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PERFORMANCE-BASED APPROACH FOR THE SEISMIC DIAGNOSIS OF HISTORIC BUILDINGS

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Abstract: Peru has a wealth of historic earthen architecture built after the arrival of the Spanish in the 16th century. However, little is known about the seismic behaviour of these buildings. This paper presents a decision-tree based diagnostic approach aimed at identifying the vulnerability of two traditional earthen buildings, and locating areas where strengthening can be implemented. The diagnosis is carried out in two stages; a preliminary diagnosis based on onsite observations, and a detailed, more quantitative diagnosis based on results of numerical analysis and experimental testing. At each stage, four parameters are assessed; the initial structural concept, the interaction between structural components, the quality of the connections, and the quality of the structural fabric. The effect of deterioration, and how this influences the other variables is also considered. The approach has been applied to two types of historic earthen buildings in Peru with very different structural systems. It is shown to be applicable to both building types, with only minor adaptations, and has proven to be a useful tool for identifying vulnerable aspects of the building.

Introduction

Peru has many historic earthen buildings dating from the period of the Peruvian Viceroyalty (1542-1824), which are still in existence today. These buildings were constructed using locally available materials such as mud, stone, and timber, but the influence of Spanish architecture and construction techniques resulted in a distinct form of architecture and structural system. Peru is one of the most seismically active countries in the world, and suffers from frequent damaging earthquakes. Adobe structures are known to be particularly susceptible to earthquakes (Cancino 2011), however there is little published research on their structural behaviour or how they can be protected. In order to better understand the seismic behaviour of these buildings, a collaborative project was set up between University College London (UCL), The Getty Conservation Institute (GCI) and the Pontificía Universidad Católica del Perú (PUCP) under the heading of the "Seismic Retrofitting Project" (SRP). The SRP aims to research, design and validate seismic retrofitting techniques for historic colonial buildings in Peru (Cancino et al., 2012).

This paper presents a diagnostic approach developed within the SRP to systematically identify the vulnerability of a building, and determine areas where strengthening may be required. This diagnostic tool has been applied to two historic building types found in Peru, a residential building and a church. The same approach has been taken for both buildings, but the outcomes were very different due to the inherent structural differences. The approach has been found to be easily applicable to both building types considered, requiring few adjustments according to the specific case study. Using this process, the most vulnerable aspects of the building are identified and the need for repair, strengthening or modification is established. This paper describes the methodology in detail, before outlining the significant outcomes of the diagnosis of two buildings.

Methodology

The diagnostic approach presented here was conceived due to the need for a concise method in which to bring all aspects of the assessment campaign together so that a clear

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conclusion could be achieved. The approach has been developed taking into consideration the principles for the diagnosis for architectural heritage outlined by ISCARSAH (2003), along with the procedures for on-site investigations and condition assessment in ASCE 41-13 (2014). The approach developed is easy to follow, yet does not omit valuable information and is not oversimplified. It can also be carried out collaboratively, involving all project partners and stakeholders in the assessment. The diagnosis of the buildings is performed in two steps. The preliminary diagnosis is carried out at an earlier stage in the assessment process. It uses the information collected through onsite visits, as well as data obtained from archives, literature, historic sources, and preliminary numerical models. This provides a first synthetic judgement on the structural behaviour of the case studies, yet relies largely on the expertise of the analyst and their ability to interpret these data sources. The detailed diagnosis is carried out later in the project. It is more quantitative and uses data obtained through experimental tests and numerical models. The two stages of the approach apply the same overall concepts and methodology, but use different sets of information.

Before the preliminary diagnosis is carried out, the structure is divided up into individual components, and is considered as a system composed of individual entities that interact with each other. Each of these individual entities is considered to be a '*macroelement*'. A macroelement can be defined as a part of the structure that may be considered independent from the rest. In the event of an earthquake, each macroelement shows a distinct seismic behaviour, but interacts with other macroelements (Novelli and D'Ayala 2011). This division into macroelements is particularly relevant to architectonic heritage buildings with complex layouts where parts of the buildings behaving independently can be clearly identified. The decomposition can be done at different levels, namely at the level of the structural system (whole structure), substructures (such as the nave, baptistery, roof, and floor), components (walls, buttresses, arches, etc.) and elements (tie-beams, wall-plates, etc.). The coarser level is easily distinguishable from a simple observation of the geometry while the more detailed levels require knowledge about materials' types and existence of discontinuities.

