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A Conceptual Model for Multi-Hazard Assessment of the Vulnerability of Historic Buildings

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ABSTRACT: It is difficult to predict the vulnerability of historic buildings in relation to destructive natural events due to their structural complexities and the condition of the built materials. Physical damage to such buildings not only causes material loss but also results in loss of cultural significance. This paper presents a methodology, MHAV(historic buildings), to assess the effects of earthquakes, windstorms, floods and lightening. The model adopted a 3 tiered assessment approach: Tier 1 involves the hazard screening of the highlighted natural perils to identify the relative damageability of a given historic building; tier 2 takes those hazards that exceed a given threshold, and through a process of building disassembly, the expected losses under a given disaster are predicted. Tier 3 is reserved for an analytical study of highlighted elements which warrant a more in-depth evaluation of the potential damage state. It is considered that this model is robust and simple in its operation and provides a cost-effective means of evaluating the vulnerability of historic buildings to natural disasters. The results derived from the model can enable intervention priorities and mitigation strategies to be developed. An English parish churches is used to demonstrate the application of key sections of the model.

1 INTRODUCTION

Due to complexities and uncertainties relating to construction materials, craftsmanship and level of deterioration, it is difficult to predict the vulnerability of a historic building in relation to destructive natural events. Previous studies have focused on deriving knowledge on damageability by analysis of post-hazard damage survey data or claimed insurance loss data. There are no known models available to assess a historic building comprehensively under various possible natural disasters.

Nations around the world have lost and continue to loose considerable qualities of unique historic fabric due to natural disasters. Recent examples include the substantial heritage losses caused by the Gujarati earthquake of 2001in India and the Bam , Iran earthquake of 2003, the floods of Prague, the continuous threats of the "acqua alta" in Venice, the heritage losses caused by the Hurricane Katerina in New Orleans in 2005, etc. Unlike modern buildings, such losses cannot be replaced by insurance payouts. They are essentially irreplaceable national artefacts which are lost forever.

While life safety should always be viewed as the principle objective when assessing the hazard resilience of buildings, it can be argued that the loss of heritage value takes equal importance when assessing historic buildings and that a specific assessment tool is needed to conduct such assessments.

In this study a methodology to assess the effect of earthquakes, windstorms, floods and lightning is presented. The model adopts a 'three tier' approach. In the 'first tier' an initial screening takes place to identify the main hazards. These are ranked using 'chief contributor gradings' and 'linear weighting combinations'. The perils whose potential loss exceeds a defined threshold are taken to the 'second tier' where element losses are predicted. 'Tier two' is a direct estimation of expected losses under a given disaster. The examined building is first disassembled into subdivisions and 'loss sensitive elements' are identified. By comparing with a prototype building whose elements' damageability is known, the damage of each element can be predicted. At this stage the loss for the whole building is compiled as a summation of the single components, subdivisions and macro elements. Monetary loss and significance loss are computed separately. For the significance loss, the restorability of a damaged element is dependent on the availability of original material, craftsmanship and original details, besides the cultural approach to restoration and the need to follow specific guidelines.

When the loss of some unique elements in the examined building cannot be judged in 'tier two', the 'third tier', approach is pursued. Here an analytical study is undertaken to determine the damage states and probabilistic distributions for the highlighted elements.

It is considered that this model is robust and simple in its operation and provides a cost-effective means of evaluating the vulnerability of historic buildings to natural disasters. The results derived from the model can enable intervention priorities and mitigation strategies to be developed.

The model is to be referred to as MHAV (historic buildings). [Multi-Hazard Assessment of Vulnerability (applied to historic buildings)] An example application is proposed to highlight the essential steps in the methodology later in this paper. But first a review of literature is presented.

2 BUILDING DAMAGE RISK ASSESSMENT METHODOLOGIES

Existing literature on multi-hazard risk assessment is notably very sparse, especially in direct reference to historic buildings. There are two established assessment methodologies for existing building stock. An interesting system has been developed by the National Hazards Center in Australia (NHC) (2000a) to evaluate potential risks in a region under all kinds of natural perils. The parameter adopted is the historic occurrence of property insurance claims following natural hazard's events. In this way comparable vulnerability indices for each hazard can be obtained and the hazards ranked, while a combination of the indices forms the comprehensive vulnerability index of a postcode region. This type of approach however, does not provide any information on the intrinsic vulnerability of the building stock, due to its constitution and structural quality.

The HAZUS 99 (FEMA, 1999) system is a very comprehensive procedure developed for the United States, based on a standardized methodology and software program for estimating potential losses from earthquakes, floods, and wind. Currently the capability is for earthquake loss estimates, while the wind and flood models are under development. In order to define the exposure and vulnerability of a built up area, buildings are grouped into 36 model building types and 28 occupancy classes and degrees of damage are computed for groups of buildings. Typical structural types are identified and further subdivided depending on the number of stories and age to define classes of vulnerability. Finally occupancy classes are used to define the number of casualty in an event. The HAZUS 99 procedure is organized in three tiers depending on the available data input and purpose of the exercise. The lowest tier uses default data stored in the procedure database and delivers loss estimation at regional level. The highest tier can be tailored for a given damage and loss model for specific building classes not included in the classification, delivering probability distribution of damage .

To some extents, earthquakes and winds have similar effects on building structures. Chandler (2001) is the first to propose a loss-estimation model which adopts uniform intensity parameters and damage index criteria for the two hazards. The damage index is associated directly with percentage of replacement value, while the intensity parameter is a measure of the power of damage of the event. Based on vulnerability curves for specific building types, mean damage ratio are computed for given hazard intensity.

While such approaches are suitable to a 'first tier' risk assessment, they do not respond to the need of heritage building asset management.

The following literature review aims at establishing the current state of the art on the various aspect of a multi hazard risk assessment system for heritage buildings, namely:

- Ranking of the relevance of a specific hazard in a specific location
- Definition of physical vulnerability in relation to different hazards for specific historic building typologies

- Methods to define significance and heritage value of a historic building and quantification of significance losses.

2.1 Hazard relevance and prioritization

The relevance of hazards is usually carried out at regional or urban level in order to define preparedness and mitigation policies. The typical parameters considered are the magnitude of the event, surface area impacted and recurrence. The local topographic and soil conditions also have substantial influence on amplification or reduction of the effects of the hazard on the built environment. On the basis of this information scenarios may be produced for each hazard, possibly using a GIS support, mapping the parameter/s that represent/s the strength of impact on the vulnerable facility analysed. These types of application for earthquakes, hurricane or flood are fairly common nowadays, and the accuracy of the prediction depends largely on the amount of base data available for a given geographic location and the level of resolution required. (King, et al, 1996). Flood hazard, for example, is usually evaluated with an annual probability of exceedance in terms of flood height levels (CIRIA, 2004). Also, geographical-based simulation (GIS, or flood plain zonation), probabilistic modeling; and empirical evaluation are commonly used to predict flood hazards (Fan & Matalas, 1996).

