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ORIGINAL RESEARCH PAPER

Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe

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Abstract A review of damage scales for buildings is carried out with a view to assessing their suitability for use in earthquake loss modelling in Europe. A new ranking system is proposed to 'score' each scale. The ranking considers damage descriptions, building response factors, repair, cost of damage and ease of use, which are identified as the key characteristics required of damage scales used in loss modelling. The 'hybrid' RISK-UE damage scale (which uses a HAZUS-based approach) is seen to score high in the ranking, whilst 'hybrid' scales based on the EMS-98 damage scales perform poorly. However, it is found that none of the considered damage scales adequately satisfy all the criteria necessary for their use in European seismic loss estimation, especially with respect to inclusion of likely repair methods and damage costs. The development of cross-country loss models often involves using vulnerability curves or post-earthquake survey data that are commonly expressed in terms of different damage scales. Equivalence tables, showing the relationship between the damage states of each considered scale, are therefore also presented for the predominant structural systems in Europe.

Keywords Damage assessments · Damage grades · Damage scales · Earthquake loss · Europe · Loss estimation · Loss modelling · Seismic loss

1 Introduction

This work is part of a larger study developing a European-wide loss estimation framework. Seismic loss estimation is an important tool for governments and individuals (through insurance) to mitigate the consequences of earthquakes. Existing loss estimation methodologies vary (FEMA 1999; Bertogg et al. 2002) with different assumptions made for the characterization and prediction of seismic hazard, the methodology used to evaluate building response to the hazard (vulnerability), and the calculation of economic losses. One of the fundamental

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steps in the seismic vulnerability evaluation of buildings is the evaluation of building response in terms of potential damage. Differences in choice of damage scales impair direct comparison of losses and loss models between countries. The development of a Europe-wide seismic loss framework, such as HAZUS for the US (FEMA 1999), requires a single building classification system and the identification of the best damage scale for each building class. Damage scales used in loss estimation currently consist of sets of discrete damage states that are meant to represent different levels of building performance. However, many damage scales exist, each consisting of different numbers of damage states defined by different damage criteria and implied performance levels. The development of unified criteria for damage states to associate with performance objectives is becoming increasingly important in view of new performance-based design paradigms (Ghobarah 2001). Furthermore, equivalences need to be drawn between damage scales in order to compare loss models from different countries and to validate new and existing vulnerability methods with observed post-earthquake survey data.

Within this paper, a comparison and critical evaluation of existing damage scales for buildings is carried out, with a view to their use in a Europe-wide seismic loss evaluation. Many of the scales included were not specifically designed for seismic loss estimation but are included to illustrate particular features that are advantageous in loss estimation. Background information on these scales is provided in the paper together with an explanation for their inclusion in this study. In order to compare the different scales a new scoring system is proposed which considers the key features of a damage scale necessary for a reliable building vulnerability evaluation and repair and reconstruction cost evaluation. Comparisons are made as to the adequacy of the scales for the damage evaluation of the predominant European building classes. Finally, tables of equivalences between existing damage scales for each building class are proposed.

2 Choice of building classes

In this paper, vulnerability is defined as the susceptibility of a population of buildings to damage due to seismic ground motion. The evaluation of building vulnerability is a fundamental part of any loss estimation methodology. In vulnerability studies it is important to distinguish between different building types, as these will tend to respond differently under similar ground motions. Hence, before the vulnerability evaluation of an urban area can be embarked upon, the buildings must be grouped into classes with similar dynamic properties. The factors influencing the dynamic response of a building to ground motion are well documented, for example, in FEMA 450 and Eurocode 8 (BSSC 2003; CEN 2004), and include the structure's geometrical and material characteristics. A building classification system that accounts for these influencing factors allows a high-degree of differentiation in vulnerability studies and results in an improved estimate of the financial losses. Support for using building classes that consider such influencing factors has also been expressed elsewhere (Carvalho et al. 2002). Despite the stated advantages of a detailed building classification system, the level of resolution in building class definition for the comparative purposes of this paper are limited by the lack of distinction between building types (beyond building material) in the assessed damage scales.

Additionally, as this study concerns European loss models, the building classification system should represent the predominant construction types present in European countries, (especially those associated with medium to high seismicity). From an evaluation of several studies that have considered building inventory in various European countries it is seen

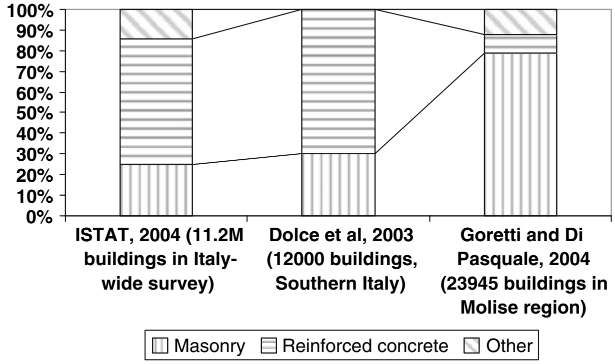

Fig. 1 Proportions of building type from various Italian sources

that European building inventory is predominately composed of reinforced concrete and masonry buildings. These studies include: Italy (ISTAT 2004; Dolce et al. 2003; Goretti and Di Pasquale 2004, see illustration in Fig. 1), Greece (Pitilakis et al. 2004), Portugal (Carvalho et al. 2002), Turkey (Bommer et al. 2002) and Europe (Lungu et al. 2001). Other classes such as timber and steel also exist, but make up a relatively small proportion of the existing inventory. Therefore, the highest resolution of relevant building type sub-categories that can be identified for the assessed scales are unreinforced masonry and reinforced concrete frames with and without masonry infill. These building class categories will be used for both the comparison of different existing damage scales and the proposal of scale equivalences.

3 Choice of damage scales

Table 11 in Appendix A briefly presents each damage scale selected and the rationale for selection. It is recognized that the review is not exhaustive, however, the scales have been chosen for their relevance to the predominant building classes in Europe (see above) and to current practice in European seismic loss estimation. As Intensity (damage) scales, i.e. EMS-98, and the US HAZUS method/damage scale have been used widely in loss estimation studies in Europe in recent times, these scales are selected in both their original form and in a 'hybrid' form. The hybrid scales are defined as scales that are adapted versions of original scales. The hybrid forms, often found in seismic loss estimation studies, have been included to highlight that adapting scales to include location-specific physical parameters or cost data can lead to an improved scale for use in loss estimation. Damage scales are also selected from a wide range of published papers in the fields of seismology, structural vulnerability, and earthquake engineering. As each scale has been developed for particular circumstances, for example damage evaluation in the field, for structural analysis, or for estimating financial losses, they may not contain some of the characteristics identified in the scoring system (see Sect. 4). However, they are included as either elements of these scales have been used in past loss estimation (notably the use of the EMS-98 damage scale) or they illustrate a particular feature that is desirable in a damage scale used for loss estimation.

4 Damage scale scoring system

Seismic damage scales are used to assign performance limit states to buildings and are used within vulnerability studies. A suitable level of differentiation between different damage states is required so that the quantity and type of damage can be adequately represented as the building structure degrades. Additionally, such differentiation allows likely repair methods for each grade to be determined. By assigning a loss or repair cost to a damage state, (typically in the form of a percentage of building replacement value or cost ratio), a detailed picture of losses can be developed for a population of buildings. This is of particular relevance to the insurance industry.

Important characteristics of damage scales used for evaluating natural hazards, such as earthquakes, have been highlighted in the past, notably by Blong (2003a). However, this paper proposes a scoring system based on the important characteristics of damage scales for use in seismic loss estimation. The authors' propose that a good damage scale for loss modelling will be one that provides damage and failure mechanism descriptions for each damage state, so that the user can readily understand the effects or identify them in a post-earthquake scenario. Additionally each damage state should be associated with thresholds of measurable dynamic response for the building type considered in order to allow the interpretation of physical damage from numerical or finite element analyses of structures and ensure that consistent results are obtained. The parameter used to define the dynamic response should be capable of representing both global and local failure mechanisms, and the parameter values defining the damage state thresholds should be derived from large quantities of high quality experimental or observed data. Each damage state should also be associated with a typical type and amount of repair for the failure mechanism and building type considered. This will allow the user to eventually obtain a reliable cost estimate based on repair prices to associate with each damage state. Alternatively (or additionally), a cost ratio should be associated with the damage state. However, the cost ratio should be determined in a robust manner and data sources be clearly stated. The scale should also provide consistent and reliable results for users.

