LOG-IDEAH: LOGic trees for Identification of Damage due to Earthquakes for Architectural Heritage

V. I. Novelli
Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, UK

D. D'Ayala
Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, UK

SUMMARY:
During the post-earthquake assessment in the historical centre of L'Aquila damaged by the earthquake of 2009, it has been observed that cultural heritage assets are particularly vulnerable to horizontal motions. For this reason, in order to identify the state of damage of architectural assets, an interactive procedure LOG-IDEAH: LOGic trees for Identification of Damage due to Earthquakes for Architectural Heritage aimed at identifying the global behaviours of architectural assets by using logic trees on the basis of the seismic damage collected on the architectural asset under consideration is proposed in this paper. The seismic damage assessment, which is performed on site or by pictures in order to provide the input for LOG-IDEAH, focuses on collecting position, type and level of damage on structural elements and artistic assets that belong to the façades of the architectonic asset under consideration. The interpretation of the damage collected at local level is carried out by using logic trees implemented as a decision-maker which captures the collapse mechanisms according to a specific recognition process defined on the basis of the knowledge and expertise of surveyors. Once this procedure been described in terms of the above-mentioned logic trees, a web-based data collection tool is used for storing the observed damage and the observed collapse mechanisms, while an analysis tool implemented in an answer set program and derived from the logic trees is used to identify the collapse mechanisms. The present work has been developed in the framework of PERPETUATE, an FP7 project funded with the aim of providing European Guidelines for the evaluation and mitigation of seismic risk to cultural heritage assets.

Keywords: damage scenarios; assessment; global mechanisms; expert system

1. INTRODUCTION

In order to identify the vulnerability at territorial scale of a historic centre exposed to earthquake hazard, it is required to adopt a methodology which supports engineers and architects to correctly recognise the global seismic behaviour and the stability of architectural assets. The first step for the identification of the failure mode of a building is to assess the damage after a seismic event, indeed several countries, such as California (ATC20 and ATC20i), Italy (DPCM 2006), Mexico (CENAPRED, 1996), and Colombia (AIS 2003), have developed guidelines to estimate the post-earthquake safety of buildings on the basis of the damage assessment. However, these procedures, which require specialised knowledge on the part of the observer, are not always efficient at scale of several hundred damaged buildings. This led to the requirement for a computational model to support the survey process. In the past, several artificial intelligence (AI) software programs for the seismic damage assessment of buildings have been developed. Most of these approaches are rule-based prototype expert systems such as the software DASE, (Melchor-Lucero and Ferregut, 1995), developed for estimating damage level and failure modes of concrete buildings, or the decision making system SPERIL (Ogawa and Fu 1981) developed for the post-earthquake assessment of concrete and steel buildings. One of the most recent AI systems, proposed to support inexperienced engineers and architects in post-earthquake assessment is EDE: Earthquake Damage Evaluation of buildings, introduced by Carreno et al. (2004). This is an artificial neural networks and fuzzy logic approach which defines the habitability and reparability level of a building by computing a damage index as a function of the damage levels on structural and non structural elements, the soil conditions and the state of the building before the seismic event. Since this approach aims at providing the level of reparability, the damage index is calibrated on the severity level rather than the type of damage. This implies that the level of stability of a damaged building is not affected by the feasible failure modes which might have occurred during the seismic event. In order to tackle this issue, Cadei et al. (1990) proposes the use of the knowledge-based system IGOR for the identification of the seismic risk of masonry buildings. In this system, the seismic risk is identified by introducing functions which capture the expertise of experienced engineers or operators and reason about the probable structures' behaviours. In general, the risk assessment that relies on assigning probabilities for possible outcomes requires good data and good capacities to predict the possible critical scenario for a building. However, it has been demonstrated that this software is not always in the position to simulate all the critical scenarios, and when this happens the decision maker often chooses the most convenient interventions in economical terms rather than structural terms (Dovers, SR and Handmer, JW, 1995). The state of art of the AI software reported in this section has pointed out that these tools are developed to provide systems able to identify the possible interventions in order to repair the buildings after seismic events. However, since no information related to the type of failure occurring on the buildings are supplied, it might be difficult to judge whether the proposed interventions are suitable to the building. For this reason, in this paper, an interactive system LOG-IDEAH "LOGic trees for Identification of Damage due to Earthquakes for Architectural Heritage", aimed at identifying the seismic global behaviour of an architectural asset is proposed to support the operator for better understanding the behaviour of a building and for better identifying the most suitable seismic interventions. LOG-IDEAH has been developed in the framework of the PERPETUATE project, an EU funded FP7 project aimed at providing European Guidelines for the evaluation and the mitigation of the seismic risk to cultural heritage assets, by proposing innovative techniques to preserve historical buildings and unmovable artworks. The intuitive logic human, used by expert engineers for the identification of the feasible collapse mechanisms of an architectural asset, is expressed in logic trees that have been implemented in LOG-IDEAH by using an answer set program. Furthermore, in order to record the seismic damage collected on site, a web-based data collection tool has been implemented and developed to store the data used as input in LOG-IDEAH.