For windstorms, wind intensity may be measured using the Beaufort Scale (which was first used by British Royal Navy in 1838) or the Saffir-Simpon Damage Scale(NHRC, 2004). The normally adopted measurement parameter for basic wind speed in most construction codes is the hourly mean wind speed at 10 meters above ground with an annual risk of being exceeded of 0.02 (BS 6339-2, 1997). Damage caused by wind is related to wind loading, which is calculated by considering the wind speed, topographical conditions and building height and size.

Lightning is an electrical discharge between clouds or between clouds and earth, consisting of one or more strokes. The process of an electrical discharge produces both mechanical force and great thermal energy. The lightning strikes at the highest point of an object and follows the way of least resistance to earth. Isoceraunic maps plot frequency of thunderstorm, measured in days/year, over a given region. From these the probability of a structure being stricken can be estimated, based on the shape of the structure, its materials, contents and setting (BRE, 1998).

Seismic hazard evaluation is also based on zonation and probabilistic modeling and the intensity of the action is measured either in terms of magnitude, macroseimsic intensity or peak ground acceleration. Standard seismic codes for common buildings might be concerned with a 1 in 500 years chance of an earthquake of a given magnitude striking a given region, while nuclear plants look at the 10,000 year time frame. The measuring parameters for engineering purposes are provided in terms of ground response spectrum.

Given their probabilistic and spatial nature, the simplest way of prioritising hazards in a region or with respect to a specific asset is to rank each hazard in accordance with its probability of causing damage. The 'FEMA model' considers 4 factors in rating hazards, namely history, vulnerability, maximum threat and probability. Each factor is evaluated as high, medium and low, and to the textual description are associated scores of 10, 5, and 1 respectively. The final score for a hazard is the summation of each factor's score multiplied by its weight. A common threshold point for all hazards is defined, beyond which mitigation measure should be considered. (Natural Disasters Organisation, 1992).

2.2 Vulnerability studies

In the following vulnerability studies and loss estimation procedures are reviewed for each separate hazard, from earthquake to flood, windstorm, lighting and fire. The aim is to identify procedures and applications that are suitable for historic buildings and are flexible enough to be interfaced for a multi hazard approach.

Earthquakes

Studies on historic building vulnerability are relatively few, due to the fact that historic buildings, by their own nature do not lend themselves to statistical treatment. However, in some cases such as for example historic churches, it has been observed that within an earthquake prone region there is substantial consistency of construction techniques and seismic performance over relatively large samples, hence general conclusions can be drawn in terms of defining a typology and its vulnerability. Work has been conducted with reference to historic churches in Italy by D'Ayala (1999, 2000), Lagomarsino (1998) and Lagomarsino and Podesta' (2004), all based on the macro-element method. It is difficult to express the collapse mechanism and damage state in a holistic and simple way, especially for a complex historic building. The macro-element method, first suggested by Doglioni et al. in 1994, derives from the observation that some elements or groups of elements in buildings of different layouts demonstrate specific damage mechanisms and corresponding levels of vulnerability, which remain consistent. These entities, which could be an assembly of components, such as a church tower, or just one element, such as a façade or side wall, are called macro-element. Augusti et al{2001} present a macro-element application to analyze the vulnerability of monumental buildings A logic diagram showing damage relations between macro-elements and the whole building was suggested. In this approach, the capacity of each macro-element damaged according to a suite of specific mechanisms is firstly calculated. Then with respect to given ground acceleration the cumulative probability distribution of collapse for each element is attained. By defining the logic relationship of elements, each damage state probability can finally be derived for the whole system.

In order to correlate the probability of occurrence of any collapse mechanism with level and proportion of damage Lagomarsino and Podesta (2004) suggested the use of vulnerability indicators, which can trigger or prevent the occurrence of a mechanism.. The total vulnerability of a church can be judged according to the total score of the indicators and the total damage state of the church can be computed as a weighted average of each macro element's damage factor. The repair and retrofitting cost are evaluated by considering, for each collapse mechanism, a specific intervention strategy with given unit cost, based on ministerial guidelines. Porter et al. (2001) proposed an assembly-based vulnerability approach (ABV), in which the structure is firstly divided into structural and non-structural components using standard taxonomy. The damage is deduced from the response parameters of each component and its fragility function. Repair cost and loss of function are also treated as probabilistic variables. Although the development of component fragility function and repair cost estimation for each damage state are time-consuming, it is a task worth undergoing if the building stock to be evaluated is sufficiently standardized.

Flood

Most historic buildings are immune to moderate floods because they were originally located away from known flood plains. For instance a very small proportion of London's building stock predating mid 19th century is at risk of flooding (Hutton & Marsh, 2004). However, sea levels rise and human exploitation of land may induce floods never or seldom occurred before (PPG 25, 2000). Neglect and deterioration also make historic buildings more vulnerable to flooding. Structural damage is caused by water-flow crushing, foundation scouring and subsidence. Flood can also cause kinetic pressure on structures when buildings are well sealed, or flood proceeds quickly, or in presence of water level differences (Kelman & Spence, 2004). In addition, water erosion, and debris action can also lead to substantial damage. For historic buildings a main concern relates to methods used in after-flood remedial work, like cleaning-up and drying-up (BRE, 1997; EH, 2004). Other factors influencing losses due to flood are warning time, location of contents, prevention strategies established and prior flood experience. Studies show that structures are rarely substantially damaged by floods, unless they are in a severe deteriorated condition (EH, 2004). Wooden structures and timber components are more vulnerable to flood and cause more insured losses than other structures or components. Surveys also reveal that foundation damage due to floods is relatively modest (Wordsworth, 2004; National Hazard research center, 2000). However, literature on systematic identification of potential failure mode is limited, and the process of defining vulnerability classes and fragility curves to be correlated with damage modes and state is still at a conceptual stage (Kelman & Spence, 2004).