A scoring system was developed to rank the damage scales according to the above criteria. The scoring system is shown in Table 1 and consists of 4 main sections and 20 subcategories. The score obtained in each of the four sections is given an equal weighting in the calculation of the total damage scale score. The system aims to remove most of the subjectivity involved in the ranking of different scales. As it can be argued that some subjectivity remains in respect to assigning categories, scoring results are only used as a qualitative indication of performance. To provide a clear indication of each scale's performance, an affirmative score is given 3 points, a negative score 0 points and where the scale partially fulfills the requirement, 1 point. For sub-categories that consider quantity of data, the scoring is based on the definition in Table 2. The scoring is applied to damage scales for reinforced concrete buildings (frames with and without infill and shear wall buildings) and unreinforced masonry building types.

Section 1 of the scoring system in Table 1 deals with the descriptions associated with each damage scale. These are important as they provide greater understanding of damage levels to users in loss estimation studies and form the basis of current post-earthquake damage surveys. They also give a qualitative basis to initiate consideration of repair and cost needs. Important characteristics identified for the damage scale descriptions are that they should be clearly understandable and simple to apply in the assessment of populations of buildings. In both cases, the description should capture the range of damage that could occur to the particular building type, including global and local aspects. A distinction should also be made between structural and non-structural components to aid damage state identification. Lastly, in a European context building damage should reflect building components used in Europe.

In Sect. 2, the scoring system deals with the criteria of having the damage scale associated with a measurable physical parameter. The physical parameter should be easily measurable

Table 1 Important characteristics of a damage scale for loss modelling

Characteristic	Subcategory	Definition	Points: yes/ extent/ no
1. Damage description	1.1 Ease of measurement	Are states clearly distinguishable and can be easily applied to populations of buildings	3/1/0
	1.2 Coverage	Does description capture range of damage to building type	3/1/0
	1.3 Global	Is global damage considered	3/1/0
	1.4 Local	Is local damage considered	3/1/0
	1.5 Non-structural	Is non-structural damage considered	3/1/0
	1.6 European relevance	How relevant are the descriptions to European building types	3/1/0
2. Physical parameter	2.1 Ease of measurement	Can the parameter be straightforwardly measured from analytical results or from populations of buildings	3/1/0
	2.2 Global	Is global damage considered	3/1/0
	2.3 Local	Is local damage considered	3/1/0
	2.4 Quantity	Are values derived from significant quantity of data	3/1/0
	2.5 Calibration	Are values mainly calibrated using experimental data (3), analytical results (2), or judgment (1)	3/2/1/0
	2.6 European relevance	How relevant are the values given to European building types	3/1/0
3. Repairs	3.1 Degree	Is degree of repair specified	3/1/0
	3.2 Repair type	Is scale associated to repair types and quantities of repair required for a specific level of damage	3/1/0
	3.3 Quantity	Are values derived from significant quantity of data	3/1/0
	3.4 European relevance	How relevant are repair types to European construction practice	3/1/0
4. Damage cost	4.1 Cost	Is scale associated to financial losses	3/1/0
	4.2 Cost parameter	Is cost parameter suitable for loss modelling over time	3/1/0
	4.3 Quantity	Are values derived from significant quantity of financial data	3/1/0
	4.4 European relevance	How relevant is the cost data to European construction practice	3/1/0

Table 2 Definition of 'significant' in judgement of quantity in parameter, repair and cost categories

Judgment of quality and quantity for damage	Definition	Score (unless otherwise stated)
Unsatisfactory	Not minimum or unspecified	0
Minimum	1 test/observation per structure type per damage level	1
Significant	Multiple tests/observations per structure type per damage level carried-out in quality-controlled manner	3

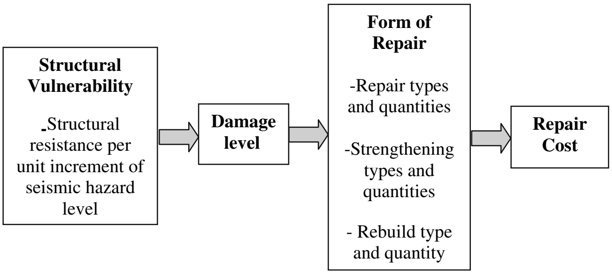

Fig. 2 Causal relationships that determine seismic recovery cost for a building

from analytical results, monitored structural response or structural surveys. This is important for maintaining the link between engineering design and in-the-field survey measurements. As previously stated, the chosen parameter must represent both global and local damage so that local building failure mechanisms, for example, soft-stories, can be identified. Additionally, the numerical values provided should be robustly derived from a significant quantity of data and calibrated in an appropriate manner. In respect to this calibration, experimental calibration is preferred as it provides data based on 'real-life' performance. Analytical and judgment-based values are second and third best, respectively. This is because analyses generally provide data with less bias and at a better resolution than judgment, although care must be taken in setting-up such simulations. Lastly, the relevance of the physical parameter's value and calibration data to European buildings is considered.

Section 3 of the scoring system deals with the association of the damage scale with building repair. In the construction industry, as in any business, actual 'jobs' have to be specified before cost estimates can be provided to clients. The repair type and quantity needed would be specified after an earthquake. An estimate of typical repairs and quantity associated with each damage state would allow the loss estimation process to align itself closer to the source of structural losses and would also be inflation-proof, (though not innovation-proof). The degree of repair is an important initial indicator relating general damage to repair. When linked to a type of repair, this then allows costs to be estimated. Lastly, the relevance of the repair to European buildings is important so that only the main repair types available are considered.

Within loss estimation studies, damage scales are used to assign mean damage levels that can be linked to a mean loss (i.e. cost of repair or replacement). In order to improve accuracy, the damage loss should consider the cost of repair, strengthening, rebuilding, and ground improvements as these are the expenditures that control building recovery (Ergonul 2005). These causal relationships are summarized in Fig. 2. The repairs carried-out will generally be specific to a structural type. Therefore, as previously suggested to achieve both enhanced precision and accuracy in loss estimations, the damage scale should also differentiate between structural types but with an adequate evaluation of repairs and their repair cost to a damage level. Through statistically rigorous determination of each variable it is consequently possible to reduce loss estimation uncertainty.

Finally, in Sect. 4 of the scoring system, the damage scale's direct association to economic losses is investigated. Most existing damage scales that associate damage states to cost use cost ratios, defined as the ratio of damage repair cost to building replacement cost. A relationship between cost and damage is fundamental to any loss estimation study and where lacking could result in inappropriate assumptions being made. It is therefore important that a scale be associated to financial losses, and that the parameter used be robustly derived from

Table 3 Weighting scenarios for scoring system

Weighting scenario	Description	Purpose
A	Equal weighting for each category and sub-category	Default
B	Damage description to have 50% of total weighting	To highlight scales more suited for in-field uses
C	Parameter to have 50% of total weighting	To highlight scales more suited for analysis of structures
D	50% of total weighting for cost section	To highlight scales more suited for economic loss analysis
E	33.3% of weighting for cost and 33.3% for repair sections	To highlight scales more suited for damage analysis
F	66% for sub-categories referring to quality/quantity of data (taken as 1.1/1.2, 2.5/2.4, 3.2/3.3, 4.2/4.3)	Highlighting scales with greater data validation
G	Sub-category values multiplied by European relevance values (1.6, 2.6, 3.4, 4.4)	Maximizing scales scores that are more relevant to Europe

a significant quantity of data. Additionally, the parameter, for example a cost ratio, should be able to provide a degree of independence from inflation. Lastly, this data should be of relevance to European buildings.

Different vulnerability or loss estimation specialists may place different weightings on the scoring categories in accordance to their specific needs. A sensitivity analysis has therefore been carried-out to assess the influence of category weighting on the final scores. The categories are weighted according to seven different scenarios (A–G) as shown in the Table 3. The weightings give a maximum score of 72 points in each case. The weightings used are for illustrative purposes.

An example of use of the scoring scale is given in Table 4. The final ranking for the damage scales considered is shown in Tables 5 and 6. The individual scores are given in the tables of Appendix B.

5 Discussion of damage scale scoring

Within this section, the performance of the scales in the different scoring categories is discussed in greater detail for all the weighting scenarios used. It is important to re-state at this point that the damage scale ranking reflects how appropriate a scale is for use in loss estimation and not how well they perform for their original purpose.

