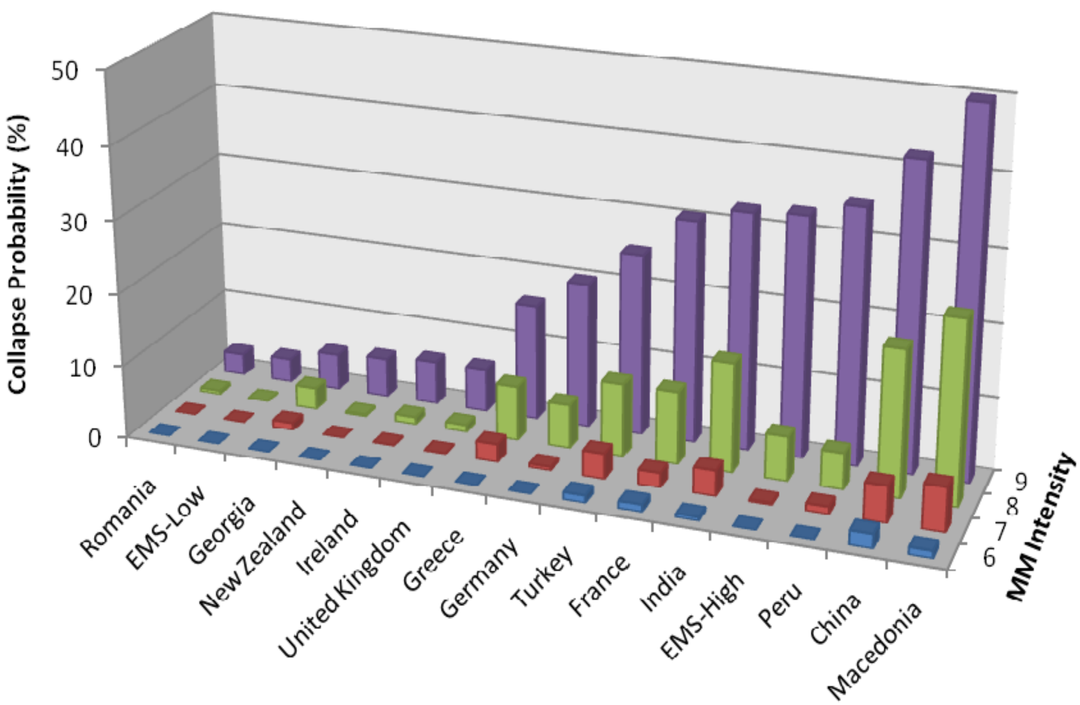


Figure 1. Expert judgment/empirical collapse fragility and expected range of EMS based collapse fragility for unreinforced fired-brick masonry in cement mortar.

To date, the WHE-PAGER Phase I survey has resulted in a development of comprehensive inventory and vulnerability database covering over thirty countries. As example, Figure 1 shows the comparison between the ranges set through the EMS'98 definitions and estimates from a number of regional experts for a particular structure type. While the majority of curves fit within the range there are some notable exceptions from countries outside Europe.

## Analytical Model Based on Push-Over Analysis

The approach chosen for the development of the analytical model in the PAGER project refers to the framework developed within HAZUS-MH. This choice raises some issues when dealing with losses at a global level. The first issue is that while the HAZUS methodology is well-documented, the approach for establishing empirically founded vulnerability parameters is not well established. The calculation of structural response and loss can require an iterative solution. This has made it challenging to produce vulnerability functions for structure types that are not included in the HAZUS-MH catalogue. Furthermore the development of capacity and fragility curves for a given typology can require a large number of parameter values, some of which it has been argued are strictly related to the behavior of engineered structures and may not be readily available or relevant for other non-U.S. structure types. This problem of a non-iterative solution has been discussed at length and an analytical solution proposed by Porter (2009). Other more generic issues relate to the shape of both the capacity curves and the response displacement spectrum used in determining the performance points and hence defining the fragility curve parameters. In this phase it was chosen to obviate to the first point by introducing capacity curves of different shapes to allow for a more realistic description of the post peak behavior for different structural types with brittle and softening characteristics. These proposed curves would more explicitly define the complete damage point in terms of both lateral strength capacity and corresponding displacement. The four idealized types used for reference are shown in Figure 2, together with a tri-linear capacity curve that approximates the linear-softening-perfectly-plastic curve assumed by HAZUS-MH.