A conceptual model suggested by Nicholas J. et al (2001) aims to standardize the flood damage assessment procedure and outcome for UK domestic property. Both building and flood characteristics are considered. The building characteristics include four main parameters: flood frequency of the building, construction material and technology, drying process of materials and prior condition of the building. The major limit of this system is the lack of consistent data. Flood damage loss is usually assessed through developing damage state curves (loss functions, or damage–depth curves) for different classes of buildings, where the loss is expressed in monetary terms against flood inundation depth. Building fabric and content loss curves can be separately established in relation to inundation depth and period (Kelman & Spence, 2004). For example, damage-depth curves for different land use categories and two durations (<12 h or >12 h) are developed by the Flood Hazard Research Centre (FHRC) in UK , FEMA in the USA and NHC in Australia. It is found that the flood models, based on over-floor water depth and flood damage cost, are positive non-linear relationships (Proverbs, 2000; Wordsworth, 2004). Currently 168 stage-damage curves for 21 house types, 4 social class divisions and 2 durations of flooding are available in UK (Smith, 1994). However these curves are region-based, and cannot be applied directly in other contexts.

In flood damage, element or component approaches have been proposed by Kelman and Spence (2003), who listed the possible damages to building elements, including windows, walls, doors, floors and foundations. While explicit data on component damage state is not readily available, damage mechanisms can possibly be judged on the basis of expertise. To this end, NHQ, (2000) has devised a procedure for identifying the main component loss or loss distribution on main construction elements, while collecting loss data for residential buildings. Details for flood damage remedial work is introduced by BRE (BRE, 1991; BRE, 1997). However EH (2004) has highlighted that codified remedial measures may actually harm or further damage architectural and historic features of heritage buildings.

Windstorm

Most wind damage to buildings come from breaching of the outer envelop by wind-borne debris (Minor, 2005) or falling trees. Usually this occurs through failure of roof or openings in walls, which are the most vulnerable element of the building envelope (Ellingwood et al, 2004), and results in substantial increase of internal pressure. Complete building failure will hence occur when the wind up-lift force exceeds the roof weight and roof-to-wall joint strength or wall to wall joint strength. Other non structural damage is caused by wind-borne rain, which can penetrate through damaged windows and roofs, causing interior spoiling and insured loss (Reinhold, 1996; Khanduri, 2003; Sparks, 1994). Post-hurricane investigations suggest that gable walls, projecting and outstanding parts of a building are also among the most vulnerable elements. Observations also conclude that wind can cause more damage to wooden structures than to masonry buildings (Nelson, 1991). Neglected buildings or houses lacking maintenance may suffer severe damage due to their pre-existed flaws or envelope breaches.

Most research on wind damage focuses on residential buildings. Fragility curves for residential buildings of given structural types have been developed by Ellingwood et al, (2004), correlating damage ratio with maximum wind speeds. Often these functions are based on statistic analysis of past insurance claim data, using post-disaster investigation findings or engineering judgment (Gunturi, 1996; Pinelli et al., 2004). Analysis of these relations shows that loss is a non-linear step function of wind speed. Specifically, a case study conducted by Sparks (1994) shows that the total loss of a building is constantly 2 times the direct wind mechanical damage in lower wind speeds (40-70 miles/second), but about 7 times once the 70miles/second threshold is overcome. This corresponds to the speed that may fail the external envelop of the building.

However, wind speed is not the only parameter affecting windstorm damage. An important role is also played by the duration and presence of rain, as far as the peril is concerned, and condition and preparedness, for the building. The use of claimed insurance losses to predict damage-wind speed relationships is froth with uncertainty. It is widely recognized that better insight on the vulnerability of a specific building is gained by considering the performance of single components. Kishor et al. (1981) firstly proposed a two-step approach for wind damage prediction in which first the damage mechanism of each component of the building is assessed by comparing the examined building features with a building of similar typology that experienced windstorms and whose behavior is known. The second step is to work out threshold wind speed for the failure mechanism of each component or its interface by wind-structure interaction analysis. At given wind speeds, the damage of the component can be determined, referring to the threshold. This component approach can predict the loss of a building in more detail, but requires substantial wind-structure and wind-component response models which might not be readily available. A similar but probabilistic damage analysis model is also suggested by Pinelli et al. (2004). By surveying the performance of each component of the building envelope, in post event reconnaissance studies, Reinhold 1996 established robust relations between component damage and wind speeds. Furthermore, laboratory experiments were conducted by Sparks, (1994) to test wind resistance capacity of some envelope components. In addition, Khanduri (2003) suggested a model to deduce or estimate loss functions for data inadequate regions by borrowing existing functions from data adequate regions. The function may be adjusted by local inventories and sampling results. This approach can also be used to derive damage functions for a specific building type when available functions are based on aggregate data for several building types.

Lightening and fire

Lightning causes direct damage to people and properties in three ways: mechanical actions (including electrical shocks and air pressure blast or explosion), fires and electrical damage (Wertz, 1996). The main mechanical damage includes explosions caused by current flows through flawed components, bending forces on the conductor and shock waves produced by return strokes. Lifting of tiles on roof is a common mechanical damage, whose consequence is severe as the envelope of a building is broken. Flying debris generated by strokes also pose threats to roofs and windows. For masonry buildings parapets, pinnacles, crosses and flashes are the most vulnerable elements, while shocks can weaken mortar joints and side flash may travel along mortar joints and flaws in the masonry fabric. Buildings with thatched or wooden roof are very vulnerable to lightning.

Lightening is the main source of nature induced fires. Vulnerability of a building is directly related to the fuel load (the potential quantity of combustible materials) of the building. Qualitative approaches to fire risk assessment are well established and are usually based on ranking systems (Watts, 2001). The multi-attribute evaluation method is widely used in the ranking process. Each risk attributing parameter is identified, scored and weighed. A final single index can be derived by linear combinations of all contributing factors. Robust methods have been developed and codified for new built, but applicability to historic buildings is limited (Kidd, 2001). Limited models have been developed specifically for historic buildings. Watts (2001) suggests an index model combining indices from existing codes modified in value by professional judgments to rank fire risk of historic buildings. Shields et. al (1991) established a management strategy to establish life safety equivalency for historic buildings. English Heritage (1999) has developed a similar assessment protocol for use by guardians of their historic properties. Copping (2002) adopted a Delphi process to score safety-contribution components for parish churches in England. This assessment tool focused on property and content protection and incorporated an evaluation of historic significance of the property.

2.3 Value and significance loss assessment

In conservation, it is important to understand the significance of a historic building. The term cultural significance can be used to mean all non-market values of a heritage site. ICOMOS‘ Burra Charter defined the significance of a cultural heritage site as: ‘aesthetic, historic, scientific, social or spiritual value for past, present and future generation’ (ICOMOS Australia, 1999). The social value can include spiritual, political and identity aspects. The economic value, an essential aspect of heritage and an important incentive for conservation activity, is not included in the definition above. Economic value may relate to use value, recreation value and other forms of interests that follow economic rules. The cultural value and economic value belongs to different spheres, using different benchmark criteria. Accordingly they cannot be simply inter-changed (GCI, 2002). Typically value assessment relies highly on expert’s judgment, and is therefore relatively easily manipulated by political or economic interests. Inclusive and extensive involvement of diverse stakeholders is seen as a mechanism to increase accountability and to provide early direction to conservation planning and implementation (GCI, 2002).

