The European building stock inventory: creating and validating a uniform database for earthquake risk modelling

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SUMMARY
This paper discusses the problem of validation of a proposed uniform European building database. It proposes a process for validation using a set of so-called "test-bed" sites in Europe in which detailed local building-by-building surveys have been made in the recent past in a variety of projects. It explains how the data from these studies has been harmonised; proposes an appropriate building classification system for validation; and proposes a set of validation metrics which can be used to assess the quality of the data in the uniform database against the data from the test-bed sites, and to estimate the uncertainties which can be assigned to the database. An example of validation against an existing approximate Europe-wide inventory is given.

Keywords: Earthquake risk, building stock inventory, modelling, validation

1. INTRODUCTION

The creation of a viable earthquake risk model depends crucially on the quality of the exposure data contained in it. A risk model for an entire country or region, such as the Global Earthquake Model (GEM) must be accompanied by the best possible inventory of the assets at risk over the whole region. The building stock is the most important part of this inventory as it contributes a high proportion of the financial and economic risk, and is also responsible for much of the human casualty and social risk.

Europe is a region with several very large concentrations of earthquake risk, and a history of highly damaging and lethal earthquakes. Its building stock is very diverse, and rapidly changing in response to economic development and changing regulations, but some of its buildings remain highly vulnerable to earthquakes. Although several European countries maintain good data on the building stock and its earthquake vulnerability characteristics, there is no uniformity across Europe about how such data is recorded, and attempts to develop a single European building stock inventory for earthquake risk assessment have to date been at a very rudimentary level. Within the NERA[1] project it is aimed to make a first attempt to harmonise the data available in each of the European countries to create the first single uniform database of the European building stock; the methods which will be used to develop this European building stock database are discussed in the accompanying 15WCEE paper (Crowley et al 2012).

A key component of the development of this database will be to develop techniques to validate the resulting data against a series of datasets collected through building-by-building field surveys previously conducted in different parts of Europe. These ground surveys have mostly been conducted for the purpose of developing and testing loss estimation tools for different regions. Surveys have been carried out in Greece (Thessaloniki, Pylos), Italy (Torre del Greco, Potenza Province), Portugal (Lisbon), Turkey (Zeytinburnu district of Istanbul), Romania (Bucharest), France (Grenoble), Austria (Vienna) and elsewhere. Their common characteristic is that they aim to collect, on a building-by-building basis, information on the principal characteristics of the building stock governing earthquake vulnerability and loss, including structural typology, age, height and occupancy class. However, widely different classifications are used, according to the requirements of the different loss modelling approaches they were designed to support. Thus significant work is needed to harmonise these datasets if they are to be used for the validation task proposed.

This paper explains how the data from these studies has been assembled and harmonised; proposes an appropriate building classification for validation; and proposes a set of validation metrics which can be used to assess the quality of the data in the uniform database against the data from the test-bed sites, and to estimate likely uncertainties which can be assigned to the database. An example of the process, using the ELER/PAGER[2] European building stock database is presented.

2. IDENTIFYING AND ASSEMBLING TEST-BED AREA DATA

Over the past two decades, numerous local building stock studies have been carried out in the European area in order to generate exposure and vulnerability data for loss estimation studies for earthquakes, volcanic eruptions and other hazards. To create a dataset suitable for use as a set of test-bed areas (TBA) in the NERA Project a selection was made from among these datasets of those which were recent (or still representative), unaffected by earthquake damage (and subsequent reconstruction), contained a suitable range of separate types of settlement, and were either complete surveys (ie including all buildings within the surveyed area), or a very significant sample. It was essential that each survey included adequate data for each sampled building including the construction typology, height, occupancy, and where possible age. The willingness of those institutions which had gathered the data to cooperate in making the data available was also crucial.