2. HEIRARCHICAL STRUCTURE OF ARCHITECTURAL ASSETS

LOG-IDEAH depends upon a hierarchical approach in which the architectural asset is deconstructed into macroelements, the macroelements into structural elements and the structural elements are identified as being linked to or being in itself artistic assets.

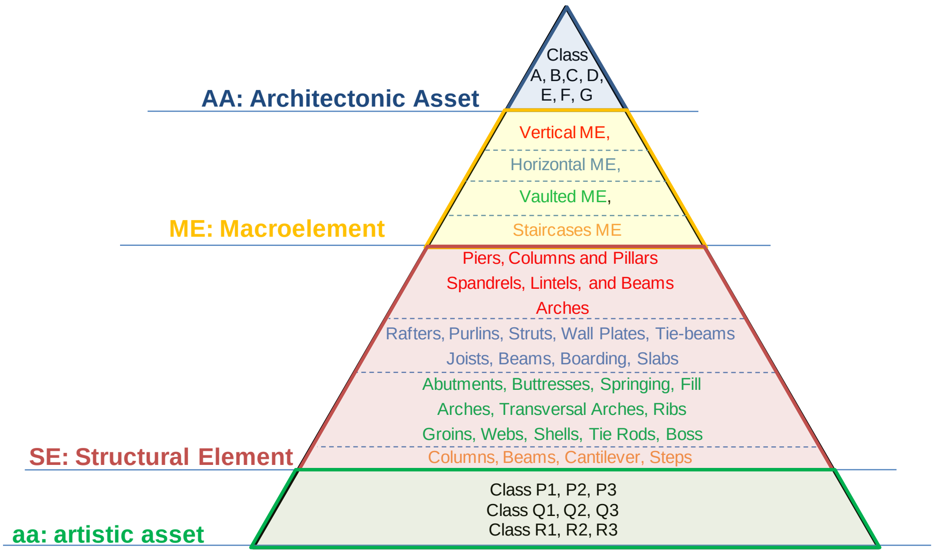

Figure 2-1 Hierarchic Pyramid of Architectural Assets

Data collection for LOG-IDEAH entails to record information related to the damage position, damage type and damage level, that are observed at level of the structural elements and artistic assets of the architectural asset under inspection. The collected data is then interpreted by logic trees which represent knowledge and expertise of professionals as they would use it for the identification of the global behaviour of an architectural asset, and to recognise the failure modes of the architectural asset in question. A comprehensive ontology has been developed and represented as a pyramid, see Figure 2-1; that captures and defines the domain concepts and their relationships. There are four top-level concept classes:

- **Architectural asset (AA):** this covers seven classes of buildings, (A…G), from mansions, trough mosques, and churches;
- **Macro-Elements (ME):** this covers four classes such as Vertical ME, Horizontal ME, Vaulted ME and Staircases ME, which group the structural elements,
- **Structural element (SE):** this comprises four groups, corresponding to the MEs above, such as piers and spandrels (vertical), rafters and tie beams (horizontal), abutments and arches (vaulted) and cantilever and steps (staircases),
- **artistic asset (aa):** this is a set of three groups: (P: Structural elements with artistic value, Q: artistic value which are strictly connected to structural elements and R: artistic assets which are not strictly connected to structural elements).

3. ACQUISITION OF SEISMIC DAMAGE IN SITU OR BY PHOTOGRAPHIC OBSERVATION

The data acquisition is performed in-situ or via detailed photography and the level of reliability for the collected information has to be explicitly recorded as an entry in the database by the surveyor according to three possible levels, Low, Medium and High, depending on the quality of the photographic record and the direct observation. Since the post-earthquake assessments are often carried out from the street without entering the building due to the unknown level of risk of collapse, and usually augmented by pictures, the data is often collected on Vertical MEs rather than Horizontal ME, Vaulted ME and Staircases ME.