The most common method for quantification of economic heritage value, is the contingent valuation method (Carlson, 2002) first used in environmental policy assessment. The worth of intervening on a heritage site, is usually measured by the willingness to pay (WTP) of different stake holders. The method has a severe limitation as there is an intrinsic difficulty in reaching all potential end-user' classes in a given survey. It is also difficult to correctly quantify the share of the cost of maintaining or intervening on the asset for each class (Navrud, 2002).

A number of quantitative approaches have been devised for the assessment of cultural heritage of historic buildings. Social judgment theory has been used by Carrera (1997) to assess the restoration priority of statues in Venice. This approach uses different stakeholders to make judgments on different criteria i.e physical, artistic, social etc. A compound score method is used in an evaluation methodology devised by the City of Vancouver planning department. In this approach a historic building accumulates a score by being assessed under 4 criteria: architectural history, cultural history, context and integrity. The HIST, Historic Importance Software Tool, devised by the Public Building Service (PBS) in the USA, also adopts a compound score approach. It assigns a separate rating in accordance with their importance, to each element, zone and whole of the building. The 3 rating levels are then converted into a comprehensive rating index by introducing weighted parameters. The indices indicate the relative significance of a historic building and can be used for conservation and intervention policies development.

Most important in the context of this paper is the quantification, if at all possible, of the loss of significance or value, when an historic building is damaged by a natural event. As the significance and value of an historic building is imbedded in its fabric it can be argued that the loss of significance is closely correlated to the physical damage state. However, as not all elements have the same significance or damaging process, it does not always follow that the loss of heritage value is directly proportional to the physical damage value. In general, the loss or damage of a heritage structure of significance tends to be considered as unacceptable (Navrud, 2005), and hence measures of immediate recovery and long terms repairs and restorations are usually developed in the aftermath of a destructive natural event. However, as significance and cultural values are usually attributed to the original and historic fabric of the building, repairs strategies can contribute to heighten the losses rather than helping the recovery of value. Post-disaster intervention solutions are heavily influenced by the perception of cultural significance loss. For instance, in dealing with restoration, different cultures have different approaches. Eastern cultures emphasize the integrity and spirits embodied in the building (Chung, 2005) rather than its original fabric as advocated by the original subscribers of the Venice Charter. In some countries, reconstruction or restoration of a building to its most magnificent state is perceived as the aim of conservation (Gustschow, 1998).

3 A MULTI-HAZARD APPROACH

The major feature of the MHAV [historic Building] methodology proposed is the dissection of the historic building in two separate aspects of evaluation: vulnerability due to physical attributes and structural behaviour and vulnerability due to cultural attributes and significance potential loss (see fig. 1). The multi-hazard vulnerability assessment is based on the following assumptions:

- The cultural significance of a historic building is imbedded in its fabric and settings. Physical damage induced by seismic, flooding or other natural hazard will result in loss of significance. Post-event repair can minimize this loss by cash injection but the original cultural significance will be altered. Any intervention on the building can have positive or negative effects on its present significance.
- A historic building can be regarded as an integration of a common physical structure and heritage values. Physical damage caused by specific hazards can be obtained from historical data for common buildings, and the specific loss can then be incremented based on the inherent additional heritage significance of the building under assessment.
- While life safety is always the principle objective when assessing the vulnerability of a building, loss of heritage value should also be seen as a priority for assessment of historic

buildings and explicit performance criteria should be developed. The loss of value produced by damage should be balanced against the alteration of value induced by intervention.

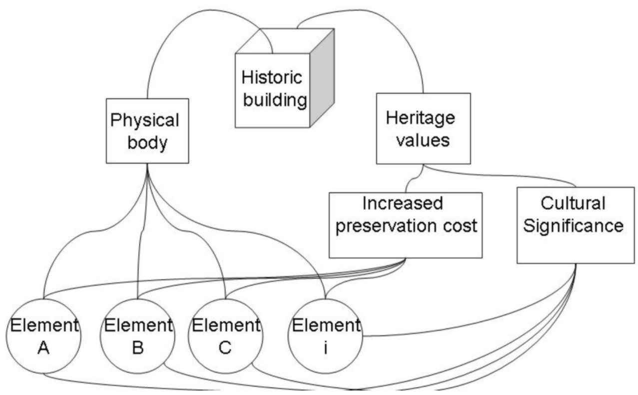

Figure 1: The concept of building disassembly in the MHAV [historic building] methodology

The assessment procedure is organised in a three tier approach:

- firstly the natural perils are ranked to define which one poses the greatest hazard. The ranking is carried out by indexing, and the perils for which the index is greater than a pre-assigned value, will be considered further in the evaluation procedure.
- The second tier relates directly to the vulnerability of the historic building under study. The building is subdivided into subcomponents and elements depending at which level data and models are available for the quantification of the vulnerability to a specific peril. Each subcomponent and elements also undergoes a significance valuation and evaluation of potential loss.
- The third tier relates to the specific structural analysis and in depth evaluation of the vulnerability and loss of significance of a specific building or component if data is not available.

In this paper the first two tiers will be described in detail with reference to a case study.

3.1 Tier 1: Hazard screening

In order to rank the relative potential damageability of a given building to different hazards it is not sufficient to simply consider the expected magnitude of each event at its location over a given period. A measure of the effects of each peril on the building should be considered so as to be commensurate to the effect of other perils. As information on damage to a specific building by different events might not be readily available, the evaluation is based on the following assumptions:

- A common building typology in the region is chosen for which loss data for different perils is readily available. It can be assumed that in general, the historic building under consideration will be built to better construction and material standards than ordinary buildings of the same period.
- A common measure of peril effect in terms of physical damage should be adopted, and this can be the monetary loss, as obtained through insurance claims.
- The basic effect parameter is modified by considering a number of attributes which are recognized to alter the effect of a peril on a given building. The various attributes are weighed to reflect the different relevance that they might have on the expected loss.