In order to provide accurate, rapid estimates of damage and casualties, the PAGER model should also represent the performance of major non-U.S. or less-engineered construction types. Current work is aimed at identifying capacity curves and fragility functions for 25 of the most recurrent and critical of these types. The curves are divided by construction material: brick, stone and concrete block masonry, concrete frames, concrete frame and shear wall systems and confined masonry, timber, adobe and mud. Experts contributed the push-over capacity curves and fragility curves, either by analysis of existing experimental results or by use of numerical procedures.

In delivering this work, validation is required to extend the results obtained by numerical approaches to similar structure types in other regions, and to extend experimentally derived pushover curves to large sets of buildings. This validation ensures the reliability of the PAGER estimates of building damage and associated casualties, particularly in countries where construction is non- or marginally-engineered, and where the construction materials and technologies are not well-documented (low-engineered concrete structures, and various subtypes of brick and stone masonry). The strategy adopted for this phase of the project includes: a) literature survey of existing proposed representative push over curves for given building types from either experimental or analytical models developed by established researchers; b) compilation of tests details, representativeness of models, obtained results, etc and similarly for the analytical procedures (methodology, range of parameters considered, type of analysis, type of results); c) by use of selected specific procedure/s delivery of analytical pushover curves on the basis of data already available and region specific; d) comparison of derived curves with relevant present in literature; e) derivation of mean and standard deviation of the collapse capacities for generating the collapse fragility curves for given building types.

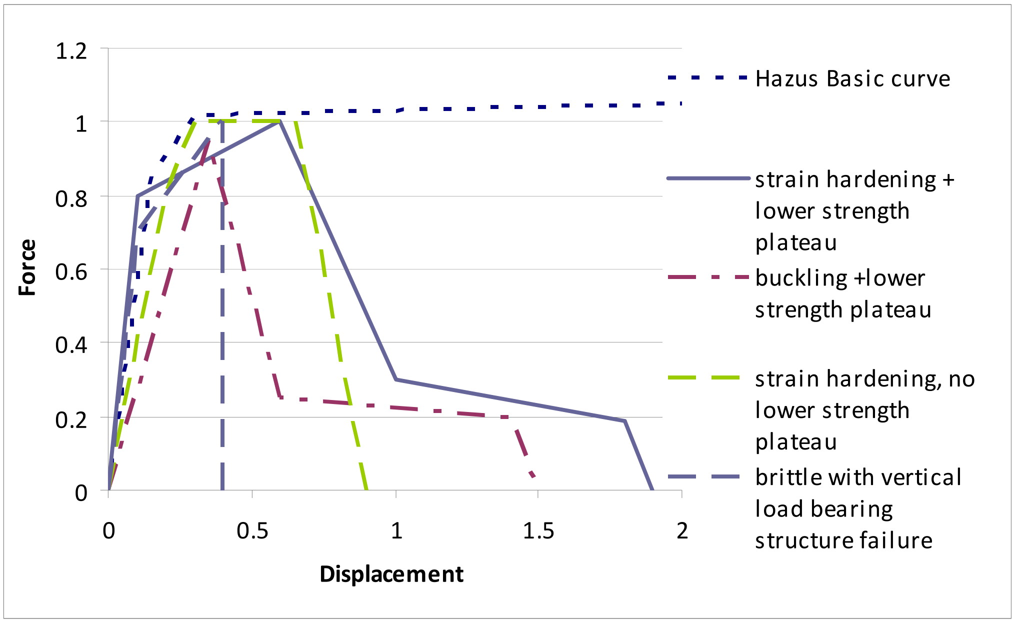


Figure 2. Idealised curves for structural types with different postpeak behaviour.