5.1 Weighting scenario A

As previously stated, seven weighting scenarios were considered in the comparison (see above). For weighting scenario A, equal weighting for each category was adopted. This weighting scenario provides an overall view of the damage scale performances in loss estimation. It is the authors' belief that each of the features identified in Table 2 are equally important in loss estimation and it is recommended that this weighting scenario is used with the proposed damage scale scoring system. According to this assessment, the damage scales

Table 4 Example use of scoring system for HAZUS RC scale

Scale	HAZUS RC Response[a]	Weighting scenario A	Final score
1.1	3	1.0	3.0
1.2	3	1.0	3.0
1.3	3	1.0	3.0
1.4	3	1.0	3.0
1.5	3	1.0	3.0
1.6	1	1.0	1.0
2.1	3	1.0	1.0
2.2	3	1.0	3.0
2.3	1	1.0	1.0
2.4	3	1.0	3.0
2.5	3	1.0	3.0
2.6	1	1.0	1.0
3.1	0	1.5	0.0
3.2	0	1.5	0.0
3.3	0	1.5	0.0
3.4	0	1.5	0.0
4.1	3	1.5	4.5
4.2	3	1.5	4.5
4.3	3	1.5	4.5
4.4	1	1.5	1.5
Total			45.0/72.0

[a] Response: 3 = yes, 1 = to some extent, 0 = no

in HAZUS (FEMA 1999), RISK-UE (Milutinovic and Trendafiloski 2003) and Rossetto and Elnashai (2003) rank top three for reinforced concrete structures. For unreinforced masonry instead, the 'hybrid' scale adopted by Bommer et al. (2002) replaces Rossetto and Elnashai (2003). General points to consider are that the HAZUS scale contains detailed descriptions for reinforced concrete and masonry building types, has a methodology for calculating physical parameter values and has a link between the damage levels and cost through cost ratios. The RISK-UE (LM2) method follows similar principles to that use in HAZUS. However, physical parameter values are provided for some of the building types in the RISK-UE scale, which considers European construction in their calibration (calibration being structural analysis using acceleration time-histories, statistical data-generally observational, and cross-validation). By contrast, detailed descriptions are not given with the scale so the differences between damage to European construction and US construction are absent. Additionally, lack of information regarding the data used for the derivation of cost ratios and the relevance of the cost data to Europe, affects the final score for the RISK-UE scale. The damage scale by Rossetto and Elnashai (2003) is seen to score highly despite not having any repairs or costs associated with its damage categories. This is due to the very good damage state descriptions used and the extensive experimental calibration of the scale with a physical parameter. Like the RISK-UE scale, it would be expected that the hybrid scale in Bommer et al. (2002) would also outperform the HAZUS scale, as the physical parameters specified are relevant to

Table 5 Ranking of damage scales: reinforced concrete

RC scale (H = Hybrid scale)	Rankings by weighting scenario						
	A	B	C	D	E	F	G
Reinforced concrete frames with masonry infill							
HAZUS (FEMA 1999)	1	1	2	1	1	1	8
EMS-98 (Grünthal 1998)	12	8	12	12	12	12	6
FEMA 356 (FEMA 2000)	5	4	6	7	7	6	11
Vision 2000 (SEAOC 1995)	9	7	7	10	10	8	12
Blong (2003b)	7	3	9	4	4	5	6
Rossetto and Elnashai (2003)	3	2	3	6	5	3	1
Okada and Takai (2000)	13	13	13	13	13	13	13
RISK-UE: Milutinovic and Trendafiloski (2003) (H)	2	9	1	2	2	2	2
Bommer et al. (2002) (H)	4	12	4	3	3	4	5
Crowley et al. (2004) (H)	6	6	5	8	9	7	3
Akkar et al. (2005) (H)	11	11	8	11	11	11	10
Roca et al. (2006) (H)	10	9	11	5	6	10	8
GNDT (2007)	8	4	10	9	8	9	4
Reinforced concrete frames							
HAZUS (FEMA 1999)	1	1	2	1	1	1	8
EMS-98 (Grünthal 1998)	11	8	11	11	11	11	6
FEMA 356 (FEMA 2000)	5	4	6	7	7	6	10
Vision 2000 (SEAOC 1995)	9	7	7	10	10	8	11
Blong (2003b)	7	3	8	4	4	5	6
Rossetto and Elnashai (2003)	3	2	3	6	5	3	1
Okada and Takai (2000)	12	12	12	12	12	12	12
RISK-UE: Milutinovic and Trendafiloski (2003) (H)	2	9	1	2	2	2	2
Bommer et al. (2002) (H)	4	11	4	3	3	4	5
Crowley et al. (2004) (H)	6	6	5	8	9	7	3
Roca et al. (2006) (H)	10	9	10	5	6	10	8
GNDT (2007)	8	4	9	9	8	9	4
Reinforced concrete shear wall buildings							
HAZUS (FEMA 1999)	1	1	2	1	1	1	8
EMS-98 (Grünthal 1998)	10	7	10	10	10	10	6
FEMA 356 (Fema 2000)	5	3	6	6	6	5	9
Rossetto and Elnashai (2003)	3	2	3	5	4	3	1
Vision 2000 (SEAOC 1995)	8	6	7	9	9	7	10
RISK-UE: Milutinovic and Trendafiloski (2003) (H)	2	8	1	2	2	2	2
Bommer et al. (2002) (H)	4	10	4	3	3	4	5
Crowley et al. (2004) (H)	6	5	5	7	8	6	3
Foca et al, 2006 (H)	9	8	9	4	5	9	7
GNDT, 2007	7	3	8	8	7	8	4

Table 6 Ranking of damage scales: unreinforced masonry

URM scale (H = Hybrid scale)	Rankings by weighting scenario						
	A	B	C	D	E	F	G
HAZUS (FEMA 1999)	1	1	2	1	1	1	8
EMS-98 (Grünthal 1998)	11	10	11	11	11	11	6
FEMA 356 (FEMA 2000)	4	2	4	6	6	4	10
Vision 2000 (SEAOC 1995)	8	6	5	9	9	6	11
Blong (2003b)	6	5	8	4	4	5	6
Okada and Takai (2000)	12	12	12	12	12	12	12
RISK-UE: Milutinovic and Trendafiloski (2003) (H)	2	8	1	2	2	2	1
Bommer et al. (2002) (H)	3	11	3	3	3	3	3
Lang and Bachmann (2004) (H)	10	7	6	10	10	10	3
Khudiera and Mohammadi (2006) (H)	5	4	7	7	7	8	9
Roca et al. (2006) (H)	9	8	10	5	5	9	5
GNDT (2007)	7	2	9	8	7	7	2

European buildings. However, again the score is affected by the lack of sufficiently detailed damage descriptions and cost evidence, suggesting the scale simply adopts HAZUS cost ratios rather than developing new ones more appropriate to a European context.

It is concluded that with certain modifications to key areas the damage scales in RISK-UE and Bommer et al. (2002) could outperform the HAZUS scale, for the equal category weighting scenario. It can also be noted that the scale by Rossetto and Elnashai (2003) provides a template for developing detailed damage descriptions and parameter values.

5.2 Weighting scenario B

In weighting scenario B the damage description category is given greater importance than the others. Scales developed primarily for post-earthquake field investigation such as EMS-98 (Grünthal 1998), GNDT (2007) or (Okada and Takai 2000) improve their scores significantly and often improve their ranking. As do the earthquake engineering scales from FEMA 356 and Vision 2000 (FEMA 2000; SEAOC 1995). Nonetheless, HAZUS (FEMA 1999), Rossetto and Elnashai (2003) and Blong (2003b) are the top three ranked reinforced concrete damage scales, though only the former two can be considered to explicitly cover one of the most important European building classes, that of infilled reinforced concrete frames. HAZUS (FEMA 1999), FEMA 356 (FEMA 2000) and GNDT (2007) are the top three ranked damage scales for unreinforced masonry. The FEMA 356 (FEMA 2000) and GNDT scale (2007) also perform well for reinforced concrete. It is important to note that it is insufficient for damage scales to be ranked highly if they only have detailed damage descriptions, but they need to also perform well in other scoring categories. For example, Blong (2003b) outperforms EMS-98 (Grünthal 1998) despite similar damage descriptions because it links damage level to cost. It must also be considered that although EMS-98 (Grünthal 1998) does well in this weighting scenario, some of its damage state descriptions lack detail. For example descriptions of damage to masonry buildings do not describe permanent movements (e.g. in-plane and out-of-plane failures), and there is insufficient detail on the behaviour of masonry infills, which strongly influence structural behaviour and especially the achievement of lower damage states, and are particularly relevant to European buildings. This has also resulted in difficulties in establishing the equivalence tables in a subsequent section of the paper. The ranking of the GNDT scale in this scenario underlines the quality of its damage descriptions for reinforced concrete and masonry. Finally, 'hybrid' scales, such as RISK-UE (Milutinovic and Trendafiloski 2003), are not seen to perform well. Whilst providing more information particularly with regards to physical parameter, these scales often provide only implied links to compatible sources of damage descriptions.