Table 1 summarises the characteristics of the survey data for the 9 test-bed areas selected and available to date, focusing on the residential buildings in the TBA. Most of these studies have been carried out in the context of previous EU-funded risk projects. Those for Bucharest and Thessaloniki derive from the Risk-UE project, 2001-2004 (Lungu et al 2005, Penelis et al 1989, Kappos et al, 2008), although later updated; those for Istanbul and Lisbon were used in the LessLoss Project 2005-2007, (Spence, 2007, Aydinoglu and Polat, 2004, Oliveira et al, 1994); the work on Potenza Province was based on the methodsof the EnSerVes Project (Dolce et al, 2003, 2006, Masi et al forthcoming); that for Pylos was part of the multi-hazard SEAHELLARC project (Pomonis et al, forthcoming) , while that for Torre del Greco was carried out before and within the EXPLORIS volcano risk project (2004-2006) (Barratta and Zuccaro, 1989, Zuccaro et al, 2008). The studies for Grenoble and Vienna are the most recent, that for Grenoble being part of a study for the Rhone-Alps Region of France (Guéguen et al, 2007) while the study for Vienna is within the current SYNER-G project (www.vce.at//SYNER-G).

Table 1: Characteristics of Test Bed Areas. Notes: S = Sample, B = Building-By-Building

Country	TBA name	Date	Type of study	Number of residenti al	Classification	Height information	Occupan cy informat ion

[1] NERA - Network of European Research Infrastructures for Earthquake Risk Assessment.
[2] ELER – Earthquake Loss Estimation Routine (Demircioglu,et al., 2010); PAGER - Prompt Assessment of Global Earthquake's Response (Jaiswal and Wald, 2008).

				buildings			
Romania	Bucharest	2001	B	615	HAZUS	3 height ranges: L, M, H	Yes
France	Grenoble	2011	B	560	EMS/BDT	Number of storeys	Residential
Portugal	Lisbon (Anjos and Campolide)	1983, 2002	B	2584	Study specific	Number of storeys	Yes
Italy	Potenza (Marsicovetere, Villa D'Agri and Sarconi)	2001, 2005	B	1844	AeDES	Number of storeys	Yes
Greece	Pylos			39	Study specific	Number of storeys	Yes
Greece	Thessaloniki	2003	S	1236	Risk-UE (modified)	3 height ranges: L, M, H	No, Mainly residential
Italy	Torre del Greco	2009	B	914	AeDES and MEDEA	Number of storeys	Yes
Austria	Vienna	2011	B	182	Study specific	Number of storeys	Yes
Turkey	Zeytinburnu	2010	B	5220	Study specific	3 height ranges: L, M, H	Yes

Table 1 shows that a range of different methods of describing and categorising the building stock were used, even though data on the same basic characteristics were collected. To harmonise the data so that it could be used in a systematic manner for validation therefore required development of a uniform classification onto which each dataset could be mapped, discussed below. For use in validation a single rectangular 30” x 30” gridcell was selected from each study area, within the grid to be adopted for the NERA European building stock inventory (Crowley et al, 2012).

3. HARMONISING THE BUILDING CLASSIFICATION

3.1 Existing building classifications

The different countries for which TBA data were collected use different building classifications to describe structural typologies (Table 1). It is considered of particular importance to use a common classification system with a level of detail which allows the key vulnerability characteristics of the buildings to be maintained. After consideration of a number of options, the EMS-98 building classification (Grünthal, 1998), presented in Table 3 has been chosen as the basis for a common classification to represent the structural typologies for each TBA for the following reasons:

- It classifies European building typologies according to their vulnerability.
- It has a sufficient number of classes of buildings without demanding too high a level of detail.
- In some cases, collected TBA building data already uses the EMS-98 building classification (Grenoble) and has an assigned EMS-98 vulnerability class (Grenoble, Torre del Greco, Potenza Province).
- Many European studies are based on EMS-98 structural types and vulnerability definitions.

3.2 Mapping to EMS-98

In order to represent the building typology distributions for each TBA in EMS-98, a mapping is needed between the country-specific and the EMS-98 typologies. The key characteristics of this mapping and the uncertainties are summarised for each dataset in Table 2.