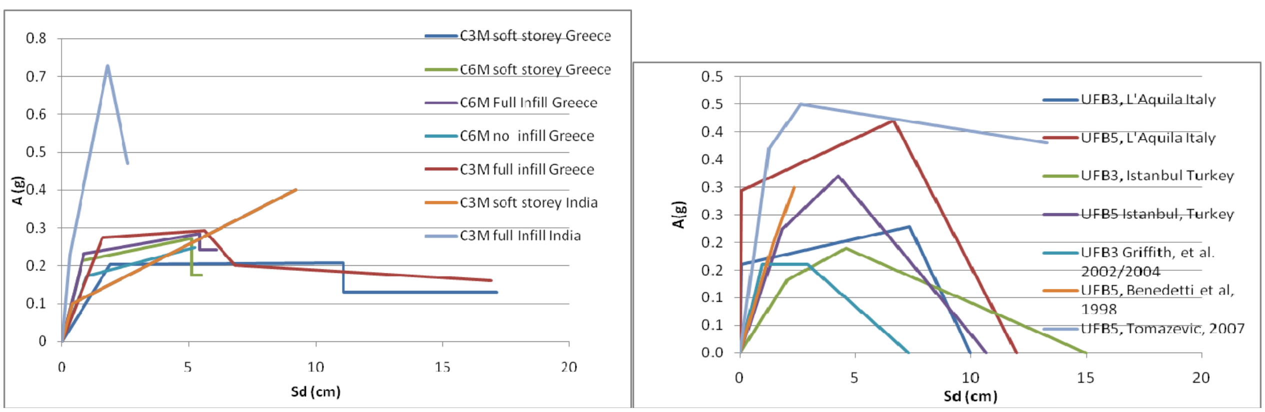


Figure 3. Push-over/capacity curves a) non ductile concrete frames and dual system for Greece and India, b) unreinforced fired-brick masonry in lime mortar without and with concrete slabs and comparison with experimental references.

While the current phase is not yet completed the results obtained for 14 of the 25 initially identified buildings types covered: various types of stone masonry, from rubble to massive, set in different types of binder and with flexible or stiff horizontal structures; various type of brick masonry; confined masonry; ductile and non ductile reinforced concrete frames with and without masonry infills; dual systems of concrete frames and shear walls. These building types were representative of wide geographic coverage: North India, Nepal, Italy, Greece and the south Mediterranean, Turkey, Chile, Mexico and Peru'. Data are limited for non-HAZUS timber structures types, for adobe structures, for steel moment frame and steel frames with masonry infills, and for precast reinforced concrete moment resisting frame with masonry infill walls. Table 3 provides a summary of the structural types and regions covered so far.

Table 3. Summary of analytical phase contributions

| Country/Region | Structure Type | Description/Coverage | Contributors |
|---|---|---|---|
| Turkey | Mid-rise reinforced concrete frame | Urban building stock of Turkey | P. Gulkan and A. Yakut (1 type) |
| Peru | Confined masonry | Typical two story dwelling in coastal cities of Peru | A. Munoz (1 type) |
| Mexico | Reinforced masonry. Confined masonry with hollow/solid blocks. Unreinforced fired brick masonry | Mexican building stock. | R. Meli (4 type) |
| Northern India | Unreinforced fired brick masonry with RC lintel band | North India, modern brick building construction following Indian Standard IS4326 | D. Rai ( 1Type) |
| Slovenia/ Mediterranean | Unreinforced fired bricks, dressed stone masonry, confined masonry | Experimental shaking table results | M. Tomazevic and M. Lutman (3 types) |
| Italy/Southern Europe | Unreinforced fired brick, dressed stone, massive stone, rubble stone masonry | Historic buildings in Turkey, Italy, Middle East, 2 to 4 storey high | D. D'Ayala & K. Collins (24 types) |
| Greece | Ductile and non-ductile reinforced concrete frame with or without infill Reinforced concrete-dual frame | Low, mid and high rise with low and high code construction. No infill, full infill, and soft story types | A. Kappos and G. Panagopoulos (total 5+18 types) |
| India | Unreinforced fired brick masonry | Various types of binder and floor structure 1 to 2 storey | D. Lang and Y. Singh (total 6 types) |
| India | Non-ductile reinforced concrete frame with or without infill. | Typical 4storey full infill and soft storey. Modern construction in North-India. | H. Kaushik (total 5 types) |
| South America | Confined masonry with concrete block/brick | Mexico, Peru and Chile. One, two and four story. | A Lang & GM Benzoni (24 types) |