5.3 Weighting scenario C

In weighting scenario C the parameter category is given 50% of the weighting. A high score in this section is obtained if an appropriate structural response parameter is associated by the scale with its damage states, and if the threshold values of the parameter for the damage states is defined using large anounts of observational or experimental data. This allows the damage scale to be adopted for the interpretation of structural engineering analysis results. In this particular scenario RISK-UE (Milutinovic and Trendafiloski 2003), HAZUS (FEMA 1999) and Rossetto and Elnashai (2003) are the top three in the ranking for reinforced concrete scales. Instead, for unreinforced masonry Bommer et al. (2002) replaces Rossetto and Elnashai (2003). This is a similar result as in weighting scenario A, however, the RISK-UE scale outperforms HAZUS due to the presence of parameters that are more relevant to European buildings. Many of those related to masonry and reinforced concrete buildings can be found in the report by Milutinovic and Trendafiloski (2003) and paper by Lagomarsino and Giovinazzi (2006). The data used to determine these parameters appear in varying reports and papers (RISK-UE project website 2007; RISK-UE BEE special edition 2006), for example, the report by Pitilakis et al. (2004) details use of time-history analysis and post-earthquake survey statistics for use in determining parameters. The scales in this weighting scenario generally performed better by incorporating physical parameters developed using a HAZUS-type method. Many scales adopt global drift as the response parameter, for example FEMA 356 (FEMA 2000). This parameter considers global response but can overlook a local 'soft-storey' failure and therefore is not ideal for linking to damage. Crowley et al. (2004) instead use a local (strain-based) damage parameter for structural damage. This is also inappropriate for use in damage scale calibration as it can overlook global response. A better parameter is inter-storey drift, as demonstrated by Rossetto and Elnashai (2003), which scores well as the parameter is correlated to its damage description via a substantial amount of experimental data. Inter-storey drift is also used with the HAZUS and RISK-UE scales but is not used exclusively or for correlation with the damage descriptions. Although inter-storey drift may have advantages over some of the other parameters mentioned here, as a damage parameter it may nevertheless miss certain brittle failure modes such as column shear failure, which may sometimes occur in European reinforced concrete buildings not constructed in accordance with modern codes.

5.4 Weighting scenario D

In weighting scenario D the cost category is given 50% of the weighting. In the context of loss estimation, a link between cost and damage is essential. The use of cost ratios is currently widely used for this purpose with only a 100% construction replacement value being updated with time. In this particular scenario scales from HAZUS (FEMA 1999), RISK-UE (Milutinovic and Trendafiloski 2003; Vacareanu et al. 2004) and Bommer et al. (2002) rank top three. It is important to note that the HAZUS cost ratios derived using empirical data for the

US. Limited information is presented by RISK-UE (Milutinovic and Trendafiloski 2003) and Bommer et al. (2002) to prove that the cost ratios are derived for European buildings, so their use in Europe is currently unsatisfactory. Another scale that performs well is the hybrid scale used by Roca et al. (2006) which has cost ratios presented for use with an Intensity damage scale but again presents limited information on the quality of data used to derive the cost ratios. The scoring highlights a void in cost data relevant to Europe and damage scales that provide strong links between damage and cost, whether those links are through direct consideration of repair or through use of post-earthquake financial data or research of the construction market. It is apparent that more research needs to be conducted with respect to providing more evidence as to whether these cost ratios are suitable for use with European buildings.

5.5 Weighting scenario E

In weighting scenario E the cost category is given 33% of the weighting and the repair section 33%. In this particular scenario scales from HAZUS (FEMA 1999), RISK-UE (Milutinovic and Trendafiloski 2003) and Bommer et al. (2002) are again the top three. However, it is clear that most of the scales provide limited information with respect to repair methods. In fact, few scales score at all in this section. The notable exceptions are FEMA 356 (FEMA 2000) and RISK-UE (Milutinovic and Trendafiloski 2003). In the case of FEMA 356 a general repair level is associated to each damage state although this would be insufficient to define a repair brief. The RISK-UE scale (Milutinovic and Trendafiloski 2003, p. 65; Kappos et al. 2006) assigns repair functions in terms of physical response. The functions have been derived from repair cost data for different repair types Greece (Kappos et al. 1998, 1991). The RISK-UE scale is therefore scale is therefore the only scale that provides a link between a response parameter and repair types. One reason why the RISK-UE scale does not ‘score’ as well in this section as it might is because actual values are not provided. Additionally, elsewhere in the methodology reference is also made to direct transfer of HAZUS cost ratios without determining applicability in Europe (Vacareanu et al. 2004, p. 24). It is therefore recommended that further research is carried-out in these areas.

In general, scales used in loss estimation could be significantly improved by considering the main repair types as this will help capture the source of costs. Pagni and Lowes (2006) correlate damage states to types of repair that could be used for concrete beam-column joints. As only one type of failure mechanism is considered this is insufficient for a scale that must take into account global building damage. However, a solid basis for creating a link to repair, and consequently cost of damage, can be formed by extending this work to include other failure mechanisms within the building. Determining cost information from repair types is much more intuitive than from more ‘abstract’ damage descriptions and has previously been shown to closely correlate to statistical data (Kappos et al. 1991). By using repair types, cost ratios can also be updated at suitable time intervals through consultation with the local construction industry. This is particularly relevant for the insurance industry which generally has insufficient recorded financial losses for estimation purposes and where previous losses will have been affected by price inflation. It is again apparent that more research needs to be conducted with respect to providing more links between damage levels and repair requirement (see Fig. 2 for further explanation).

5.6 Weighting scenario F

In weighting scenario F, 66% of the weighting is given to ‘quality/quantity’ sub-categories. The purpose is to give more weight to those scales with greater data validation input. HAZUS

(FEMA 1999), RISK-UE (Milutinovic and Trendafiloski 2003) and Rossetto and Elnashai (2003) were the top three in the ranking for reinforced concrete. Again, in the case of unreinforced masonry Bommer et al. (2002) replaces Rossetto and Elnashai (2003). In general, this validation tends to be greatest for the physical parameter category (see comments for Sects. 4 and 5).

5.7 Weighting scenario G

The weighting scenario G results in the greatest movement in rankings. Apart from the individual scores for European relevance within the scoring it was decided that weighting scenario G would maximise European relevance. The top three scales for reinforced concrete were Rossetto and Elnashai (2003), RISK-UE (Milutinovic and Trendafiloski 2003) and Crowley et al. (2004), with Bommer et al. (2002) and GNDT (2007) also performing well. For unreinforced masonry the top ranking scales were RISK-UE, Bommer et al. (2002), and Lang and Bachmann (2004). The scale by Crowley et al. (2004) is a European scale that has a detailed description and infers physical parameters and repair features. The hybrid scale used in the study by Lang and Bachmann (2004) is an enhanced version of EMS-98 (Grünthal 1998). It should also be mentioned that the HAZUS scale is noticeable by its absence in the top rankings. This is an illustration that it is essentially a high-quality non-European damage scale that meets many of the requirements for loss estimation.

5.8 Scoring conclusions

The proposed scoring system is a general tool for comparison of damage scales in the context of loss estimation. It cannot catch all nuances but qualitatively gives a clear indication of which are the better scales for seismic loss prediction and the reasons for this. Firstly, it is seen that the position of these scales in the ranking does not change markedly between the structural types but can change markedly in respect to the chosen weighting scenarios. The following conclusions are made in the context of current seismic loss estimation practice where damage scales are taken currently from HAZUS or Intensity scales like EMS-98. Of the considered damage scales it is seen that the HAZUS damage scale (FEMA 1999) outperforms other scales in many respects. However, in a European context the scale performs inadequately. This highlights that damage scales derived for European buildings do not fully capture the characteristics that are required for effective loss estimation. Whilst the RISK-UE scale was developed specifically with European buildings in mind, it lacks certain features within the description and cost fields, which have been identified as necessary for an effective loss estimation. Nonetheless, the RISK-UE ‘hybrid’ scale (Milutinovic and Trendafiloski 2003) performs well in all the weighting scenarios and should be considered the preferred option. Further investigation into damage descriptions (see Rossetto and Elnashai 2003; GNDT 2007) and cost ratios relevant to European buildings is recommended.