Table 2: Key Characteristics of Mapping from TBA data to EMS-98
***A = EMS-98 Given in Dataset; B = Conversion from Survey Parameters or C = Conversion from HAZUS/PAGER**

TBA	TBA original classification	No. classes	Mapping to EMS-98 classes*	Main classifiers	Secondary classifiers	No. EMS classes used	Mapping uncertainties
Buch.	HAZUS	52	C	Material and number of stories	n/a	4	Difficult to assess level of ERD. A number of HAZUS classes have no EMS-98 equivalent
Gren.	EMS/BDT	19	A	Structural system	Age and location	9	Typology defined including level of ERD as a function of age. Most probable EMS class assumed
Lisb.	Study specific	9	B	Structural system	Age	5	Lack of detailed information on structural system and level of ERD
Pot.	AeDES	24	B	Structural system and code level	Masonry: main horizontal and vertical structure	5	Vulnerability mapping of masonry structures performed using expert judgement and damage data; mapping of RC structures based on level of ERD and framing system used.
Pylos	Study specific	4	B	Constructi on material	Age	2	Post 1985 RC structures assumed to have a high level of ERD
Thess.	Risk-UE (modified)	28	B	Structural system, height and level of code	n/a	4	RC dual system has no EMS equivalent, therefore assumed to be RC shear wall
Torre	AeDes and MEDEA	39	B	Main vertical structures and main horizontal structures	Age	7	Uses region specific detailed typology information not commensurate with EMS-98 classes. Mapping of masonry structures performed using expert judgement and age.
Vienna	Study specific	16	B	Material, age and number of stories	Age	4	Lack of detailed information on structural system
Zeyt.	Study specific	18	B	Structural system	Age	9	Pre-2000 RC structures assumed to have a low level of ERD

Each dataset has an initial classification scheme for the buildings (column 1) which is mapped to EMS-98 classes. The mapping makes use of primary dataset characteristics such as information on structural typology and where necessary, also uses secondary characteristics, such as year of construction, to enable more specific assignment of EMS-98 classes. Additionally, in some situations, expert opinion of the dataset provider was sought for further clarification on the mapping.

In this study, an effort was made to assign levels of earthquake resistant deign (ERD) that are consistent between countries. For example, because of the earlier introduction of earthquake codes in Thessaloniki, Greece, a building constructed there in 1970 would be expected to have a higher level of ERD than a similar building constructed in Naples, Italy at the same time. In the case where there are multiple options for possible EMS-98, the preference is to be conservative in terms of the vulnerability of the building, e.g. selecting RC1.1 rather than RC1.2.

3.3 Mapping to GEM building inventory classification

In addition to representing the TBA building classification in terms of EMS-98, a proposed mapping between the EMS-98 classification and the GEM taxonomy (Brzev et al 2012) has also been developed (Table 3), which will be important to enable the test-bed area data to be used for validation of European or global exposure datasets created using the GEM taxonomy.

Table 3: Proposed GEM Inventory Classifications and Original EMS-98 Building Classifications.

EMS-98		GEM Material Main	GEM Material Secondary	GEM Lateral load resisting system Main	GEM Lateral load resisting system Secondary	GEM Roof	GEM Floor
M1	Rubble stone, fieldstone	MO MUR	STRUB	LN LWAL	ND		FW99
M2	Adobe	MO MUR EU W	ADO CLBRS CLBRH CLBLH WWD ETR ETC ETO	LWAL LFINF LPB	ND DU	RM99 RE99 RW99 RC99	
M3	Simple Stone	MO MUR	STDRE	LWAL		RM99 RE99 RW99	
M4	Massive Stone					RM99 RW99	
M5	Unreinforced, with manufactured stone units	MUR MO	CLBRS CLBRH CLBLH CBS CBH	LWAL		RM99 RW99	FW99
M6	Unreinforced, with RC floors	MUR	CLBRS CLBRH CLBLH	LWAL LFLS		RM99 RW99	FC1
M7	Reinforced or confined	MR	STDRE CLBRS CLBRH CLBLH CBS CBH	LWAL	DU	RM99 RW99 RC99	
RC1.1	Frame without ERD	CR	CT99	LFM LFINF	ND	-	FC99
RC1.2	Frame with moderate level of ERD	CR	CT99	LFM LFINF	DU	-	FC99
RC1.3	Frame with high level of ERD	CR	CT99	LFM LFINF	DU	-	FC99
RC2.1	Walls without ERD	CR	CT99	LWAL	ND	-	FC99
RC2.2	Walls with moderate level of ERD	CR	CT99	LWAL	DU	-	FC99
RC2.3	Walls with high level of ERD	CR	CT99	LWAL	DU	-	FC99