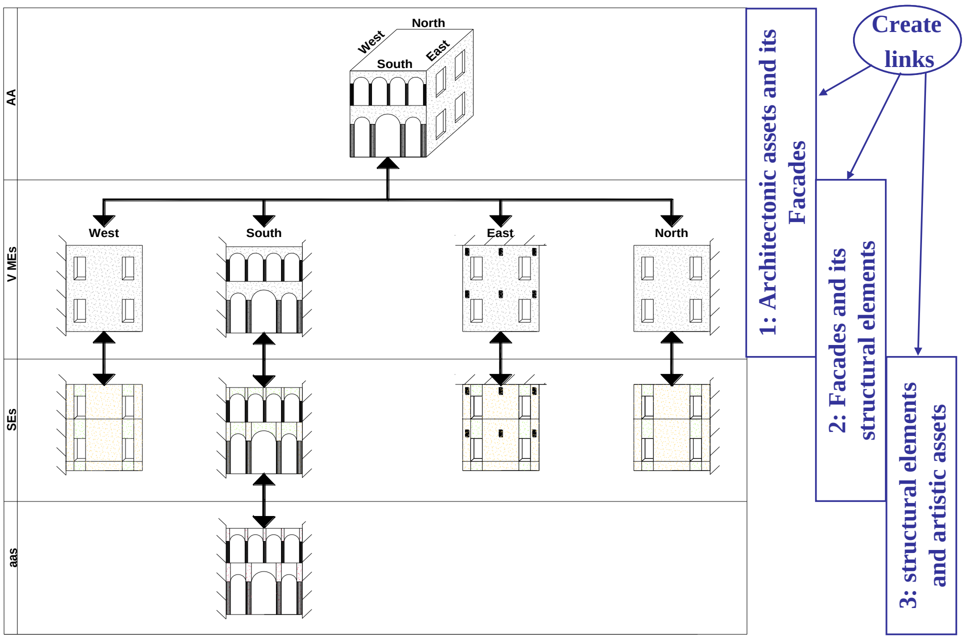

Figure 3-1 Relationships between AA, VME, SEs, aas

For this reason, the method adopted in LOG-IDEAH for the identification of the global seismic behaviour of an architectural asset assumes that the feasible collapse mechanisms is identified on the basis of the damage collected at SE and aa level, interpreted first at VME level and then at AA level. This entails that the essence in the survey of an AA, such as the mansion represented in Figure 3-1, is to deconstruct the AA in question, into VEMEs, west VME, south VME, east VME and north VME in Figure 3-1; the VeMEs into SEs, piers in yellow, spandrels and arches in green in Figure 3-1; and the SEs into aas, decorated columns in pink in Figure 3-1.

Once all the entities which belong to AA has been identified, then the issue will become to establish links among AA and VMEs; VMEs and SEs; SEs and aas, in order to reconstruct the AA under consideration. The relationship between AA and the Vertical MEs is set by dividing the map, wherein the AA is located, into blocks and to enumerate the blocks and the buildings located therein. Once this is done, the name associated with the AA in question is given by: (block number + building number), and that associated with the inspected façades by adding the façade orientation.

The next sections are reported in order to illustrate how the nomenclatures which link SEs and aas to Vertical macroelement are defined.

3.1. Relationships between vertical Macroelements and Structural Elements

In order to create links between MEs and SEs, the inspected façades are deconstructed in horizontal and vertical structural elements and a univocal system of identification for each element is provided.

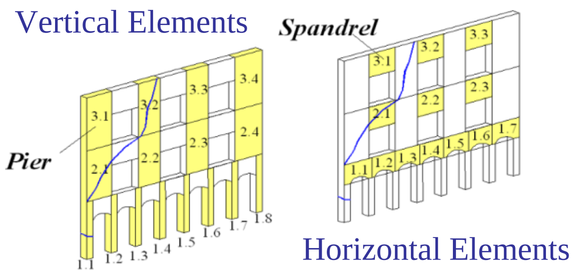

Figure 3-2 Correlation Identification and naming of the structural elements of a façade