At the other end of the ranking the presence of EMS-98 Intensity damage scale is notable. Although not designed for use in seismic loss estimation, Intensity damage scales have often been used in such studies. However, it is clear that the scales do not capture a sufficient quantity of the characteristics that are required of such a scale. The hybrid scale used by Roca et al. (2006) and the scale developed by Blong (2003b) are based on Intensity damage scales. They do not perform as well as might be expected since despite having relations between damage level and cost they do not consider physical behaviour to the extent that other scales with physical parameter values do or provide sufficient evidence for cost assumptions. The scale by Lang and Bachmann (2004) also outperforms EMS-98 by enhancing its descriptions to consider physical performance. Where Intensity damage scale is to be used, use of it through the RISK-UE ‘hybrid’ scale (Milutinovic and Trendafiloski 2003) should also be considered the preferred option (method LM1). In the context of Intensity scale EMS-98, it is recommended that damage descriptions be further enhanced (see Rossetto and Elnashai 2003; GNDT 2007; Lang and Bachmann 2004). Further investigation into cost ratios relevant to European buildings is recommended but this will be difficult to incorporate into a loss estimation method using an Intensity scale damage scale without careful consideration of the physical response.

It is seen that few scales consider the relationship between repair and cost and therefore a general recommendation is that further research should also be focussed on this area.

6 Damage state description equivalences

Seismic loss estimation studies frequently require that post-earthquake survey data collected using one damage scale is expressed in terms of another damage scale in order to assess seismic vulnerability Equivalences between damage scales are required in order for consistency within the study to be maintained. Different authors (Milutinovic and Trendafiloski 2003; Rossetto and Elnashai 2003) have proposed equivalences in the past between a variety of scales including notably EMS-98 and HAZUS. However, these are seen to differ hence an assessment of the scales and consequent equivalences are proposed here.

In the previous section, it was highlighted that some damage scales are better for loss estimation than others and that many lack essential characteristics that are required for effective loss estimation. As has been noted, damage descriptions are associated with the majority of scales whilst, for example, physical parameters are often not present or are of a different type. Therefore, within this paper equivalence tables between existing damage scales are drawn from a comparison of their detailed damage descriptions.

Similar and sometimes exact phrases have been taken from the most detailed part of each description, not necessarily the titles, in order to make the equivalences. An example of this is where looking at scales for reinforced concrete frame equivalences it can be noted that the FEMA 356 ‘operational’ and EMS-98 ‘grade 1’ states start at a level of damage corresponding to architectural elements, for example with “fine cracks in plaster/partitions” whilst the HAZUS “slight” state refers to “flexural or shear type hairline cracks” in structural elements. The equivalence of the start of the HAZUS state to other states is therefore made beyond the start of FEMA 356 ‘operational’ and EMS-98 ‘grade 1’ states. Another example can be taken from the EMS-98 ‘grade 3’ equivalence which extends beyond the end of the HAZUS ‘moderate’ equivalence, due to reference to “buckling of reinforcement” in the EMS-98 state and in the HAZUS ‘extensive’ state. Elsewhere, it can be seen there is more uncertainty between equivalences. An example of this is when considering scales for unreinforced masonry equivalences it is seen that EMS-98’s descriptions contain some details such as “hair-line cracks in very few walls” that can be related to those of say HAZUS which refers to “diagonal, stair-step hairline cracks on masonry wall surfaces”. However, EMS-98 does not refer to movements of walls, for example, HAZUS’s moderate level refers to “masonry walls may have visible separation from diaphragms”. Therefore more judgement is required when making the equivalences, which is also necessary in the presence of certain title descriptions in EMS-98, hence the dashed lines in Tables 7–10.

Where the damage predicted for a damage state is not clearly aligned with another scale, the state is apportioned appropriately between states. Damage scales are continuous, however

Table 7 Reinforced concrete frame buildings with masonry infill

<table>
<tr><td rowspan="1">HAZUS ‘99</td><td colspan="2"></td><td colspan="3">Slight</td><td colspan="4">Moderate</td><td colspan="2">Extensive</td><td colspan="2">Complete</td></tr>
<tr><td>FEMA 356</td><td></td><td colspan="3">Operational</td><td colspan="2">Immediate Occupancy</td><td colspan="3">Life safety</td><td colspan="2">Collapse Prevention</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Vision 2000 (index and damage descriptions) (SEAOC, 1995)</td><td>10: Fully Operational</td><td>9: Fully Operational</td><td colspan="3">8: Operational</td><td colspan="2">7: Operational</td><td>6: Life safety</td><td>5: Life safety</td><td>4: Near collapse</td><td>3: Near collapse</td><td>2: Collapse</td><td>1: Collapse</td></tr>
<tr><td colspan="2">Fully Operational</td><td colspan="5">Operational</td><td colspan="2">Life safety</td><td colspan="2">Near collapse</td><td colspan="2">Collapse</td></tr>
<tr><td>EMS- 98</td><td></td><td colspan="2">Grade 1. Negligible to slight</td><td colspan="6">Grade 2. Moderate</td><td>Grade 3. Substantial to heavy</td><td colspan="2">Grade 4. Very heavy</td><td>Grade 5. Destruction</td></tr>
<tr><td>GNDT</td><td></td><td colspan="2">Light</td><td colspan="7">Moderate-significant</td><td colspan="3">Very significant</td></tr>
<tr><td>Milutinovic and Trendafiloski, 2003 (RISK-UE: LM1-EMS based)</td><td>D0: None</td><td colspan="2">D1: Slight</td><td colspan="6">D2: Moderate</td><td>D3: Substantial to heavy</td><td colspan="2">D4: Very heavy</td><td>D5: Destruction</td></tr>
<tr><td>Milutinovic and Trendafiloski, 2003 (LM2 –from equivalence provided)</td><td>None</td><td colspan="2">Minor</td><td colspan="6">Moderate</td><td>Severe</td><td colspan="3">Collapse</td></tr>
</table>

Table 7 continued

<table>
<tr><td>HAZUS ‘99</td><td colspan="2"></td><td colspan="3">Slight</td><td colspan="4">Moderate</td><td colspan="2">Extensive</td><td colspan="4">Complete</td></tr>
<tr><td>FEMA 356</td><td></td><td colspan="3">Operational</td><td colspan="2">Immediate Occupancy</td><td colspan="3">Life safety</td><td colspan="2">Collapse Prevention</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Vision 2000 (index and damage descriptions) (SEAOC, 1995)</td><td>10: Fully Operational</td><td>9: Fully Operational</td><td colspan="3">8: Operational</td><td colspan="2">7: Operational</td><td>6: Life safety</td><td>5: Life safety</td><td>4: Near collapse</td><td>3: Near collapse</td><td colspan="3">2: Collapse</td><td>1: Collapse</td></tr>
<tr><td colspan="2">Fully Operational</td><td colspan="5">Operational</td><td colspan="2">Life safety</td><td colspan="2">Near collapse</td><td colspan="4">Collapse</td></tr>
<tr><td>Blong, 2003b</td><td></td><td colspan="2">Light</td><td colspan="6">Moderate</td><td>Heavy</td><td colspan="4">Severe</td><td>Collapse</td></tr>
<tr><td>Rossetto and Elnashai, 2003</td><td>None: $DI_{HRC} = 0$</td><td>Slight: $DI_{HRC} = 10$</td><td>Light: $DI_{HRC} = 20$</td><td colspan="2">Light: $DI_{HRC} = 30$</td><td>Light: $DI_{HRC} = 40$</td><td>Moderate: $DI_{HRC} = 50$</td><td>Moderate: $DI_{HRC} = 60$</td><td>Moderate: $DI_{HRC} = 70$</td><td>Extensive: $DI_{HRC} = 80$</td><td>Extensive: $DI_{HRC} = 90$</td><td colspan="3">Partial Collapse: $DI_{HRC} = 100$</td><td>Collapse</td></tr>
<tr><td>R&E –HAZUS</td><td></td><td colspan="5">Slight</td><td colspan="3">Moderate</td><td colspan="5">Extensive</td><td>Collapse</td></tr>
<tr><td>R&E –EMS</td><td></td><td colspan="4">Grade 1</td><td colspan="2">Grade 2</td><td colspan="2">Grade 3</td><td colspan="4">Grade 4</td><td colspan="2">Collapse</td></tr>
<tr><td>R&E –V2000 NDF</td><td></td><td colspan="3">Fully Operational</td><td colspan="3">Operational</td><td colspan="2">Life safety</td><td>Near collapse</td><td colspan="5">Collapse</td></tr>
<tr><td>Crowley et al, 2004</td><td colspan="7">None to slight</td><td colspan="2">Moderate</td><td colspan="3">Extensive</td><td colspan="3">Complete</td></tr>
</table>