**Validity of Curves Extracted from Experimental or Analytical Work Published by Others**

For non engineered structures and structures which are not directly compliant to a seismic code in a specific region, the availability of experimental tests aimed at characterizing the seismic resilience of that structure type, might be a valuable resource in producing a representative push-over curve to be used in a casualty loss analytical model. Specifically, shaking table tests were singled out as potentially very useful to this end. Tests results were collected for adobe structures (e.g., by McGowan 2009), stone and brickwork masonry structures, and confined masonry, concentrating on cases were 3D models of entire structures had been tested, rather than single structural components. Even in cases where results were presented directly in the form of push over curves, several issues arose, primarily related to the scale of the test, the amount and completeness of information published, the scope of the test, the geographic and typological validity of the results. One very important issue is whether the tests had been actually performed to complete or partial collapse, or only to some extent beyond the post peak capacity point to validate given ductility assumptions. In the latter case it is not possible to define ultimate conditions and associated casualty rates. A second issue relates to the applicability of a series of tests to a particular section of the building stock and how can this be treated from a stochastic point of view. In other words whether the tests results should be considered as representative of an average or a limit behavior, whether the tests campaign had sufficient repetition that scatter and standard deviations could be computed, and whether such figures are applicable to the fragility curve representative of the whole building stock for the region of interest.

**Definition of Collapse Point**

For the analytical procedure the identification of collapse condition of a given typology and hence the coordinate of the point in the acceleration/displacement space which identify its performance is the single data point needed to define the collapse fragility curve. Even though numerical non linear analyses are increasingly robust and allow the identification of the post peak behavior and softening branches of a backbone curve, they often requires input parameters that are not known and ultimately the failure condition might be numerically governed, rather than be representative of a physical state. The use of a limit state/collapse numerical tool, avoids some of the numerical problems arising from using finite elements, but it can have the pitfall of overlooking some collapse conditions, or underestimating capacity. The examples in Figure 3a and 3b, illustrate the range of solutions obtained with different approaches for concrete and masonry structures. For masonry structures it was assumed that there would be no residual strength capacity at collapse, associated with out-of-plane failures. Results appear reasonably constrained by experimental tests available in literature.

## Conclusions

We analyzed the empirical and analytical collapse fragility data compiled under the auspices of the WHE-PAGER project and provided some preliminary findings. The project was carried out in two phases involving international engineering experts from more than thirty countries. Several aspects related to Phase I exercise were detailed including addressing some of the concerns associated with definition of structural type, input shaking hazard in terms of shaking intensity, defining collapse and also providing improved guideline document to the expert for conducting future surveys. The comparative analysis for selected building type indicated that except few countries, most contributions were within the acceptable range of the EMS-based collapse vulnerability limits. The pushover curves obtained within analytical framework showed large spread in terms of yield and ultimate points; however some of the spread is expected given the potentially large variations in building design and construction practices within the same structure type from country to country and even within a country (rural vs. urban; pre or post code or level of building code enforcement). Efforts are underway to broaden this newly formed international initiative in other seismic-prone countries of the world for better understanding of the collapse vulnerability of buildings worldwide and most importantly improving the knowledge and data-sharing mechanism among the research community.

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