4. DEVELOPING METRICS FOR TESTING

In order to validate the overall European building inventory, it is necessary to develop metrics for comparing the proposed building inventory in each country with the test bed area data. There are two ways in which we propose to compare the two datasets. The first method is to use direct comparison metrics such as absolute difference and chi-square tests. The second is to calculate damage estimates for a scenario event based on both the TBA and the inventory building distributions and compare the results.

4.1 TBA dataset- uncertainties

For the TBA building-by building data, as with all field-surveys, there are a number of uncertainties associated with the data collection including incorrect assignment of classes. However, as these surveys are conducted by experts, this may be considered to be a small error source.

A second source of uncertainty is associated with selection bias, i.e., the reasons why the data was collected in the TBA. For example, data may have been collected in the TBA as it is an area with particularly vulnerable buildings. This source of uncertainty also arises when the TBA data consists of sample (as for Thessaloniki) rather than building-by-building information. The third uncertainty source is that associated with interpretation of regional classifications and the mapping to EMS-98 classes as shown in Table 2.

4.2 Dataset comparisons

The first proposed comparison metric is Pearson's chi-squared test, which is a goodness-of-fit test. The procedure is:

1. Calculate the test-statistic: $\chi 2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$
2. Determine the number of degrees of freedom
3. Calculate a p-value comparing the value of the test-statistic to the chi-squared distribution to determine whether or not the null hypothesis should be rejected.

In this study, the null hypothesis is that the European building inventory distribution is a sample from the true description of buildings in the population classified as the TBA distribution. Chi-squared is used to establish whether or not an observed frequency distribution differs from the theoretical distribution. If the calculated chi-squared statistic exceeds the tabulated value for 1 degree of freedom with p-value ≤ 0.05: $\chi 2 = 3.84$, therefore observed values are significantly different from theoretical values at the confidence level indicated by the p-value.

The building distributions for each dataset are represented in terms of the relative proportions of masonry and RC typologies and this test can be used to assess the probability that the observed data (European building inventory data) is taken from the same distribution as the validation data (TBA).

The chi-squared test metric gives one clear estimate of whether or not the data is consistent with the TBA data. This test can be used in conjunction with two other simple metrics to provide more information on the difference between the percentage of buildings in each dataset in each class. The first of these is the modal class, i.e. a comparison of the most common class of building for each dataset. The second is the absolute difference between the percentages of individual building typologies in the different datasets.

4.3 Damage estimation comparisons

A validation metric which arises from the practical applications of the development of the European building inventory is an assessment of the impact of different building classification distributions on damage estimates made for a region. Therefore, in addition to using the direct comparison metrics described in the previous section, the two sets of building distributions can also be compared by using each building distribution to calculate the expected proportion of damaged buildings resulting from a scenario event.

For each dataset, the macroseismic method of Lagomarsino and Giovinazzi (2006) will be used to obtain an estimate of the number of buildings in each class which are estimated to be damaged at EMS-98 levels 3 and above. The procedure is as follows:

- Obtain vulnerability index value, *V* for each EMS-98 structural typology (from Lagomarsino and Giovinazzi (2006))
- Set ductility index, *Q* = 2.3 for all classes.
- For intensity levels: I = 8 and 9, for each EMS-98 class (and therefore *V*), calculate mean damage: using $\mu_D = 2.5\left[1 + \tanh\left(\frac{I+6.25V-13.1}{Q}\right)\right]$
- For damage grades: k = 1 to 5, the probability of a certain class of building being in a particular damage grade is given by the binomial distribution: $p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1-\frac{\mu_D}{5}\right)^{5-k}$, ($\mu_D$ is the mean damage ratio calculated in the previous step.)