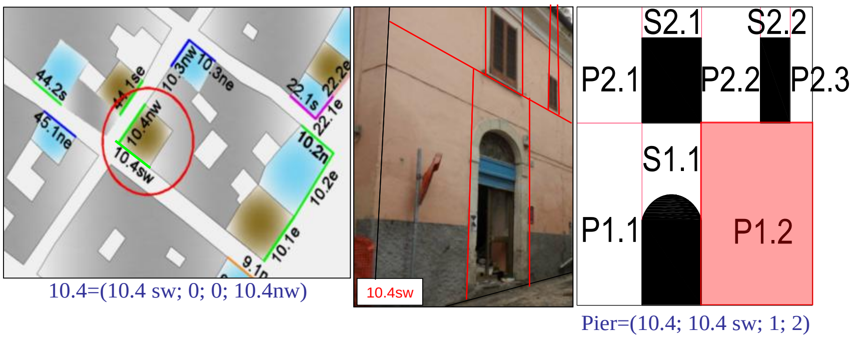

Figure 3-3 Structural enumeration convention of the façade 10.4sw

This process is accomplished by defining a grid on the façade, which defines a unique topology, see Figure 3-2, by associating two labels (nf, i) to each vertical (piers/columns/pillars) and horizontal (spandrels/arches) element of the façade, where (nf) and (i) identify the horizontal alignment (floor number) and the vertical alignment (position of the element at each floor as identified by the presence of openings) respectively. The example in Figure 3-3, which refers to the façade 10.4sw of the historic building introduced previously, illustrates how the mentioned façade is deconstructed into structural elements to enable reference to pier 2 on floor 1.

3.2. Relationships between Structural Elements and artistic assets

The correlation between SEs and aas is set by defining a string which contains the name of the inspected AA, the name of the observed façade, position of the SE to which the artistic asset is associated, and name of the artistic asset type. For instance, in order to define the artistic asset highlighted in red in the façade 2.1e in Figure 3-4, the string (2.1, 2.1e, 2, 1, Q2) links the architectural asset 2.1 to the façade 2.1e, the façade 2.1e to the position of the SE (first position on the second floor) to which the aa in question is located and the position of the SE to the type of aa, that is Q2, according to a classification introduced in the PERPETUATE project.

Figure 3-4 Artistic enumeration convention of the façade 2.1e

4. LOCAL DAMAGE TYPE AND LOCAL DAMAGE LEVEL

The method of the seismic damage assessment used to collect the data which will be used as input for encoding the logic trees is introduced in this section.

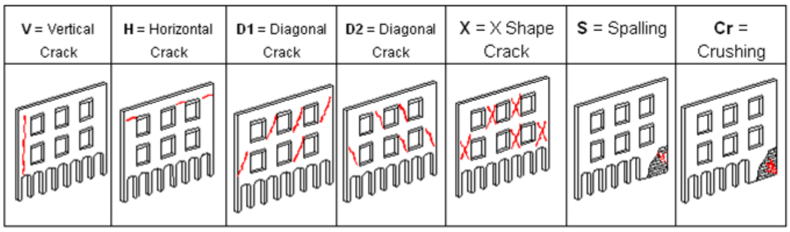

Figure 4-1 Structural damage types

The approach used is first to construct a rectilinear grid of each façade based on the structural elements (SE) and (aa) and then to associate with them the damage type and damage level. The possible structural damage types are listed in Figure 4-1 while damage levels are the following: LD: light damage, SD: significant damage, NC: near collapse and C: collapse. Figure 4-2(a) shows how the seismic damage types and levels of a façade are reported in the string (Pier_cracklocation) and (Spandrel_cracklocation) defined for the damaged piers and damaged spandrels respectively. Once these strings are defined, the reliability of the collected data is also included in the string. In this case the reliability is classified as High, since the data has been collected on site and photographic documentations is also available.

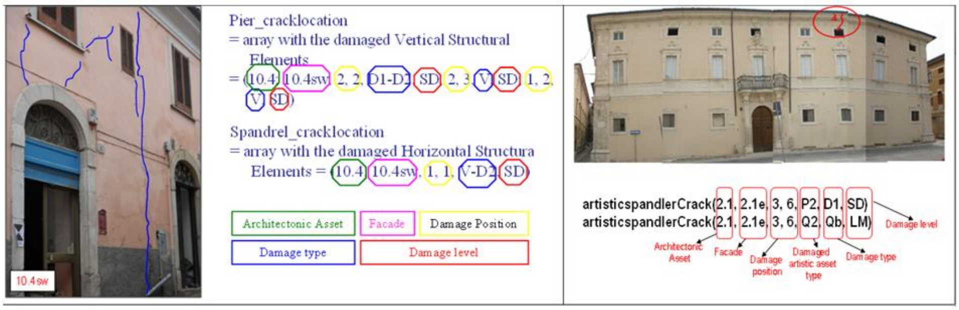

Figure 4-2 a): Damage identification for the SEs of the façade 10.4sw and b) damage identification for the aas of the façade 2.1e