The diagnosis relies on the assessment of five key variables, which have been selected, as they significantly affect the seismic behaviour. These five variables remain the same for each typology considered, although their influence, and relative importance may vary. The five variables are Resilience (R), Interaction (I), Connections (C), Fabric (F), and Deterioration (D). A brief description of the meaning of each of these is outlined in Table 1.

Table 1. Definition of the Variables

Variable name	Definition
Resilience	Evaluates how well the structure was originally conceived and constructed and how these attributes influence its response under earthquake loading.
Interaction	Regards the nature and mechanisms of interaction of the various macroelements. Emphasis is put on the connections between macroelements, which often determine the global behaviour of the building, and its ability to respond to external actions.
Connections	Related to the original conceptual design and construction of the connections between structural elements within a given macroelement and relates to the local behaviour which in some circumstances can lead to partial collapse
Fabric	Evaluates the quality of the units, mortar, their bond and the general layout of the fabric of a given macroelement made of masonry or more generally the layout and integrity of the materials and fabric constituting a given macroelement.
Deterioration	The level of deterioration changes the structural performance of a system. Although this variable is related to Resilience, since a structure that is well-conceived and constructed would have less propensity for deterioration, external actions can trigger the deterioration of the materials and connections up to a point where safety is compromised even if the structure is robust.

It is worth mentioning that the fifth variable, *Deterioration*, is different from the rest in that it is both time dependent and can influence the state of the other variables. While all the other variables remain more or less constant throughout the lifespan of the building, unless manmade alterations are brought to it, the state of deterioration will inevitably evolve with time. Due to this, it is dealt with separately from the other four variables. Considering deterioration alongside the other variables could mean that the same building could have vastly different results if this process was applied at a different time. In addition, the effect of deterioration will always be negative. For simplicity, deterioration is omitted from the preliminary diagnosis. For purposes of the detailed diagnosis, when assessing the *Resilience*, *Interaction*, *Connections*, or *Fabric*, the judgement is made ignoring the effect of damage or deterioration. For example, if the building originally had tie beams, but some have since failed, the building is considered assuming that all tie beams are well connected. Deterioration is considered separately, and will always be negative, although the relative importance with respect to the other variables will vary.

Preliminary Diagnosis

Using evidence from the on-site investigations and archival research, for each macroelement within the structure a series of judgements are made on the relevance that each of the key variables has on the structural response. The five variables are ranked by letters from A to D, according to Table 2.

Table 2. Classes of influence of the variables for the preliminary diagnosis

Classes of influence	Relevance
A	Critical
B	Significant
C	Influential but not significant
D	Negligible influence

The second judgement is made on the nature of the variable, i.e. whether it has a favourable or unfavourable influence. For example, a timber joint which is well conceived and constructed (and therefore contributing positively) would be judged to have a favourable influence. This is described by using the symbols '+' and '-' following the letter.

Finally, a level of confidence in this judgement is assigned, expressed in terms of a percentage assigned to each variable. The level of confidence per macroelement or per variable is obtained by applying, respectively:

$$c_j = \frac{\sum_{i=1}^{m} C_{ji}}{m} \qquad (1a)$$

$$c_i = \frac{\sum_{j=1}^{n} C_{ji}}{n} \qquad (1b)$$

Where C_{ji} is the confidence of the diagnosis for macroelement j as far as variable i is concerned, m is the number of variables classified for each macroelement and n is the total number of macroelements. Moreover, an overall level of confidence could be obtained by applying Equation 2:

$$c_G = \frac{\sum_{i=1}^{n} c_j}{n} \qquad (2)$$

This level of confidence at macroelement and building level is a complementary measure of the level of uncertainty associated with the diagnosis, and hence together with the relevance of a specific variable provides an indication of which investigations, numerical or experimental, should be further pursued to aid the diagnostic process. The preliminary diagnosis can be summarised in a matrix similar to that shown in Table 3.

