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DO EXISTING DAMAGE SCALES MEET THE NEEDS OF SEISMIC LOSS ESTIMATION?

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ABSTRACT :

A seismic loss estimation model for direct financial losses requires three primary components: probable ground motions, damage to representative building types, and subsequent cost of damage. An effective damage scale that allows the components to be tied together is also essential. This is because a damage scale is used initially to define a level of damage caused by seismic ground motions, and subsequently to relate that damage level to cost. Several different damage scales are used in European seismic loss estimation modeling within the insurance industry, but do existing damage scales meet loss estimation needs? This paper explores the current usage of damage scales in European seismic loss estimation and presents a scoring method for assessing their suitability for this purpose. The scoring system both provides a rational and unbiased method for ranking damage scales but also highlights their weaknesses, providing a means for suggesting improvements to the current state-of-the art in earthquake loss estimation. It is concluded that no existing damage scale meets all the criteria for effective use in seismic loss modeling in a European context, and there is a need to improve links between damage, repair and direct financial losses in damage scales.

KEYWORDS: Damage scale, seismic loss estimation, Europe

1. INTRODUCTION

A damage scale is a tool used in vulnerability (fragility) assessment for differentiating between distinct levels of structural damage. Where vulnerability curves or damage probability matrices are used in seismic loss estimation, the predicted frequency of occurrence of different levels of structural damage are converted to an estimate for financial loss by relating the damage scale used to an equivalent cost value. Therefore, damage scales and their definition are of great importance in the seismic loss estimation process. A very large number of damage scales exist in the earthquake engineering literature, but there is currently no guidance provided as to which damage scales to use for the purpose of seismic loss estimation.

This paper describes a piece of research that considered a variety of damage scales that have been, or could be, used in loss estimation studies, with particular emphasis on Europe. The first step of the study was to identify a set of important characteristics that a damage scale must possess in order to be used in loss estimation. On the basis of these characteristics, a scoring system was developed that can be used to compare damage scales, and provide guidance for their choice in loss estimation applications.

2. IMPORTANT CHARACTERISTICS OF DAMAGE SCALES IN LOSS ESTIMATION

Damage scales are used for a variety of purposes, for example rapid post-earthquake damage assessment or in the rehabilitation of structures, but few have been developed explicitly for seismic loss estimation. A notable exception is for the United States' Federal Emergency Management Agency's HAZUS (FEMA 1999). Nevertheless, scales with varying objectives have been or might be considered for use in loss estimation studies. For example, the damage scale within the European Macroseismic Intensity Scale (EMS-98, Grunthal 1998, see Table 1), is often used by the reinsurance industry to calculate seismic losses, due to its implicit correlation with felt intensity and its consideration of damage in both masonry and reinforced concrete buildings. However, the main objective of this damage scale is assignment of Intensity values in post-earthquake scenarios and not for loss prediction before earthquakes have occurred. Nonetheless, could the damage scale still be adequate for the latter purpose? The only way to answer this question is to assess the damage scales in terms of which characteristics would enable it to effectively link hazard to damage and consequently to cost.

Table 1 The EMS-98 damage scale (label titles only)

Damage State	Damage Title
Grade 1	Negligible to slight damage
Grade 2	Moderate damage
Grade 3	Substantial to heavy damage
Grade 4	Very heavy damage
Grade 5	Destruction

2.1. Damage scale descriptions

All damage scales contain a damage description, some of which are very detailed such as that in the Italian GNDT (Gruppo Nazionale per la Difesa dai Terremoti) manual (Baggio et al 2008), some of which are more brief, for example in EMS-98 (see Table 1). Damage descriptions are of fundamental importance as they readily allow users to understand post-earthquake effects. It is preferable that each damage state has clearly defined damage and failure mechanism descriptions which should also be usable in post-earthquake situations. However, damage scale definitions using quantifiable parameters, either directly or indirectly related to cost, would provide a more robust manner in which to develop loss estimates and would be more in keeping with construction practice.