Table 8 Reinforced concrete frame buildings

HAZUS '99			**Slight**		**Moderate**			**Extensive**			**Complete**
FEMA 356		**Operational**		**Immediate Occupancy**		**Life safety**		**Collapse Prevention**			
Vision 2000 (index and damage descriptions)	**10: Fully Operational**	**9: Fully Operational**	**8: Operational**	**7: Operational**	**6: Life safety**		**5: Life safety**	**4: Near collapse**	**3: Near collapse**	**2: Collapse**	**1: Collapse**
	Fully Operational		**Operational**		**Life safety**			**Near collapse**		**Collapse**	
EMS- 98		**Grade 1. Negligible to slight**	**Grade 2. Moderate**		**Grade 3. Substantial to heavy**				**Grade 4. Very heavy**		**Grade 5. Destruction**
GNDT		**Light**	**Moderate-significant**						**Very significant**		
Milutinovic and Trendafiloski, 2003 (RISK-UE: LM1-EMS based)	**D0: None**	**D1: Slight**	**D2: Moderate**		**D3: Substantial to heavy**				**D4: Very heavy**		**D5: Destruction**
Milutinovic and Trendafiloski, 2003 (LM2 –from equivalence provided)	**None**	**Minor**	**Moderate**		**Severe**				**Collapse**		

Table 8 continued

<table>
<tr><td>HAZUS ‘99</td><td colspan="2"></td><td colspan="3">Slight</td><td colspan="3">Moderate</td><td colspan="3">Extensive</td><td>Complete</td></tr>
<tr><td>FEMA 356</td><td></td><td colspan="2">Operational</td><td colspan="3">Immediate Occupancy</td><td colspan="2">Life safety</td><td colspan="2">Collapse Prevention</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Vision 2000 (index and damage descriptions)</td><td>10: Fully Operational</td><td>9: Fully Operational</td><td>8: Operational</td><td colspan="2">7: Operational</td><td colspan="2">6: Life safety</td><td>5: Life safety</td><td>4: Near collapse</td><td>3: Near collapse</td><td>2: Collapse</td><td>1: Collapse</td></tr>
<tr><td colspan="2">Fully Operational</td><td colspan="3">Operational</td><td colspan="3">Life safety</td><td colspan="2">Near collapse</td><td colspan="2">Collapse</td></tr>
<tr><td>Blong, 2003b</td><td></td><td>Light</td><td colspan="3">Moderate</td><td colspan="3">Heavy</td><td colspan="3">Severe</td><td>Collapse</td></tr>
<tr><td>Rossetto and Elnashai, 2003</td><td>None
$DI_{HRC} = 0$</td><td>Slight
$DI_{HRC} = 10$</td><td>Light
$DI_{HRC} = 20$</td><td>Light
$DI_{HRC} = 30$</td><td>Light
$DI_{HRC} = 40$</td><td>Moderate
$DI_{HRC} = 50$</td><td>Moderate
$DI_{HRC} = 60$</td><td>Moderate
$DI_{HRC} = 70$</td><td>Extensive
$DI_{HRC} = 80$</td><td>Extensive
$DI_{HRC} = 90$</td><td>Partial Collapse
$DI_{HRC} = 100$</td><td>Collapse</td></tr>
<tr><td>R&E –HAZUS</td><td></td><td colspan="4">Slight</td><td colspan="3">Moderate</td><td colspan="3">Extensive</td><td>Collapse</td></tr>
<tr><td>R&E –EMS</td><td></td><td colspan="2">Grade 1</td><td colspan="2">Grade 2</td><td colspan="3">Grade 3</td><td colspan="3">Grade 4</td><td>Collapse</td></tr>
<tr><td>R&E –V2000 NDF</td><td></td><td colspan="2">Fully Operational</td><td colspan="3">Operational</td><td colspan="2">Life safety</td><td>Near collapse</td><td colspan="3">Collapse</td></tr>
<tr><td>Crowley et al, 2004</td><td colspan="5">None to slight</td><td colspan="3">Moderate</td><td colspan="2">Extensive</td><td colspan="2">Complete</td></tr>
</table>

Table 9 Reinforced concrete shear-wall buildings

HAZUS '99				Slight		Moderate					Extensive			Complete
FEMA 356		Operational		Immediate Occupancy		Life safety					Collapse Prevention			
Vision 2000 (index and damage descriptions)	10	9	8	7	6			5		4		3	2	1
	Fully Operational		Operational		Life safety					Near collapse			Collapse	
EMS- 98		Grade 1. Negligible to slight	Grade 2. Moderate		Grade 3. Substantial to heavy				Grade 4. Very heavy					Grade 5. Destruction
Milutinovic and Trendafiloski, 2003 (RISK-UE: LM1-EMS based)	D0: None	D1: Slight	D2: Moderate		D3: Substantial to heavy				D4: Very heavy					D5: Destruction
Milutinovic and Trendafiloski, 2003 (LM2 –from equivalence provided)	None	Minor	Moderate		Severe				Collapse					
Rossetto and Elnashai, 2003	None $DI_{HRC} = 0$	Slight $DI_{HRC} = 10$	Light $DI_{HRC} = 20$	Light $DI_{HRC} = 30$	Light: $DI_{HRC} = 40$	Moderate $DI_{HRC} = 50$		Moderate $DI_{HRC} = 60$	Moderate $DI_{HRC} = 70$		Extensive: $DI_{HRC} = 80$	Extensive $DI_{HRC} = 90$	Partial Collapse $DI_{HRC} = 100$	Collapse
R&E –HAZUS		Slight				Moderate					Extensive			Collapse
R&E –EMS		Grade 1		Grade 2				Grade 3				Grade 4		Collapse
R&E –V2000 NDF		Fully Operational		Operational			Life safety				Near collapse		Collapse	
Crowley et al, 2004	None to slight						Moderate				Extensive		Complete	

Table 10 Unreinforced masonry walls

HAZUS '99			Slight		Moderate		Extensive		Complete	
FEMA 356		Operational		Immediate Occupancy	Life safety		Collapse Prevention			
Vision 2000 (index and damage descriptions)	10: Fully Operational	9: Fully Operational	8: Operational	7: Operational	6: Life safety	5: Life safety	4: Near collapse	3: Near collapse	2: Collapse	1: Collapse
	Fully Operational		Operational		Life safety		Near collapse		Collapse	
EMS- 98		Grade 1. Negligible to slight			Grade 2. Moderate		Grade 3. Substantial to heavy		Grade 4. Very heavy	Grade 5. Destruction
GNDT		Light			Moderate-significant				Very significant	
Milutinovic and Trendafiloski, 2003 (RISK-UE: LM1-EMS based)	D0: None	D1: Slight			D2: Moderate		D3: Substantial to heavy		D4: Very heavy	D5: Destruction
Milutinovic and Trendafiloski, 2003 (LM2 –from equivalence provided)	None	Minor			Moderate		Severe		Collapse	
Lang & Bachmann, 2004 (EMS based)			DG1: Negligible to slight Damage		DG2: Moderate		DG3: Substantial to heavy		DG4: Very heavy	DG5: Destruction
Blong, 2003b		Light			Moderate		Heavy		Severe	Collapse

where inconsistencies between states arise due to lack of corresponding detail or contradictions in the text, a dashed line is shown. This indicates that there is a greater degree of uncertainty between one damage state and the next and that the state could cover a bigger or smaller damage range than shown. At the start or finish of a scale, a blank space may be present to show that the scale has not explicitly considered those areas. The equivalence tables are derived for different structural material types, but as stated previously, the resolution of these categories is limited by the existing damage scale descriptions. The final equivalences are given in the following tables with reinforced concrete shear wall buildings being included for completeness.

From the scales' descriptions, it can be observed that some states have a reduced detail compared to others. This is of particular relevance to the EMS-98 damage scale (Grünthal 1998) where uncertainty is introduced in the determination of some states due to lack of detail in damage descriptions relative to other scales. Additionally, most scales ignore the 'no damage' state and often fail to adequately distinguish between an initial 'non-structural' damage state prior to the commencement of structural damage.

In the equivalence table for reinforced concrete frames with masonry infill, Table 7, damage to infill controls the attainment of lower damage levels. HAZUS (FEMA 1999), Rossetto and Elnashai (2003) and GNDT (2007) are the only damage scales that explicitly include the infill and structural frame behaviour at each stage. Whilst both infill and reinforced concrete damage scales are given in FEMA 356 (FEMA 2000) and Vision 2000 (SEAOC 1995), the interaction between the frame and infill is unspecified. Additionally, the EMS-98 descriptions provide limited detail on frame and infill interaction for most states. Despite the limitation resulting from lack of explicit frame and infill behaviour in some scales the different scales damage states' tend to agree.