Table 3. Matrix of preliminary diagnosis

MACROELEMENTS	VARIABLES			
	Variable 1		…	Variable *i*
Macroelement 1	Class of influence *(A,B,C or D)*	+ or -		
	C_{ji} (%)			
…				
Macroelement *j*				

Detailed Diagnosis

The detailed diagnosis is performed at a stage in the project when the results of the numerical model have been finalised, and the performance criteria have been identified using results from experimental tests carried out by Vicente and Torrealva (2014) and Torrealva and Vicente (2014), or using reference values from codes or literature. The methodology for the detailed diagnosis is more complex, resulting in an assessment supported by numerical or experimental estimations of structural performance indicators, in which the criteria for evaluation of the vulnerability are based upon. The assessment criteria are divided into global and local criteria. Local criteria take into account the existence of stress concentrations and local fragilities, while global criteria evaluate the global response of the whole structure or sub-structures, in terms of drift and capacity.

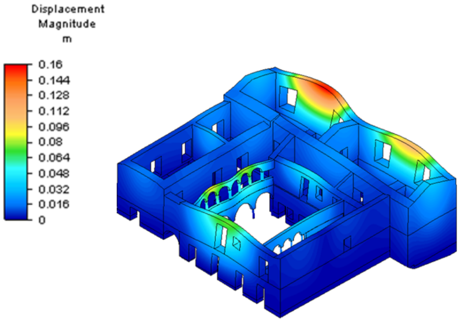

Figure 1: Displacement results of response spectrum analysis (Pisco 2007 earthquake) for Casa Arones (C.A.)

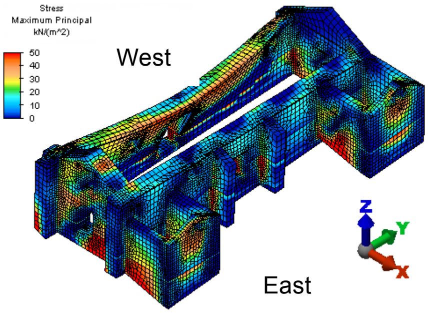

Figure 2: Maximum principal stresses after pushover analysis (equivalent acceleration of 0.3g) for the Church of Kuño Tambo (K.T.)

The approach for the detailed diagnosis compares the expected performance of the building with reference limits obtained from seismic codes or guidelines, experimental results, and analytical studies. The expected performance outputs for each building are obtained through global and local numerical models that have been developed for each of the buildings (see Figure 1 and 2). A reference acceleration of 0.3g was used for the pushover analysis, which is the maximum ground acceleration with a probability of 10% exceedance in 50 years (return period of 475 years) for the region according to the Peruvian seismic code (E.030, 2003). A detailed description of the numerical modelling process can be found in Fonseca Ferreira and D’Ayala (2012) and D’Ayala and Fonseca Ferreira (2012).

Global Criteria - Resilience: Resilience is assessed according to global criteria. The following criteria are applied: (a) Regularity in elevation; (b) Regularity in plan; (c) In-plane and out-of-plane drift. The first two criteria are based on the principle that a regular structure in elevation and plan should perform better than an irregular structure. Several procedures are available in existing literature to evaluate these criteria (e.g. E.030, 2003; EN 1998-1, 2004, ASCE 41-13 (2014), and NZSEE (2006)).

From the capacity curves obtained from the global models of the case studies, described in terms of drift and total base shear, a conclusion can be made on whether a macroelement is responding in the linear or post-elastic range. The values of drift can be compared with reference values for unreinforced masonry walls available in literature. A summary of selected reference maximum drift limits is shown in Table 4. The damage states are as defined in EN 1998-3, (2005).

Table 4. In-Plane and Out-of-Plane Drift Limits according to various sources

Source	**In-plane drift (%)**			**Out-of-plane drift (%)**		
	Damage Limitation	Significant Damage	Near Collapse	Damage Limitation	Significant Damage	Near Collapse
D'Ayala (2013) (*Masonry Walls) Results for combined behaviour of the FaMIVE procedure.*	-	-	-	0.030-0.168	0.099-0.582	0.198-1.401
D'Ayala (2013) *Based on review of experimental work*	0.18-0.23	0.65-0.90	1.23-1.92	0.33	0.88	2.3
Eurocode 8, Part 3 (EN 1998-3, 2005)	Shear force capacity	0.4-0.6	0.533-0.8	Shear force capacity	0.008(H_0/D) to 0.012 (H_0/D)	0.011(H_0/D) to 0.16(H_0/D)]

Where H_0 is the distance between the section where the flexural capacity is attained and the contraflexure point, and D is the in-plane horizontal dimension of the wall (depth)

Local Criteria - Interaction: The nature of interaction between the macroelements is evaluated by considering the maximum stresses and strains at interfaces. These interfaces may be between two macroelements of the same material, or between different materials. The expected stresses and strains are taken from global and local numerical models. The occurrence of cracking between adjacent walls, or sliding of the adobe over the base course is considered by comparing the expected values with reference values for capacity obtained from experimental tests. The same approach is taken for the interaction between macroelements such as tie beams and a wall, or floor beams and a wall.