Therefore, for a given intensity level, the probability of each EMS-98 building class being damaged at each level can be calculated. Next, the distribution of buildings across the EMS-98 classes for each dataset can be used with the damage probability matrix to provide an estimate of the percentage of damaged buildings in each class. The percentage of buildings damaged at levels 3 or above according to the TBA distribution can then be compared to that predicted using the European building inventory.

The two sets of metrics presented, provide complementary sets of information on the adequacy of the proposed distribution. The direct comparison metrics show the discrepancy between the datasets in the way in which the buildings are classified in a particular country. The damage estimation indicates how the difference in the vulnerability associated with the classification affects the results of analyses conducted using the data.

4.4 Example comparison with PAGER distributions

In order to provide an example application of the proposed validation metrics, the metrics are used to compare the TBA distributions of buildings in each of the TBA countries with the PAGER distributions of urban residential buildings for these countries. The PAGER distributions (Jaiswal et al, 2008) were developed for estimation of casualties, and therefore show the distribution of the population by buildings class, using a classification derived from HAZUS. Before a comparison can be made, it is necessary to map the PAGER classification to EMS-98. Using data on typical numbers of dwelling units per building given by Jaiswal et al 2008, the distributions have also been converted to an approximate distribution by numbers of buildings. In the analysis presented only residential buildings have been considered, and non-residential buildings have been removed from the TBA datasets. This process of course introduces significant uncertainties into the comparison..

Figures 1 and 2 show histograms for the distribution of buildings from the TBA dataset and the equivalent PAGER country dataset. It is clear from Figs 1 and 2 that there are a number of discrepancies between the PAGER distribution of buildings and the TBA building distribution in each country. It is also evident that TBA distributions for different TBAs within the same country (e.g. Greece: Pylos and Thessaloniki) are markedly different. Therefore, in order to provide clearer comparisons, the TBA and PAGER distributions are now compared in terms of simple metrics. Table 4 shows the modal building class in each country for both TBA and PAGER datasets. Interestingly no TBA and corresponding PAGER distribution have the same modal class, although in most cases there is consistency between the general typology (RC or masonry).

Table 4: Comparison of the Modal Classes for each Country Given by PAGER and TBA

Country – TBA dataset	PAGER modal class	TBA modal class	Country – TBA dataset	PAGER modal class	TBA modal class
Austria - Vienna	M5	M7	**Italy - Potenza**	M5	M1
France - Grenoble	M5	M3	**Italy - Torre del Greco**	M5	M6
Greece - Pylos	RC1.1	M3	**Portugal - Lisbon**	M7	M5
Greece - Thessaloniki	RC1.1	RC2.2	**Romania - Bucharest**	M1	M5