On the other hand, the scales descriptions' for reinforced concrete frame behaviour alone, Table 8, are more detailed. It is interesting to note some of the discrepancies between scales for this structural type. For example, when comparing HAZUS and EMS-98 it is seen that damage states with similar titles are associated with significantly different levels of described damage. This gives rise to unaligned damage states. The equivalence table for reinforced concrete shear wall buildings, Table 9, has been included for completeness. Like the equivalences for reinforced concrete frame buildings with infill, these also are limited by the level of detail in the descriptions. Nonetheless, a different pattern between scales emerges.

In the unreinforced masonry equivalence, Table 10, the 'slight' damage limit state of EMS-98 states there is no structural damage. However, the description refers to fine cracking in walls. As walls are structural elements in masonry buildings, there is a contradiction in this description. The correlation between scales differs from those for other structural types. For example, the HAZUS and EMS states agree relatively closely unlike in the other equivalence tables. However, there is a degree of uncertainty in making equivalences between EMS-98 moderate, substantial and very heavy damage states and other scales. This is mainly due to a lack of a detailed description for permanent movements in the structure and due to the title nomenclature which gives the impression structural damage would be less than the equivalent damage titles provided by other scales.

Overall, it can be seen that when considering the detailed descriptions and common levels of damage of each scale, there are inconsistencies between damage states. This is unsurprising since the scales generally have different authors leading to some states for some types of building behaviour being described in more detail or capturing different orders of damage. It is not necessary for numerous damage states to be included in a scale as the appropriate quantity can be inferred from the number of repair types that could be implemented and/or their consequent cost. Nonetheless, the damage states should be well-defined and should sufficiently describe the range of possible damage. The equivalence tables also clearly demonstrate that when damage data from different sources is compared it is incorrect to assume that similarly named damage states correspond directly. This is of particular importance when, for example, mixing vulnerability analysis using HAZUS-style damage states with, for example, hazard data which uses the EMS-98 intensity damage scale as this information is collected by survey and those conducting it will aim to assign damage levels as close to this scale as possible. Whether it is possible or not to assign damage levels accurately with the level of detail provided by the descriptions is a separate issue.

7 Conclusion

This study has identified important characteristics that should be considered for an effective damage scale for loss estimation. A scoring system was developed for the qualitative review of damage scales and particular consideration was given to potential use in seismic loss estimation in Europe. It is found overall that a scale such as HAZUS (FEMA 1999) 'captures' to a greater extent the characteristics that an effective damage scale for loss estimation should have. However, its applicability to Europe is limited by the fact that it is calibrated (in terms of response parameter and cost) with data deriving solely from the US. The RISK-UE scale (Milutinovic and Trendafiloski 2003), which follows a HAZUS-based procedure, also performs well in most categories and is designed for European buildings. However, the scale lacks detail in respect to damage descriptions which should be inferred from equivalences given and presents insufficient cost data to justify use of the cost ratios presented.

A particular concern raised by the damage scale scoring is the weak or inexistent associations made by existing damage scales between damage level, repair and cost. It is recommended that further research be carried out to strengthen these relations. It is also recommended that damage scales for loss estimation are defined in terms of physical response parameters as well as descriptions.

In seismic loss studies many sources of data may be used to estimate building vulnerability, amongst which is past earthquake damage survey data. The damage scales used may vary. Hence, equivalence tables between existing damage scales are proposed for the main European building classes. These equivalences are based on the damage level described by the scales. It is found that equivalences between damage states vary according to the building class, and the lack of detail or clarity from some damage scales introduces uncertainty in the equivalences. Another key issue is found to be the nomenclature of damage states in existing damage scales. Different scales contain damage states with similar names but imply very different degrees of sustained physical damage in their descriptions. This raises concern over past studies that have assumed a direct correlation between similarly named damage states and may have introduced further uncertainty into their loss estimates. The authors' believe that the proposed equivalence tables herein, provide a more robust basis for the interpretation of vulnerability or post-earthquake survey data from different sources and recommend future scales include more consistent and detailed descriptions for use with European building stock.

Acknowledgements This work is part of a PhD funded by Benfield Group Ltd. and the UK's Engineering and Physical Sciences Research Council (EPSRC) via its CASE for New Academics scheme.

Appendix A: Summary of damage scales

Table 11 Summary of damage scales selected

Reference	Description of scale
EMS-98 (Grünthal 1998)	Damage scale: Mainly descriptive with some graphics Main application: Aid to determine seismic Intensity to EMS-98 (most recent European Intensity scale) Data set: Update to EMS-92 (previously based on MSK scale and other Intensity scales) mainly using 7 earthquakes occurring between 1992 and 1998 (Grünthal 1998) Reason for inclusion: Damage scale developed for post-earthquake surveys to determine seismic intensity. Other stated design aim of EMS-98 include that the “needs of civil engineers and other non-seismological users can be met” (Grünthal 1998)
HAZUS (FEMA 1999)	Damage scale: Descriptive with physical parameters and cost ratios Main application: Seismic loss estimation in the USA Data set: The main sources of data are too numerous to cite in detail. In Chap. 5 of the HAZUS99 manual (FEMA 1999) 31 reports and other research documents are cited. More information and references can be found in Whitman et al. (1997) but research included a review of existing studies through FEMA-249 (FEMA 1994) and use of thirty earthquake experts over three year period calibrating using existing literature and previous earthquake data including Northridge, although the extent of this latter research is unknown as it is unpublished. Quantitative methods used are based FEMA/NIBS methodology developed since 1989 and accompanying research (Kircher et al. 1997). The HAZUS ‘damage factors’ are similar to those of ATC-13 but are ‘better calibrated’ (Kircher et al. 1997). Empirically-derived cost ratios are associated with the damage states and show reasonable accuracy compared to observed results for Los Angeles residential buildings after the 1994 Northridge earthquake (Kircher et al. 1997) Reason for inclusion: Damage scale developed for seismic loss estimation that includes scales for masonry and reinforced concrete structures (relevant to European inventory)
Vision 2000 (SEAOC 1995)	Damage scale: Mainly descriptive but some reference to physical parameters Main application: Performance-based earthquake engineering in USA Data set: Original report from SEAOC Reason for inclusion: Representing recent trend in development of performance-based earthquake engineering (includes scales for masonry and reinforced concrete)
FEMA 356 (FEMA 2000)	Damage scale: Mainly descriptive but some reference to physical parameters Main application: Performance-based earthquake engineering in USA Data set: Based on research that led to FEMA 273 and 45 other documents.

Table 11 continued

	Reason for inclusion: Representing recent trend in development of performance-based earthquake engineering including scales for masonry and reinforced concrete (Note: different scale to Vision 2000)
Okada and Takai (2000)	Damage scale: Graphical with relations to Intensity scales
	Main application: Rapid earthquake field investigation
	Data set: Compilation of several secondary data sources and judgement
	Reason for inclusion: Representing development of graphical damage scales for use in rapid earthquake field investigation. Includes scales for masonry and reinforced concrete.
RISK-UE (based on Milutinovic and Trendafiloski (2003) (H))	Damage scale: Physical parameters, cost ratios, relations to EMS-98/HAZUS scales
	Main application: Seismic loss estimation in Europe
	Data set: EU-backed research programme comprising six European universities. Damage scale is aligned to EMS/HAZUS levels and for two-tier methodology, leading to different data sets for each case-study location in project. Reference sources too numerous to mention but further information can be found at the RISK-UE project website (2007) and in the RISK-UE BEE special edition (2006) particularly Lagomarsino and Giovinazzi (2006). analysis using acceleration time-histories, statistical data (generally observational) and judgement through cross-validation
	Reason for inclusion: Example of how existing damage levels (EMS-98/HAZUS) are used in European seismic loss estimation methodology developed by RISK-UE project
Blong (2003b)	Damage scale: Descriptive with cost ratios
	Main application: Natural hazard (including seismic) loss estimation in Australia (but methodology aimed at general use)
	Data set: Descriptions developed from EMS-92. Cost ratios developed using data from the Australian building code, with nationally respected cost and property guides from sources for 1999
	Reason for inclusion: Example of damage scale developed for natural hazard (including seismic) loss estimation. Developed using European source
Rossetto and Elnashai (2003)	Damage scale: Descriptive with physical parameters, and relations to existing scales
	Main application: Seismic vulnerability studies of European reinforced concrete buildings
	Data set: Damage scale developed from data from large-scale reinforced concrete experiments
	Reason for inclusion: Example of damage scale developed for use in vulnerability studies of European buildings
Bommer et al. (2002) (H)	Damage scale: Physical parameters, cost ratios, HAZUS-based methodology