2.2. Assigning cost ratios to damage states

The cost ratio is the ratio of repair (recovery) cost to building replacement cost. In existing literature, cost ratios have sometimes also been termed damage ratios or damage factors, (e.g. Whitman et al 1975 and ATC 1985). Cost ratios allow damage to be converted to financial losses, and have the advantage that studies in past and future are comparable as only an absolute 'replacement' value is required to determine a final value. Cost ratios have been generally determined through either expert judgment or empirical post-earthquake studies of loss data. In seismic loss estimation studies a cost ratio is assigned to a specific damage level. A variety of cost ratio values within damage scales have been proposed. Whitman (1973) defines a damage scale with cost ratio equivalences based on damage cost data from the 1971 San Fernando earthquake, see Table 2. The ATC (1985) study adopts a damage scale with cost ratio values for use with a questionnaire where experts are asked to predict losses from earthquakes directly in terms of cost ratio, see Table 3. The HAZUS earthquake loss estimation methodology (FEMA 1999) also provides a predefined set of cost ratios for buildings to be used with its damage scale where more accurate information is unavailable. These values are "consistent with and in the range of the damage definitions and corresponding damage ratios presented in ATC-13" (FEMA 1999, page 15-11) and are given in Table 4. Bal et al (2008) use retrofitting data from 231 buildings damaged in the 1998 Ceyhan and 1999 Kocaeli earthquakes to derive cost ratios for use with the HAZUS damage scale in Turkey. As seen from Table 4, they differ significantly from the original values. This suggests the specificity of cost ratios to location. Other damage scales, for example those found in EMS-98 and MSK, do not provide predefined cost ratios. However, different authors have adopted these scales and assigned their own cost ratios. The EMS-98 or MSK Intensity scales are considered as theoretically equivalent (Grünthal 1998) and this is therefore assumed for their damage scales. Similarities between cost ratio values for the same damage level can be observed from Table 5, although the precise reasons for these differences are difficult to ascertain.

Table 2 The Whitman (1973) cost ratios

Whitman (1973) extended cost ratios			Whitman (1973) shortened cost ratios	
Damage State	Cost Ratio Range (% replacement value), referred to as damage ratio	Central Cost Ratio	Damage State	Central Cost Ratio
0	0-0.05	0	None	0
1	0.05-0.3	0.1	Light	0.3
2	0.3-1.25	0.5		
3	1.25-3.5	2	Moderate	5
4	3.5-7.5	5		
5	7.5-20	10		
6	20-65	30	Heavy	30
7	65-100	100	Total	100
8		100	Collapse	100

Table 3 The ATC-13 (1985) cost ratios

Damage State	Cost Ratio Range (% replacement value), referred to as damage factor	Central Cost Ratio
1-None	0	0
2-Slight	0-1	0.5
3-Light	1-10	5
4-Moderate	10-30	20
5-Heavy	30-60	45
6-Major	60-100	80
7-Destroyed	100	100

Table 4 HAZUS and Bal et al (2008) cost ratios

Damage State	HAZUS Cost Ratio (% replacement value)	Bal et al (2008) Cost Ratio (% replacement value)
Slight	2	16
Moderate	10	33
Extensive	50	105
Complete	100	104

Table 5 Cost ratios used in studies with EMS-98 or MSK damage scales

EMS-98 or MSK Damage State	Study and country of application with cost ratio as % replacement value (ranges or central cost ratio indicated where defined)				
	Blong (2003), Australia	Timchenko (2002), Georgia	Roca et al (2006), Spain	Di Pasquale et al (2005), Italy	Mouroux (2004), (RISK-UE), Europe
1	1-5 (2)	2	1	1	2-5
2	5-20 (10)	10	20	10	10-20
3	20-60 (40)	30	40	35	50
4	60-90 (75)	80	80	75	100
5	90-100 (100)	100	100	100	100