Under these assumptions the hazard ranking index illustrated in Fig. 2 is a holistic score obtained by using standard multi-attribute evaluation method, i.e. using a linear additive weighted measure of the type:

$$I_h(x_1, x_2, ..., x_n) = \sum_{i=1}^{n} (w_i R(x_i)) \quad (1)$$

where $I_h(..)$ is the ranking index for each hazard, w_i are the constant weights for each contributing factor, and $R(x_i)$ are normalized functions of the contributing attribute. In the present application the weight w_i is normalized with respect to the sum of the weights $\sum_1^n w_i$, and the normalized functions R are expressed as:

$$R(x_i) = \frac{L_j F_i}{3} \quad (2)$$

where Lj is the normalized loss of a conventional house in the region with reference to peril j and F_i is a numerical score for the contributing attribute i. The score ranges from 1 to 5 and the benchmark value, i.e the attribute as relating to the ordinary building, has a value of 3 (median in the range). Then, for the historic building each attribute can be assigned a value greater or smaller than 3 depending on whether it is perceived by the assessor to increase or decrease the risk of damage. These attributes should be independent and they have been chosen to represent parameters that have influence in the loss for all hazards considered. These are: specific hazards at the site, terrain conditions, materials used, fabric condition, significance or restoration cost of value-rich components, performance in past events.

In the definition of the weights the FEMA methodology (National Disaster Organization, 1992.) has been applied. However, for more general validity a Delphi process by submission to a panel of expert should be considered. As the attributes might be specific to a building type the list provided above is not exhaustive and accordingly the weights are not normalized to a score of 100 but they are simply compared in couples and scored relatively to each other.

Name of building: *Bathampton church* Registration number: 001

Location: *Bathampton, Bath, England*

Construction date: *1750 AD* Loss adjustment factor C =1.2

Importance factor $K_1 = 3$ Size factor $K_2 = A_h/A_o$ =3.5

Natural hazards / parameters	Earthquake	Flood	Wind storm	Lightning	Weight of parameter
Hazard risk index for residential buildings L_h	L_e	L_f	L_w	L_l	
	16	8	2	1	
F_1 Area risk (1—5)	2	5	4	3	10
F_2 Structure and material (1—5)	4	2	2	2	5
F_3 Setting (terrain) condition (1—5)	3	5	4	4	5
F_4 Maintenance condition (1—5)	3	3	4	4	3
F_5 Significance rich components (1—5)	4	4	4	3	2
F6 Historic records (1—5)	3	5	3	3	5
$I_h = L_h * (\sum_{i=1}^{6} FiWi)/(3\sum_{i=1}^{6} Wi)$	15.5	11.3	2.3	0.97	
Priority Index $I_p = C*K_1*K_2*I_h$	130	94.8	19.6	8.1	
Hazard risk ranking	1	2	3	4	

Figure 2 : MHAV [historic building] Tier 1 hazard ranking form.

Furthermore some building specific coefficients are also included to take into account differences between individual historic buildings. Although these factors are not hazard specific and hence do not change the ranking of hazards for a given building, they modify the final priority value and hence can help in considering priority of assessment when sets of buildings are considered. These coefficients are:

- A vulnerability typology coefficient C which takes into account the increased or reduced know vulnerability of a typology with respect to the reference residential building
- An importance coefficient relating to the listing K_1 calculated on the basis of a non linear scale ranging from 1, for ordinary building, to 5 for buildings of international status (World heritage site or other listing system); and
- A size factor K_2 calculated as the ratio between the plan area of the historic building being assessed and the average plan area of the reference building as obtained from insurance data.

Finally a threshold of 100 is defined and the perils totaling a score greater than such threshold should be considered for tier 2 assessment. The Tier 1 hazard ranking form is shown in Fig. 2. Values are calculated for a grade II* listed parish church in the South-west of England. Earthquake and flood are considered as perils in the next tier.

3.2 Tier 2: Historic building disassembly and vulnerability measure

Based on the preliminary assessment in Tier 1, for the hazards with priority index I_p exceeding the threshold value, the vulnerability of the building is further evaluated to identify specific vulnerable and value rich elements and to provide more reliable data for decisions on preventative measures.

As explained at the beginning of this section, the vulnerability assessment procedure devised here is based on two axioms. The first is that the historic building vulnerability is affected by loss of significance and increased restoration cost and that these two parameters are not necessarily inversely proportional, hence they should be considered separately. There is also an added heritage value associated to the integrity of the building in its original and authentic state, i.e. its survival as a whole, in the event of exposure to a hazard, without the need of post event restoration.

The second axiom relates to the possibility of measuring the mechanical behaviour and hence the physical vulnerability of an historic building, by using concepts and procedures well established for ordinary buildings; specifically the correlation between loss and hazard intensity, as it has been developed by the insurance industry for other buildings categories.

These axioms allow each heritage building to be assigned to a class for which a prototype building can be considered. For instance it can be assumed that most parish churches built with traditional materials, are likely to have similar plan layouts, constructions techniques, distribution of structural elements and architectural elements, so that the mechanical vulnerability associated with a particular hazard can be studied with reference to the prototype building rather than in relation to the specific building. For the prototype building, the vulnerable elements for each hazard can be identified and the level of damage, associated to a given hazard magnitude quantified and localized. Then the actual loss can be calculated specifically with reference to the embedded heritage value of the damaged elements. These are enriched by significance due to their intrinsic value or proximity or being a support to non structural elements of value.

Hence it can be concluded that the loss incurred by a historic building exposed to a given hazard can be calculated as:

$$\textit{Physical body Loss (PbL)} + \textit{Value Loss (VL)} \tag{3}$$

where *PbL* can be described in the form of damage states and damage modes, and *VL* can be described in terms of significance loss (*SL*) and restoration cost increment (*RI*).

Once the building is divided into physical attributes and value attributes, then it can be assumed that the structural behaviour will depend only on the physical attributes and will be comparable to some generic model of that building typology. In other words a prototype can be defined. The prototype building (PB) will have all the main inherent features of the typology, including configuration, structural system, construction materials and typical connections. It is assumed to be located in a site representative of the morphology and geography of the region. It is also assumed to be in good average conditions and subjected to regular maintenance. As responses to hazards for historic buildings vary considerably and it is not well documented, it would be extremely difficult to establish a reliable model with "best behaviour" with direct correlations to specific characteristics. For this reason, the prototype will be an idealized model of the given typology with average construction characteristics as can be deduced from literature or other databanks. Its performance with respect to hazards, in this first stage of development of the procedure, will also be obtained mainly from literature.

Moreover, given the authenticity and uniqueness of each historic building, it is also assumed that the physical part of the historic building will differ in some substantial component from the prototype building. Hence, the relationship between the physical body of the historic building and prototype building can be defined as follows:

$$Pb(HB) = Pb(PB) \pm \textit{Unique features } (Uf) \tag{4}$$

where the unique feature are either elements or components.