Local Criteria - Connections: The principal connections of the case studies regard the timber connections of the roof and floor structures. The capacity of the timber connections within the macroelements needs to be assessed on a case by case basis due to the wide variety of carpentry techniques present in the case studies. Reference capacity values are calculated from procedures available in literature, such as Eurocode 5 (EN 1995-1-1, 2006).

Local Criteria - Fabric: The quality of the masonry fabric is checked on the basis of geometrical characteristics and observation, without considering the strength of the material, as this variable is already evaluated by means of global criteria. Good quality masonry is deemed to have well shaped durable bricks, with regular narrow mortar joints. Reasonable limits for joint thicknesses and shape ratios can be found in Houben and Guillaud (1994) and Hendry (1990). Hence, it is assessed according to the following criteria; (a) Homogeneity of the fabric; (b) Shape ratios of units between 1:2 and 1:4; (c) Overlapping of brick units between 1/3 and ½ ; (d) Thickness and filling in of the joints and quality of the mortar.
This variable is evaluated on the basis of evidence observed onsite.

Decision-Tree Approach

This process can be presented through the construction of a decision tree where the confidence measure and a relevance measure are associated at each decision point. The direction taken depends on the positive or negative nature of the variable. The decision tree is shown in Figure 3, where each tier of the decision tree is one of the five variables defined above and the sign and confidence factor determine the most likely path for each macroelement and for the entire building.

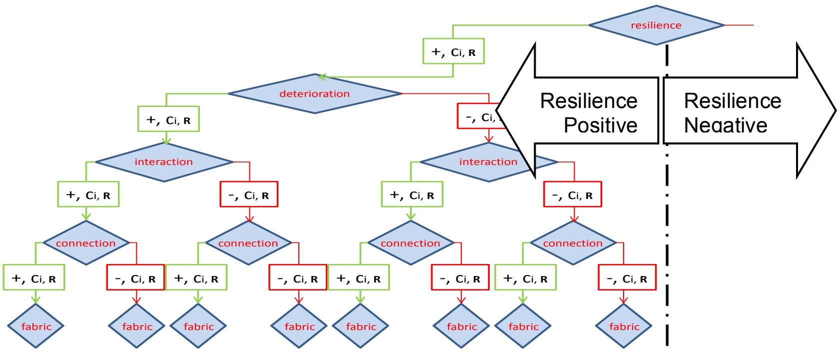

Figure 3. Possible decision tree paths for the detailed diagnosis

In the decision tree, the green path assumes good performance of the macroelement for each of the variables, indicated by a +, while C_i represents the confidence level with which this judgement is expressed, and R is the relevance of each of the variables to the overall behaviour, as explained above. C_i represents therefore the confidence for the entire building associated to a given variable. Alternatively, it can also represent the confidence of the judgment for each macroelement, i.e. C_{ji}. . The R factor can be related to the classes of influence of Table 2, even though two or more variables with the same class of influence are associated to different R factors in the presence of more detailed data. Sixteen different diagnoses are possible and the relevance and the summative confidence factor will indicate which should be pursued in the rest of the study. Paths with a negative outcome and with the highest relevance are those in which further study should be concentrated. Additionally, further investigation is required where there is a low confidence factor. In addition, although the final outcome at each extreme (left and right) end of the flow chart represents the best and worst possible cases, the other possible outcomes are not ranked since there is no hierarchy. Therefore, it cannot be assumed that the outcomes furthest to the left of the chart represent the best behaviour, as this obviously depends on the relative relevance of the five variables in each judgment. It is important to note that in some cases, two paths can be taken, either for different aspects of the structure, or if the level of confidence is such that either path could be realistic. This is further demonstrated with the case studies.