Table 11 continued

	Main application: Seismic loss estimation in Turkey
	Data set: Damage scale: HAZUS damage scale and cost ratios. Parameters similar to used using capacity-spectrum method similar to HAZUS were determined using existing research and judgement with calibration from damage data from 1999 Kocaeli and Duzce earthquakes and research by Coburn and Spence (2002).
	Reason for inclusion: Example of how existing damage scale (HAZUS) can be adapted for use in seismic loss estimation in a European country
Crowley et al. (2004) (H)	Damage scale: Descriptive with physical parameters
	Main application: For use As part of a European seismic loss estimation method
	Data set: Scale based on judgement and research from Priestly (1997) and Calvi (1999).
	Reason for inclusion: Example of damage scale developed for vulnerability studies in context of seismic loss estimation
Khudiera and Mohammadi (2006) (H)	Damage scale: Mainly descriptive but some reference to physical building (elastic) response and general post-earthquake actions
	Main application: Scale used as part of a seismic loss estimation study in USA
	Data set: Based on a seismic loss estimation study of New Madrid seismic area of USA in 1985
	Reason for inclusion: Example of damage scale for unreinforced masonry building type
Lang and Bachmann (2004) (H)	Damage scale: Mainly descriptive but some reference to physical building response
	Main application: EMS-based hybrid scale used as part of a seismic loss estimation study in Europe
	Data set: Scale based on EMS-98 and judgement of capacity curves with respect to Swiss residential buildings.
	Reason for inclusion: Example of how existing damage scale (EMS) can be adapted for use in seismic loss estimation in Europe.
Roca et al. (2006) (H)	Damage scale: Description based on MSK, but cost ratios also used
	Main application: EMS-based hybrid scale used as part of a seismic loss estimation study in Europe
	Data set: Scale based on MSK damage states. The MSK scake is not inconsistent with EMS-98 but lacks clarity Grünthal (1998). Cost ratios are ‘rough averages’ of several other unspecified sets.
	Reason for inclusion: Example of how existing Intensity damage scale can be adapted for use in seismic loss estimation in Europe
GNDT (2007)	Damage scale: Mainly descriptive and graphical, but some reference to physical building response
	Main application: Italian post-earthquake survey form
	Data set: Scale based on existing Italian building types and construction practice
	Reason for inclusion: Example of highly detailed damage descriptions relevant to European building types

Appendix B: Damage scale scores (before weighting)

Table 12 Individual scores for reinforced concrete frame damage scales with masonry infill (before weighting)

Category Scale	1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4
HAZUS (FEMA 1999)	3	3	3	3	3	1	3	3	1	3	3	1	0	0	0	0	3	3	3	1
EMS-98 (Grünthal 1998)	3	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEMA 356 (FEMA 2000)	3	3	3	3	3	1	3	3	1	1	1	0	1	1	0	1	0	0	0	0
Vision 2000 (SEAOC 1995)	3	3	3	3	3	1	3	3	1	1	1	0	0	0	0	0	0	0	0	0
Blong (2003b)	3	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	3	3	1	0
Rossetto and Elnashai (2003)	3	3	3	3	3	3	3	3	3	3	3	3	0	0	0	0	0	0	0	0
Okada and Takai (2000)	3	1	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Milutinovic and Trendafiloski (2003) (H)	1	1	1	1	1	1	3	3	3	3	3	3	1	1	0	1	3	3	1	1
Bommer et al. (2002) (H)	1	1	1	1	1	1	1	3	3	3	3	3	0	0	0	0	3	3	0	1
Crowley et al. (2004) (H)	3	1	3	3	3	3	0	0	3	1	3	3	1	0	0	1	0	0	0	0
Akkar et al. (2005) (H)	1	3	3	3	3	1	0	1	3	1	1	1	0	0	0	0	0	0	0	0
Roca et al. (2006) (H)	1	1	3	3	3	3	0	0	0	0	0	0	0	0	0	0	3	3	0	1
GNDT	3	3	3	3	3	3	0	0	0	0	0	0	1	1	0	3	0	0	0	0

H = Hybrid

Table 13 Individual scores for masonry damage scales (before weighting)

Category Scale	1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4
HAZUS (FEMA 1999)	3	3	3	3	3	1	3	3	1	3	3	0	0	0	0	0	3	3	3	1
EMS-98 (Grünthal 1998)	3	1	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEMA 356 (FEMA 2000)	3	3	3	3	3	1	3	3	1	1	1	0	1	1	0	1	0	0	0	0
Vision 2000 (SEAOC 1995)	3	3	3	3	3	1	3	3	1	1	1	0	0	0	0	0	0	0	0	0
Blong (2003b)	3	1	3	3	3	3	0	0	0	0	0	0	0	0	0	0	3	3	1	0
Okada and Takai (2000)	3	1	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Milutinovic and Trendafiloski (2003) (H)	1	1	1	1	1	1	3	3	3	3	3	3	1	1	0	1	3	3	1	1
Bommer et al. (2002) (H)	1	1	1	1	1	1	1	3	3	3	3	3	0	0	0	0	3	3	0	1
Lang and Bachmann (2004) (H)	3	1	3	3	3	3	1	3	1	0	0	3	0	0	0	0	0	0	0	0
Khudiera and Mohammadi (2006) (H)	3	3	3	3	3	1	1	3	1	0	0	0	3	0	0	1	0	0	0	0
Roca et al. (2006) (H)	1	1	3	3	3	3	0	0	0	0	0	0	0	0	0	0	3	3	0	1
GNDT	3	3	3	3	3	3	0	0	0	0	0	0	1	1	0	3	0	0	0	0

H = Hybrid

Table 14 Scores for RC damage scales including weighting

RC scale	Subcategory totals (before weighting)				Final scores using the different weighting scenarios						
	1	2	3	4	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G
HAZUS (FEMA 1999)	16	14	0	10	45	51.3	48.7	50	40	49	42
EMS-98 (Grünthal 1998)	18	0	0	0	18	36	12	12	12	18	45
FEMA 356 (FEMA 2000)	16	9	3	0	29.5	41	31.7	19.7	22.7	28.5	18
Vision 2000 (SEAOC 1995)	16	9	0	0	25	38	28.7	16.7	16.7	24.5	15
Blong (2003b)	18	0	0	7	28.5	43	19	33	26	29	45
Rossetto and Elnashai (2003)	18	18	0	0	36	48	48	24	24	36	90
Okada and Takai (2000)	14	0	0	0	14	28	9.33	9.33	9.33	13	13
Milutinovic and Trendafiloski (2003) (H)	6	18	3	8	40.5	35	51	43	38	40	64
Bommer et al. (2002) (H)	6	16	0	7	32.5	29.7	43	35.7	28.7	33	53
Crowley et al. (2004) (H)	16	10	2	0	29	40.7	32.7	19.3	21.3	27	62
Akkar et al. (2005) (H)	14	7	0	0	21	32.7	23.3	14	14	19.5	19
Roca et al. (2006) (H)	14	0	0	7	24.5	35	16.3	30.3	23.3	20	17
GNDT	18	0	5	0	25.5	41	17	17	22	24	22

H = Hybrid

Table 15 Scores for URM damage scales including weighting

URM Scale	Subcategory totals (before weighting)				Final scores using the different weighting scenarios						
	1	2	3	4	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F	Scenario G
HAZUS (FEMA 1999)	16	13	0	10	44	50.7	46.7	49.3	39.3	48.5	29
EMS-98 (Grünthal 1998)	16	0	0	0	16	32	10.7	10.7	10.7	14	39
FEMA 356 (FEMA 2000)	16	9	3	0	29.5	41	31.7	19.7	22.7	28.5	18
Vision 2000 (SEAOC 1995)	16	9	0	0	25	38	28.7	16.7	16.7	24.5	15
Blong (2003b)	16	0	0	7	26.5	39	17.7	31.7	24.7	25	16
Okada and Takai (2000)	14	0	0	0	14	28	9.33	9.33	9.33	13	13
Milutinovic and Trendafiloski (2003) (H)	6	18	3	8	40.5	35	51	43	38	40	64
Bommer et al. (2002) (H)	6	16	0	7	32.5	29.7	43	35.7	28.7	33	53
Lang and Bachmann (2004) (H)	16	8	0	0	24	37.3	26.7	16	16	18	54
Khudiera and Mohammadi (2006) (H)	16	5	4	0	27	39.3	24.7	18	22	23.5	20
Roca et al. (2006) (H)	14	0	0	7	24.5	35	16.3	30.3	23.3	20	17
GNDT	18	0	5	0	25.5	41	17	17	22	24	22

H = Hybrid

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