2.3. Assigning physical parameters and repair methods to damage states

In order to develop loss models with greater engineering precision, and/or where cost ratio is derived from structural assessments, it is important to consider quantifiable parameters which are directly or indirectly related to cost ratio. Firstly, to facilitate use of analytical studies a damage scale should be associated with thresholds of a measurable physical engineering parameter capable of representing both global and local failure mechanisms. The thresholds should preferably be derived from statistically valid experimental or observational studies and should allow the user to interpret results from advanced numerical simulations. This is done only very rarely, but a good example of this is the HRC damage scale proposed by Rossetto and Elnashai (2003), where damage states in reinforced concrete buildings are related to the response parameter of inter-storey drift using experimental observations. Secondly, for each damage level, typical repair techniques for a particular building type should also be defined, preferably with quantities indicated. This will allow cost ratios based on construction prices to be more readily developed. An example of where cost estimates have been derived using physical parameters is in the normalized empirical equations for Greek reinforced concrete structures with masonry infill given in the study by Kappos et al (2006).

2.4. Summary of important characteristics of damage scales for seismic loss estimation

In summary, important characteristics for a damage scale for use in seismic loss estimation include well-defined damage descriptions, physical parameters relating observed damage to structural response, repairs and cost ratios according to the building type being investigated. They should also be defined in a reliable and consistent manner. Consequently, Hill and Rossetto (2008a) have developed a scoring system, providing a rational and unbiased method for ranking damage scales which might be used for loss estimation to identify weaknesses and a means for suggesting improvements to them. This method is described in the following section.

3. SCORING SYSTEM

The Hill and Rossetto (2008a) finalized characteristics and scoring system for use in evaluating the adequacy of different damage scales for use in seismic loss estimation are given in Table 6. The scoring system contains the four main characteristics previously described, divided into twenty subcategories. In each subcategory a positive response is given 3 points in order to clearly differentiate scales' performances. Where a category requirement is fulfilled to an extent then a score of 1 point is given, whilst zero points are given for a negative response. As the scoring system has been developed for ranking damage scales for European seismic loss estimation, it contains subcategories on relevance to European construction practice. By assigning scores through a consistent set of criteria and by defining what constitutes a 'significant' judgment, it is the author's opinion that much of the subjectivity is removed. Nevertheless, scoring results are only used as a qualitative indication of performance for comparing scales.

Table 6 Hill and Rossetto (2008a) scoring system for damage scales for European seismic loss estimation

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 modeling 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
Definition of 'significant' in judgment of quantity in parameter, repair and cost categories			
Judgment of quality and quantity for damage		Definition	Score
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

4. RANKING OF DAMAGE SCALES FOR EUROPEAN SEISMIC LOSS ESTIMATION

The scoring system was applied to 13 damage scales for reinforced concrete buildings with masonry infill, 12 damage scales for reinforced concrete frames, 10 scales for reinforced concrete shear wall buildings and 12 scales for unreinforced masonry building types. This is because reinforced concrete and masonry buildings constitute the greatest proportion of buildings in seismic-prone Europe. Furthermore, as specialists in loss estimation may place different weightings on the scoring categories in accordance to their particular needs, a sensitivity analysis was carried-out using seven different scenarios to evaluate the influence of category weighting on the final scores, with a maximum score of 72 points in each case. Weighting scenarios are given in Table 7 whilst rankings for a subset of 6 selected damage scales for reinforced concrete buildings with masonry infill are given in Table 8. The full detailed scores for each scale assessed can be found in Hill and Rossetto (2008a).