Results of the Diagnosis of the Case Studies

This process has applied to two different case studies, which were selected as part of the SRP project because they represent four typologies of historic earthen buildings found in Peru. The methodology for selection of these typologies can be found in Cancino et al. (2012). The first construction type considered is a residential building known as a '*casona*' located in Cusco. The case study selected dates from the 17th century and is known as 'Casa Arones' (C.A.). It is two storeys in height with adobe walls and a rubble stone base course, and has an internal patio with brick and stone arcades. The roof is made from a technique known as '*par y nudillo.' Par y nudillo* is a traditional roof system consisting of unshaped timber elements fasted together with leather strapping. The second case study is a church located in Acomayo, Cusco The church dates from the first half of the 17th century and is known as the Church of Kuño Tambo (K.T.). It is composed of adobe walls and buttresses with a rubble stone base course and also has a '*par y nudillo*' roof.

Results of Preliminary Diagnosis: Figure 4 summarises some of the results of the preliminary diagnosis of C.A., while Figure 5 shows the same results for K.T. The charts show the proportion of macroelements judged to have a particular influence (A, B, C or D), as well as the positive (in green) or negative (in red) nature of the influence for each variable.

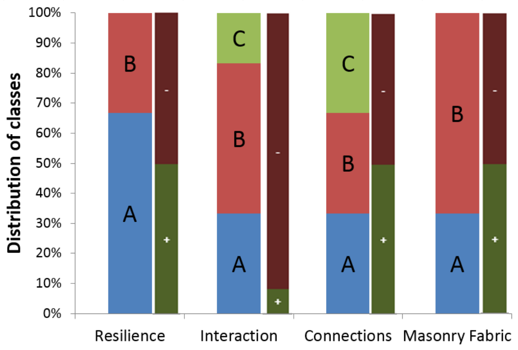

Figure 4. Distribution of influential classes and their nature per variable for C.A.

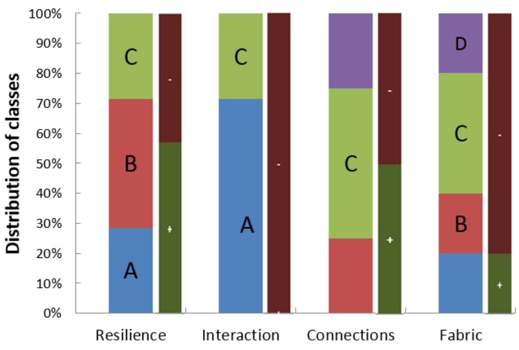

Figure 5 Distribution of influential classes and their nature per variable for K.T.

The most influential variable for C.A. was considered to be resilience, while the most influential variable for K.T. was the interaction between the macroelements. In the case of resilience, both buildings were judged to have a positive resilience in around half of the cases. This is supported by the fact that both structures are composed of thick adobe walls with high base courses which protect the walls from raising water, which are indicators of good resilience. However, there are some vulnerable aspects such as the *par y nudillo* roof, and improper anchoring of tie beams to the walls that are present in both buildings. In the case of K.T., the interaction was considered unfavourable in all cases, and for C.A, the interaction was considered unfavourable more than 90% of the time. Interaction between walls (and walls/buttresses in the case of K.T.) is made by interlocking adobe blocks at orthogonal walls, with the roof having a negligible contribution to the redistribution of loads between the walls. In the case of K.T., the walls/buttresses connection could be limited to the adobe blocks located at outer layers and therefore the core of the buttresses might be detached from the walls as shown in Figure 6. Additionally, in both buildings, most of the tie-beams connecting the long longitudinal walls are not properly anchored to the walls, or are not present at all. Finally, in C.A., the floor beams do not run continuously (see Figure 7), and the lack of wall plates may lead to stress concentrations in the walls. Taking into account the significant influence and unfavourable nature of the interaction variable, the improvement of the way how the macroelements interact with each other is a major concern.

Figure 6. Connection of buttress to lateral walls of K.T.

Figure 7. Interaction between floor beams and adobe walls for C.A.

The mean level of confidence for all variables and macroelements for C.A was 68% with the lowest levels of confidence being related to the connection details of the tie beams, which cannot be observed without removal of a substantial amount of original material. A low level of confidence was also allocated to the fabric of the arcade, where the material can be well observed, but further analysis is required as to the positive or negative nature of it. The overall level of confidence for K.T was 73%, with the lowest levels of confidence associated with levels of interaction between the macroelements. This indicates that further investigations by means of numerical analysis, experimental work, and surveying is necessary to better understand the vulnerability of the church.