Table 1 : Global vulnerability indicators

Indicator	Parameter	Ranking criteria	Scoring	Reference
Soil type	Type of soil, geologic location	• hard or average rock;	1	FEMA-154
		• dense or stiff soil;	0	
		• soft or poor soil;	-1	
Structure robustness	Base shear ratio in two coordinate directions;	• 1.5<x or y<2.8	1	Lourenco (2005)
		• 1.25<x or y <1.5;	0	
		• 1<x or y<1.25;	-1	
Structural materials	Quality and size of Stones used in construction;	• Good ashlars stone	1	EMS-98
		• Roughly cut stone;	0	
		• Rubble stone or field stone;	-1	
Quality of construction	Mortar used and joints;	• Mortar quality and joints good;	1	(Steimen 2004)
		• Mortar quality and joints medium;	0	
		• Mortar quality and joints are poor	-1	
Preservation condition	Structural flaws and alteration; Material deterioration;	• Renovated or properly retrofitted ;	1	(Steiman 2004)
		• No cracks or other deterioration ;	0	
		• Deteriorated structural components;	-1	
Earthquake secondary hazards	Occurrence of fires, land ruptures, flooding	• Unlikely ;	1	(FEMA. 1999)
		• Possible	0	
		• Probable	-1	
		Total score	-2	

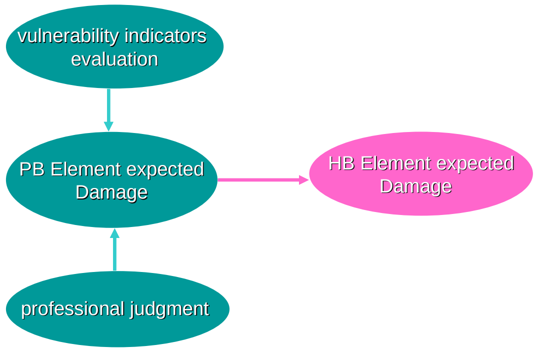

Figure 3 : Tier 2 vulnerability assessment for elements

In order to define the performance of the physical body of the HB with respect to the PB's physical body a number of global vulnerability indicators are first considered. These are typology specific and hazard specific. For each indicator a single relevant parameter and three possible states for each parameter are considered, implying better than, equal to and worse than prototype behaviour. To each state of the indicator is associated a value of 1, 0 or -1, respectively. In table 1 are listed the global vulnerability indicators for typology masonry church exposed to earthquake hazard. In yellow are highlighted the values scored using the case study of the parish church in Somerset. The resulting total score can be used to rank relative vulnerability for sets of buildings of the same typology and provide indications on which buildings should be considered farther for the elements vulnerability analysis. Buildings with negative scores should take precedence. Also the individual parameter scoring provides indication on what might be the more vulnerable aspects of the building, and hence help focusing the vulnerability assessment at the level of elements and components.

Under these assumptions the expected damage of an element of the HB can be calculated considering the known damage (mode and level) of the same element of the PB, modified by evaluating a second set of vulnerability indicators on the basis of the actual fabric and condition of the HB. As shown in Fig. 3 this calculation will be affected by professional judgment in considering the values of the vulnerability indicators, and in deciding whether the specificity of the building under study will result in better or worse performance relative to the prototype.

To perform the assessment at element level the building needs to be disassembled and this process raises a number of issues. One of the advantages of performing the assessment at element level is that once the damageability of a given element to a given hazard is known, then this can be used in the assessment of other buildings, with similar construction. This is particularly convenient, as has been shown in the literature review, where there is a wealth of information on mechanical behaviour of structural elements and where some correlation between vulnerability and damage for components is already available. However, it should be also considered that the damageability of an element or macro-element will be highly affected by its position in the structure and connections to other elements and this should be a critical factor when considering damage behaviour. It should also be considered that if the procedure is to be used for different perils and the results on vulnerability and damageability are to be comparable over the different perils then the elements' disassembly should follow the same criteria for each hazard while at the same time highlighting single components or element with high specific vulnerability.

In Fig. 4 an example of the disassembly for a church building is shown. As historic buildings are usually rather articulated, it can be noted that the first level of the subdivision is purely in spatial terms. In some cases the various subdivisions will have only a limited influence on each other's behaviour and can be considered as substructures in their own right. Beyond this first level, each of the divisions is constituted of structural elements which qualify the response to the specific hazards and have specific structural behaviour. In Fig. 4 the elements which represent the buffer and connection between two subdivisions are indicated by joining arrows. Already at this level some generalisation can be introduced as, for instance, all columns and arches can be expected to exhibit similar performance in a given peril, notwithstanding to which subdivision they belong. Their specific behaviour, however, will be influenced by their spatial location and relation to other elements. This can be formalised by using logical chains as shown by Augusti et al. (2001). In order to consider the vulnerability of the historic fabric, however, a more detailed level of disassembly need to be undertaken, as shown by the components level in Fig. 4. This highlights, not just the structural components, but also all the constructional and finishing components, as well as specific architectonic or other decorative apparatus present on that element or subdivision.

It is hence only at the level of the component that a full significance evaluation can be carried out. Once the disassembly has been performed the damage judgement will be carried out as follows:

- For each element the main damage mechanism are identified for each peril.
- For each damage mechanism one triggering and one inhibiting factor are identified. It is considered that the specific mechanism will occur if either the triggering factor is present or the inhibiting factor absent or both conditions occur.
- A series of fabric related vulnerability indicators are also considered, with ranking between -1 and + 1 which relates to the quality of the construction and structural capacity and give a further measure of vulnerability, when a specific mechanisms is considered as triggered.