Table 7 Weighting scenarios

Weighting scenario	Definition
A	Equal weighting for each category and sub-category
B	Damage description to have 50% of total weighting
C	Parameter to have 50% of total weighting
D	50% of total weighting for cost section
E	33.3% of weighting for cost and 33.3% for repair sections
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)
G	Sub-category values multiplied by European relevance values (1.6, 2.6, 3.4, 4.4)

Table 8 Rankings of selected damage scales for reinforced concrete buildings with masonry infill

Damage scale	Ranking position by weighting scenario						
	A	B	C	D	E	F	G
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
RISK-UE: Milutinovic and Trendafiloski (2003)	2	9	1	2	2	2	2
Rossetto and Elnashai (2003)	3	2	3	6	5	3	1
GNDT (2008)	8	4	10	9	8	9	4

5. DISCUSSION ON DAMAGE SCALES FOR LOSS ESTIMATION AND COST RATIOS

Overall it was found that the HAZUS (FEMA 1999) damage scale includes most of the characteristics required of an effective damage scale for loss estimation, as it scored between 39 and 51 points in most weighting scenarios. This should not be surprising as it is also the only damage scale specifically derived for use in seismic loss estimation. However, HAZUS is limited in its application to loss estimation in a European scenario as it is calibrated (in terms of response parameter and cost) with data deriving solely from the US. This is evidenced by the difference in cost ratios for US and Turkey reported in Table 4. The European RISK-UE damage scale (Milutinovic and Trendafiloski 2003), which is developed using HAZUS as a model, also performs well in most categories. However, the damage scale lacks detail in respect to its damage descriptions and presents insufficient cost data to justify use of the cost ratios presented. At the other end of the ranking the presence of EMS-98 Intensity damage scale is notable. This is attributed mainly to its lack of a detailed damage description in addition to not having any of the other three characteristics shown in Table 6. Scales with better damage descriptions and some of the other required characteristics are seen to perform better, for example, Rossetto and Elnashai (2003) and Baggio et al (2008).

In general, a weakness identified in most damage scales is the lack of a link made between damage level, repair and cost. In the literature a general lack of research into the evaluation of cost ratios and their relationship with repair methods and damage is evident. Naturally, traditional seismic risk assessment research has focused on seismological or vulnerability aspects; an example of the latter is Spence et al (2003). Little or no original research into developing country or region-specific cost ratios is carried out, except in the USA (e.g. Whitman 1973; FEMA 1999). Judgment is often used to assign cost ratio values, and in many recent loss estimation studies the HAZUS cost ratios (FEMA 1999) are adopted directly even in countries outside the remit of their calibration (e.g.the loss model for Turkey developed by Bommer et al, 2002). A recent European cost ratio study (Bal et al 2008) also provides evidence to undermine the current use of HAZUS ratios outside the USA without further justification. The authors believe that original research into the evaluation of cost ratios in different countries and their relationship with damage will lead to significant new insight for use in seismic loss estimation studies.

6. CONCLUSION

It is argued that within a damage scale, damage states should be described in terms of visual damage, physical parameters, appropriate repair methods, and cost ratios, in order for the scales to be used in a seismic loss assessment. The paper highlights a ranking method developed by Hill and Rossetto (2008a) for identifying weaknesses in damage scales for use in seismic loss estimation in Europe. In general the scales investigated lack many of the characteristics identified. Overall, the ranking indicates that the HAZUS (FEMA 1999) damage scale has more of the required characteristics, although the RISK-UE damage scale (Milutinovic and Trendafiloski 2003) would be better in a European context. The EMS-98 damage scale (Grünthal, 1998) does not perform well since its definitions are based solely on brief damage descriptions. However, the EMS-98 damage scales are widely used in seismic loss estimation practice despite the fact the inability to incorporate comprehensive definitions for most identified characteristics provides a long-term impediment to more precise seismic loss estimation. The paper also illustrates why definition of cost ratios themselves should not be overlooked in the seismic loss estimation process and consequently why their impact on final loss estimates should not be underestimated. It is recommended that loss estimation studies give greater consideration to the damage scale used and give appropriate justification for any accompanying cost ratios. Additionally it is recommended that more research is conducted into the relationship between damage, repair and cost ratios, for example Hill and Rossetto (2008b,c).

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