Results of Detailed Diagnosis: The detailed diagnosis of both buildings was carried out considering the results of the numerical models (Figures 1 & 2). Additionally, after the preliminary diagnosis, experimental tests were carried out by Vicente and Torrealva (2014) on original material extracted directly from K.T. It was not feasible to extract original material from C.A. so suitable values for the material characteristics had to be obtained from literature. Figure 8 shows the results of the detailed diagnosis of C.A. The results for C.A. do not differ extensively from the preliminary diagnosis. This is due, in part to the lack of experimental data available from material extracted from site. However, the numerical model showed the long unsupported adobe walls to be vulnerable to excessive drifts, and the interactions between orthogonal walls to be vulnerable to cracking (see Figure 9), which was observed on-site. A significant issue with the detailed diagnosis is also the lack of confidence on the positive or negative nature of the variables in relation to the lack of knowledge which would have been gained from having performed a good characterisation of the materials, either in situ or by extraction. This was compounded by difficulties in obtaining original connection details due to severe deterioration. In terms of resilience, the macroelements were divided and follow separate paths since half were judged to have a positive resilience, and half negative. Additionally, when interaction was considered for the arcades and tie-beams, there was not sufficient evidence to make a judgement so both paths were followed with a level of confidence of 50% each. This was also the case for the connections.

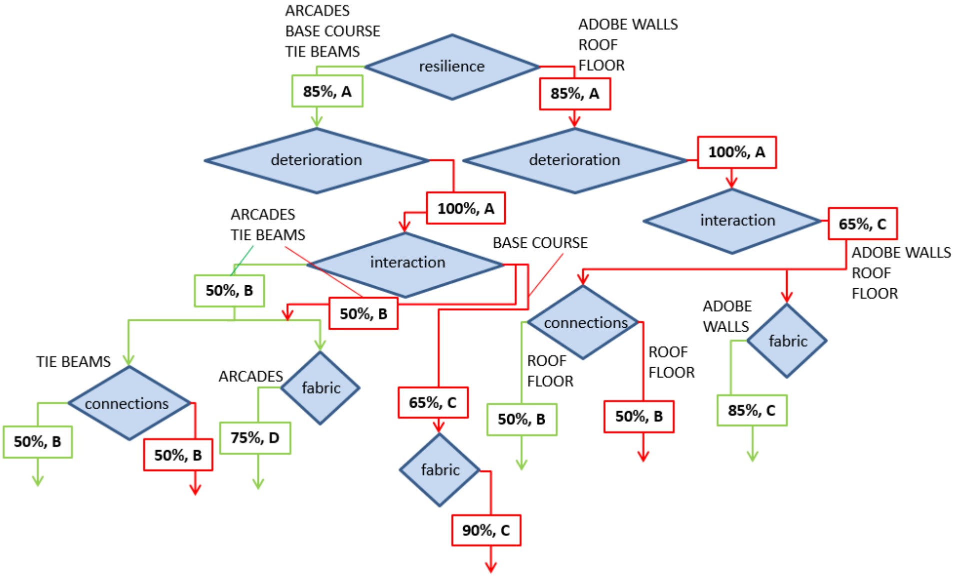

Figure 8. Performance-based diagnosis of CA (only the relevant paths are marked)

The capacity curves of K.T. presented in Figure 10, were developed from the results of pushover analysis performed with the model in Figure 2. These show that the longitudinal walls of the nave are the most vulnerable macroelements, which present a significant nonlinear plastic response from 0.20% drift, which corresponds to an acceleration of 0.2g (for details see Fonseca Ferreira *et al.*, 2014). These walls exceed the damage state of significant damage if for instance the reference drift range from FaMIVE for combined response of masonry walls (see Table 4, D'Ayala, 2013) is considered. The results of the numerical models also show that the buttresses are more beneficial to the overall response of the church than the tie-beams. Furthermore, if the buttresses of the West wall are reinstated, the wall might survive an acceleration of 0.3g without significant damage.