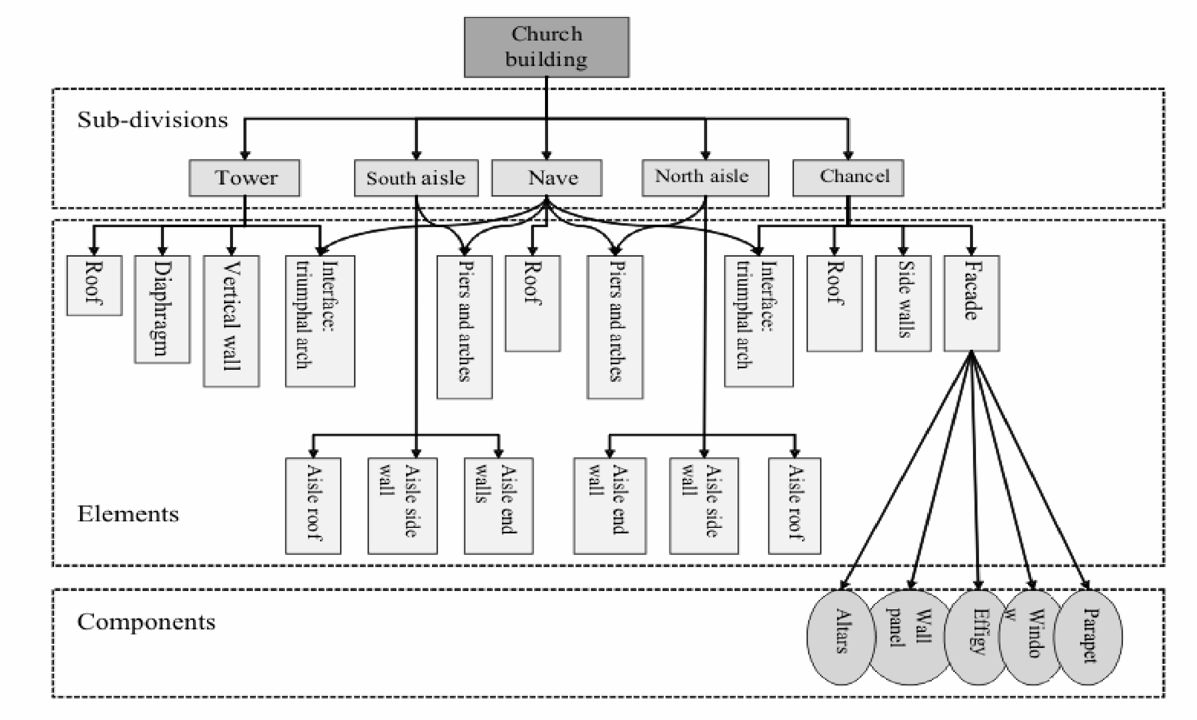

Figure 4 : Typical disassembly for a church

The first two steps are summarized in Table 2 for the masonry structural elements of the parish church exposed to earthquake. The list of mechanisms, as already stated, is not necessarily exhaustive, but represents the most common occurrence as obtained by experience and literature survey. At this stage only the likelihood of occurrence is considered, and if any of the inhibiting factors are not present, then a given mechanism is considered as possible.

Table 2 : Element specific damage mechanism with triggering conditions

Element	Possible Damage mechanisms (literature)	Damage triggering/ inhibiting factors	Condition for mechanism trigger
Chancel Facade	1. overturning of façade	1.1 connections between façade and side walls;	Bad
		1.2 presence of longitudinal ties or buttresses;	Not present;
	2. overturning of the gable	2.1 openings in the façade;	Wide opening;
		2.2 connection with roof structure	Lack tight connection;
	3. shear mechanism in the façade	3.1 Presence of wide openings;	Wide openings;
		3.2 connections to roof and lateral walls	Roof thrust lateral walls;
Aisles Lateral Walls	4.transveral vibration of lateral walls	4.1 slenderness of lateral walls;	Slender;
		4.2 presence of transversal tie rods or buttresses;	Not present;
Nave Piers and Arches	5.longitudinal vibration of the central nave	5.1 slenderness of columns, height of central nave;	Slender columns, high central nave;
		5.2 presence of longitudinal tie rods;	Not present;
Triumphal Arches	6. hinges formation in arch	6.1 thickness of the arch and masonry quality;	Thin arch and poor mortar;
		6.2 presence of tie rods; buttressing by lateral walls;	Ties not present, buttress insufficient;

The next step considers a new series of indicators, similar to the one presented in Table 1, relating to the quality of the fabric and aimed at identifying the most probable mechanism occurrence. Many of the indicators however are not element specific and hence they might contribute to the occurrence of more than one mechanism in different elements. Each indicator is screened using three criteria as in Table 1 above, and it is assumed that if the criterion has a positive value the parameter will not contribute to the triggering; if it has a neutral value the mechanism will occur with an average damage ratio; if the parameter has a negative value the mechanism will cause extensive damage. Some of the parameters considered for the masonry walls and piers and their interaction with horizontal structures are listed in Table 3. As already seen in Table 1, the scores corresponding to the case of the parish church have been highlighted in yellow. It can be noted that a relatively high number of mechanisms are affected and that some essential requirements for good performance in seismic area are lacking, due to the modest seismicity of the region. Hence on the basis of this scoring and the previous triggering a final judgment on mechanism occurrence can be drawn as shown in table 4. Here some very general damage ratios associated with the prevailing mechanism and as a function of the expected macro seismic intensity are quantified. It can be noted that even for modest seismicity as could be expected in Somerset the damage to certain elements would be palpable and could substantially affect some of the nonstructural but value significant element and components.

Table 3: Element vulnerability indicators

Parameter	Ranking criteria	Score	Mechanisms affected	Source
Type of units in masonry wall	Ashlar stone	1,	M12.1, M8.2	(Grunthal. 1998)
	Roughly cut stone;	0;		
	Rubble stone or field stone;	-1		
Quality of construction of the wall	Good mortar and Joints are properly made;	1;	M6.1, M 8.2	Steimen (2004), Lagomarsino (2004)
	Mortar and joints intermediate;	0;		
	Mortar and joints poor quality	-1;		
Cross section of the wall	Well-connected two leafs or solid	1;	M4.1; M12.1; M7.1; M1.1, M3.1;	D'Ayala & Kansal (2004)
	Two leafs with moderate connection;	0		
	Multi-leaf, with irregular fillings;	-1		
Connection detail at corners	Enhanced connection;	1;	M11.1, M 8.2	D'Ayala & Speranza (2003)
	Standard connection;	0;		
	Weakened or poor connection;	-1;		
Longitudinal tie rods or buttressed at roof truss or arches,	Both present	1;	M5.2; M7.1; M11.2, M9.1	Lagomarsino (2004)
	One present	0		
	None present	-1;		
Openings in walls	openings <1/3 total wall size;	1;	M1.1, M3.1; M7.2;	
	openings 1/3 to ½ total size;	0;		
	openings >1/2 total wall size;	-1;		
Roof connection with façade or lateral walls and thrust	Connection ties or ring beam	1;	M2.2, M1.2, M3.2	D'Ayala (2000)
	Good seating of beams on walls;	0	M 5.2, M4.2;	
	Deteriorated or lack of connection	-1;	M 6.2; M 9.1	
Slenderness of lateral walls and piers	H/D<9; 9	1;	M4.1, M5.1; M 12.1;	ASCE. (2003)
	9<H/D<13	0;		
	H/D>13	-1;		