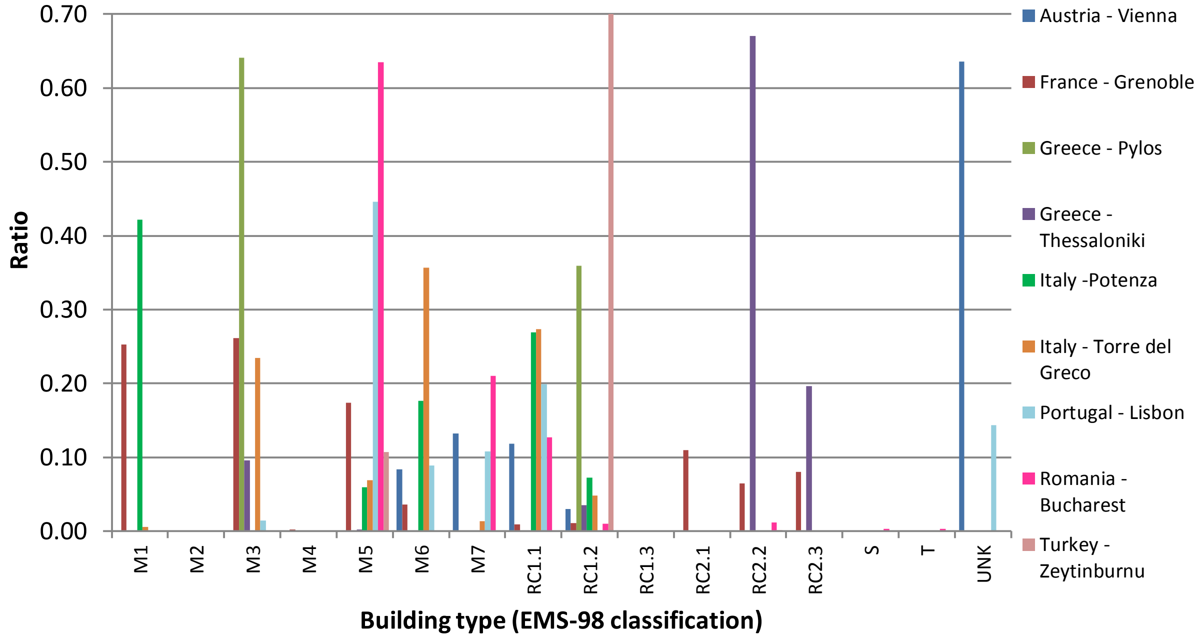

Figure 1: TBA Distributions in EMS-98 Classification of building types.

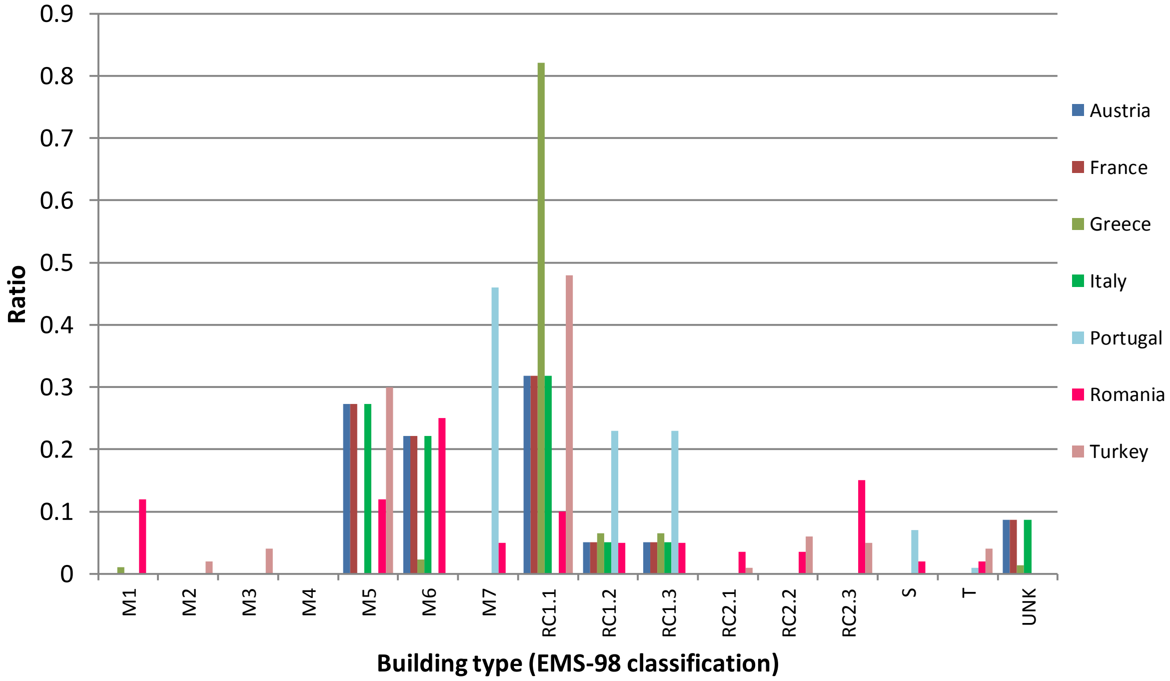

Figure 2: PAGER Urban Residential Distribution in EMS-98 Classification

These two comparison methods suggest that the PAGER-based distribution is not generally representative of the information collected in the TBAs even at the level of relative proportions of masonry and reinforced concrete buildings.