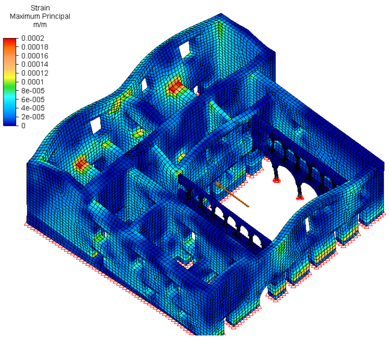

Figure 9: Out-of-plane deformation and locations of max. principal strains for C.A. after pushover analysis (equivalent acceleration of 0.3g)

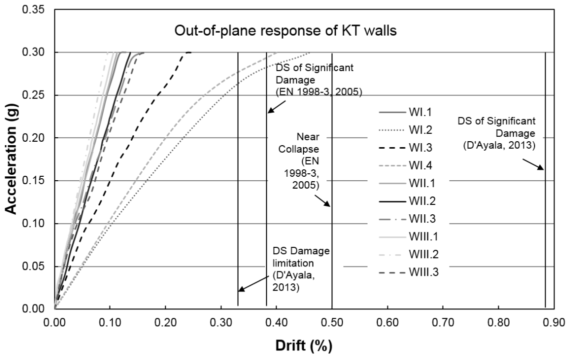

Figure 10: Maximum principal stresses after pushover analysis (equivalent acceleration of 0.3g) for K.T.

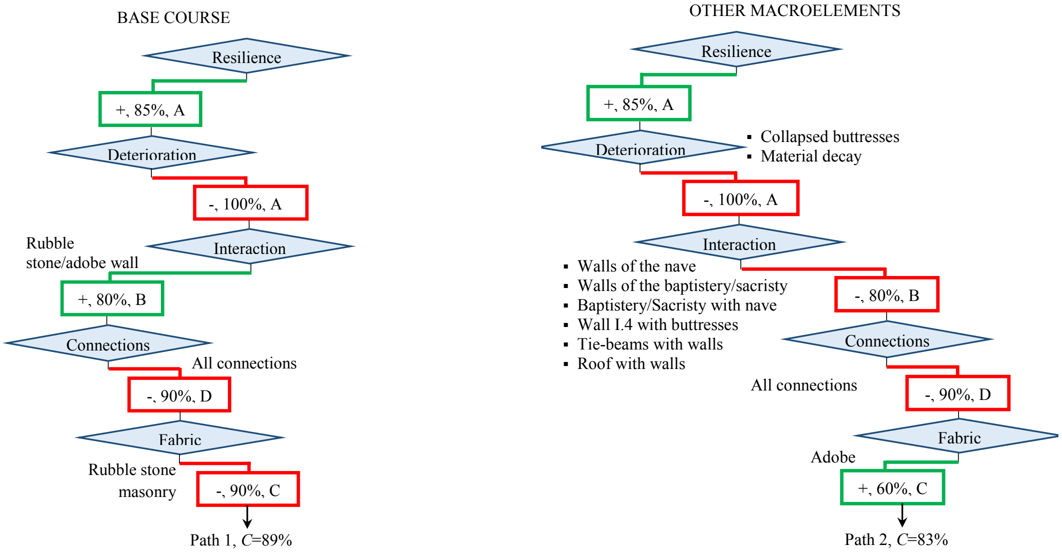

Figure 11. Performance-based diagnosis of KT

The overall diagnosis for K.T. is shown in Figure 11, where deterioration is considered as one of the most relevant variables due to the significant influence of the buttresses on the response, as interpreted from the results of the structural analysis. It can be seen that the decision-tree for K.T. is significantly less complex than that of C.A. This is due to the lower complexity of the building, and the higher level of confidence as a result of material testing.

Conclusions

A diagnostic approach has been developed to assess the seismic vulnerability of different types of historic earthen buildings found in Peru. It uses a decision-tree based approach considering five variables. This method has been applied to two buildings, a residential building (C.A.), and a church (K.T.). By considering the results of the detailed diagnosis for each building, weak or vulnerable parts of the structure can be identified, while the presence of common weaknesses in both buildings confirms the robustness of the assessment procedure. Major weaknesses in both buildings were found to be the interaction between macroelements, and weaknesses in the timber connections. These could be key areas for strengthening measures to be implemented. The inclusion of both global and local criteria allows us to locate where critical conditions are reached and where strengthening measures may be best implemented. While it has been demonstrated that the approach can be applied to buildings with a very high level of complexity, such as C.A., the outcome of the assessment highlights the importance of having robust initial knowledge, as otherwise the results of sophisticated analysis cannot be used with a level of confidence that delivers a conclusive diagnosis. This contrasts with the results of K.T., where more tests were carried out on original material resulting in a significantly higher level of confidence.

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