Table 4 : Mechanism occurrence and associated damage ratios

Elements	Indicators score	Mechanism score	Active ?	*Damage ratio* V	VI	VII	VIII
	M1.1 (0) M1.2 (-1)	M1 (-1)		.15	.25	.35	.55
Chancel façade	M2.1 (-1) M2.2 (-1)	M2 (-2)	√				
	M3.1 (-1) M3.2 (-1)	M3 (-2)	√				
Aisle lateral wall	M4.1 (1) M 4.2 (-1)	M4 (0)		.1	.20	.40	.5
Nave long. arches	M5.1 (1) M5.2 (-1)	M5 (0)		.15	.25	.40	.65
Triumphal arches	M6.1 (0) M6.2 (-1)	M6 (-1)	√	.15	.25	.40	.65
Chancel lat. wall	M7.1(-1) M7.2 (-1)	M7 (-2)	√	.12	.25	.45	.55
Bell tower	M8.1 (1) M8.2 (1)	M8 (2)		.25	.35	.50	.75
	M9.1 (1) M9.2 (1)	M9 (2)					
Roofs	M10.1 (-1) M10.2 (1)	M10 (0)		.10	.15	.30	.50
Other walls	M11.1 (1) M11.2 (-1)	M11 (0)		.1	.25	.45	.65
	M12.1 (1) M12.2 (-1)	M12 (0)					
Spires and projections	*M13.1 (-1) M13.2 (-1)*	*M13(-2)*	√	*.15*	*.35*	*.55*	*.75*

3.3 Significance evaluation

This step first involves quantifying the significance of each component, component groups and finally the building. Accordingly, the significance loss will then be evaluated for these 3 levels. Only in extreme cases will the statutory grading of a damaged building change following restoration or repairs. In the present study it is assumed that although value rich components maybe lost, substantial change in significance, and hence measurable loss, at the level of the building will not occur. Therefore, the final value of significance loss assigned to a building will be a linear combination of the significance loss measured at component and element levels.

The significance loss of a component (or element) is defined as:

$$L_c = S_i * \left(1 - R_i\right). \tag{5}$$

where, S_i is the significance index of component i and R_i is its restorability.

While significance valuation is based on a wide range of criteria including social, cultural and economic attributes, the significance value is essentially a function of the authenticity and originality of the element, i.e of its historic and aesthetic character. Using precedent reference, in a manner similar to the one at the basis of HIST 1.0 (Lippiatt, 1995) each element can be ranked in a 10 point scale for significance where 1 is associated with least significance and 10 with highest. Further elements of quantification can include weighting factors depending on size and uniqueness. In this way the significance index S_i can be defined for each component and then summed up to define the index for the elements, subdivision and whole building..

The significance loss of a component or element is a loss of its authenticity and originality. The restorability is a measure of the extent to which a building or a component can be restored to its pre-damage state, physically and culturally. Hence the restorability is an intrinsic function of the level and type of damage, but is also highly influenced by the understanding and interpretation of historic significance.

As restorability implicitly requires some level of judgment and decision making relative to the successful outcome of possible interventions, besides cultural and philosophical attitudes ,such as acceptability of restoration and sentimental attitude to patina, restorability of a damaged component is dependant on the following factors:

- availability of original building materials in restoration;
- availability of traditional craftsmanship or skills, availability of sophisticated preservation technologies;
- availability of original data;
- availability of substantial financial support.

Reliability on the above factors may change with time and vary from region to region. Lack of any of these factors may result in reduced or compromised restorability of a component, element or entire building. Nevertheless, at a given time and in a specific region, the restorability of a damaged object can be defined as a function of damage, culture, intervention, and economic environment, as follows:

$$R_i = f(d_i, c, i, e) \tag{6}$$

Furthermore the relationship between restorability and level of damage is also a function of the significance of the component restored. For a component of high significance, i.e. high uniqueness, a modest level of damage may result in a high reduction of restorability, because notwithstanding the quality of intervention and availability of the above factors, its authenticity can never be recovered. For an element of lesser significance value the reduction of restorability will clearly be less sensitive. In order to illustrate this concept two qualitative families of curves are presented in Fig. 5a and 5b, considering different types of exponential decay for the corelattin between R_i and damage level. Curves of decreasing maximum restorability are obtained for reduced availability of the context factors.

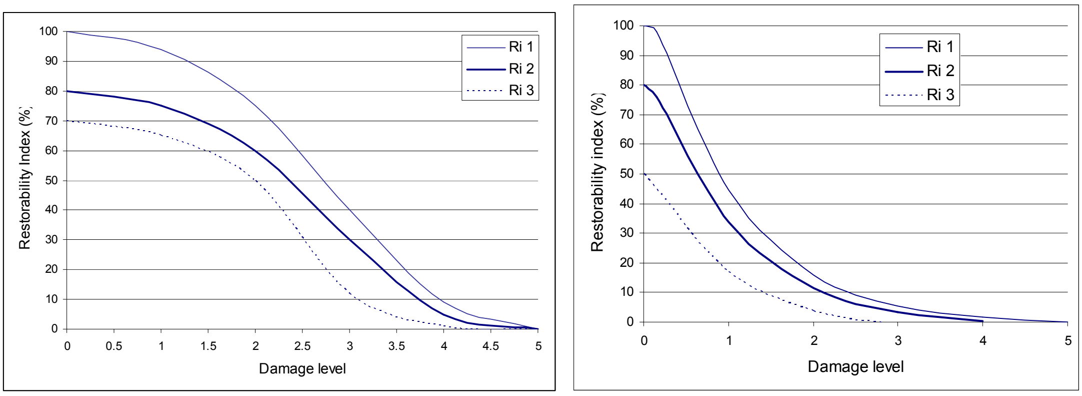

Figure 5: Relationship of Restorability Index versus Damage level; a) Low Significance elements, b) High significance elements.

In order to simplify the process, it can be assumed that within a given context the cultural and the economic environment will be constant parameters and hence the restorability will be a function of the intervention portfolio and the level of damage. Clearly the portfolio of interventions is also to a certain extent a function of type and mode of damage, but in order to define the restorability a matrix can be produced of interventions versus damage. The best available intervention strategy for a given damage type is assumed. Therefore once the damage of an element is predicted, the restorability can be determined.

4 DISCUSSION AND CONCLUSIONS

MHAV [historic buildings] is a conceptual model for the multi-hazard vulnerability assessment of historic buildings. The process builds onto substantial previous research in various field of hazards documented in literature for ordinary buildings. It has been proven that the regional geographical basis of perils intensity presentation is a robust basis to compare and rank hazards. Furthermore the disassembly of the building in elements and component and the separation between physical element and value rich elements allow the accurate calculation of the overall loss in terms of economic and significance.

Although the outline of the procedure and its applicability has been shown in the section above the details of the procedure and quantification of appropriate values need to be refined. Further elements of development will entails extensive Delphi group knowledge elicitation; identification and training of assessors; extensive model testing to check reliability and reproducibility of results.

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