The final comparison to be made is between the results of damage estimates based on TBA and PAGER building distributions. The results of this exercise are presented in Table 6. In this table, for each country, the numbers of buildings predicted to be damaged at grades 3 and above are calculated for EMS intensity 8 and 9 scenarios. This table demonstrates the impact of the building distribution These two comparison methods suggest that the PAGER-based distribution is not generally representative of the information collected in the TBAs even at the level of relative proportions of masonry and reinforced concrete buildings.

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The comparisons presented above use the PAGER distribution since it is the only currently available data, merely for the purpose of demonstrating the proposed metrics. However, it is important to note that the PAGER data was not, in fact, intended for such use.

Table 5 shows the results of the chi-squared test on the proportions of Masonry and RC buildings in the two datasets, assuming a sample of 100 buildings. The hypothesis being tested is that the TBA “observed” distribution is drawn from the PAGER-based “expected” distribution. Using a chi-squared value of 3.84, which corresponds to a 95% confidence level that the sample is not drawn from the expected distribution, the null hypothesis is rejected for all TBAs with the exception of that for Bucharest and Thessaloniki . Further examination shows that Pylos performs worst in terms of comparison between PAGER and TBA, however, it is important to note that the Pylos dataset is relatively small and may therefore not be representative of the entire Pylos building stock.

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Table 5: Results of a Chi-Squared Test on the Proportions of Masonry and RC Buildings to Compare the TBA "Observed" Distribution and the PAGER "Expected" Distribution

Country – Test Bed Area	PAGER		TBA		p-value	chi-squared
	Masonry %	RC %	Masonry %	RC %		
Austria - Vienna	81	19	59.3	40.7	<.005	31
France - Grenoble	81	19	72.6	27.4	0.04	4.6
Greece - Pylos	6	94	64.1	35.9	<.005	600
Greece - Thessaloniki	6	94	9.8	90.2	0.1	*2.6*
Italy –Potenza Province	81	19	65.8	34.2	<.005	15
Italy - Torre del Greco	81	19	67.8	32.2	<.005	11
Portugal - Lisbon	62	38	76.7	23.3	<.005	9.2
Romania - Bucharest	82	18	84.5	15.5	0.5	0.42

Table 6: Comparison of TBA and PAGER-based Predictions of the Proportion of Buildings Damaged at D3 or above for Intensity Levels 8 and 9

Country – TBA dataset	I = 8		I = 9	
	PAGER	TBA	PAGER	TBA
Austria- Vienna	0.27	0.08	0.63	0.29
France – Grenoble	0.27	0.31	0.63	0.59
Greece – Pylos	0.16	0.21	0..47	0.50
Greece - Thessaloniki	0.16	0.04	0.47	0.11
Italy – Potenza Province	0.27	0.35	0.63	0.63
Italy - Torre del Greco	0.27	0.18	0.63	0.50
Portugal - Lisbon	0.01	0.21	0.10	0.54
Romania - Bucharest	0.37	0.22	0.61	0.53

5. CONCLUSIONS

A process for testing a unified European building stock inventory has been described. Using building by building inventory data collected in earlier research projects, a dataset of 9 test-bed areas (TBA) has been assembled, each of approximately 1 km^2 extent. In order to harmonise this data for use in testing, a simplified building classification system has been developed, which has a limited number of classes, but fits with the range of TBA data collected, and can be mapped onto a range of alternative classifications, including the GEM Taxonomy.

A set of metrics have been proposed to test the overall error, and degree of fit as well as the probable effect on loss estimates of using any proposed estimated building inventory in comparison with the observed TBA data. These metrics were used to examine the differences between country building inventories derived using PAGER and the local TBA data. In most cases the fit of the PAGER-based estimate to the TBA data was poor, and it was found that use of PAGER-based inventories for European loss estimation would result in significant errors.

The results demonstrate the need for further studies to identify the regional and local variations in building stock as a basis for loss estimation, rather than relying on estimates made on a national basis, which may be seriously misleading.

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