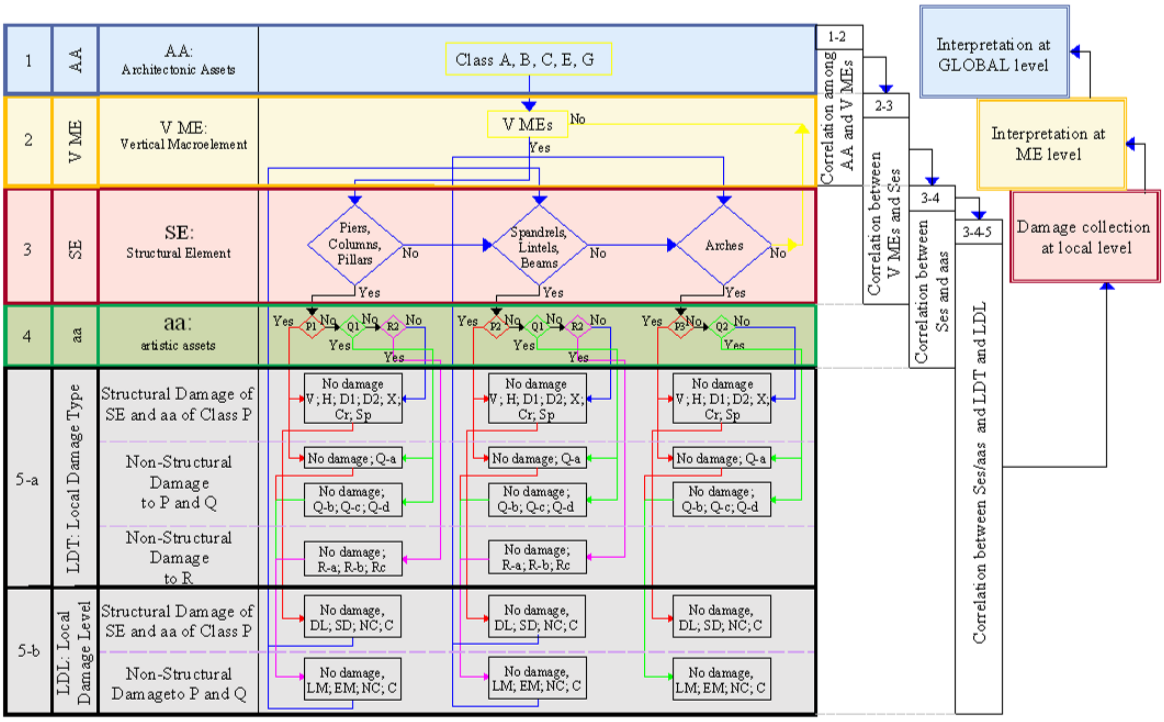

Figure 4-3 Flowchart for the data collection

As for the aas, the approach for the seismic damage collection is similar to the one exposed for the SEs. Indeed, once the damage types and damage levels have been defined for each artistic asset types, a similar string can be defined to store the damage for these elements. Figure 4-2b, shows how the seismic damage observed on aas is recorded. In order to outline the approach proposed for the data collection on the SEs and aas, the flowchart in Figure 4-3 is introduced to recapitulate the logic adopted in a post-earthquake survey aimed at identifying the collapse mechanisms by using LOG-IDEAH. As it can be observed from the flowchart, the post-earthquake survey entails to create the correlation between AA and MEs (1-2 in Figure 4-3), MEs and SEs (2-3 in Figure 4-3), and SEs and aas (3-4 in Figure 4-3); to localise the Local Damage Types (LDT) and Local Damage Level (LDL) at SE and aa levels (3-4-5 in Figure 4-3). Once this done; as it will be discussed in the next section, the global seismic behaviour of an AA is assessed by interpreting the damage collection at ME level and at AA level with the aid of logic trees.

5. DATA CAPTURE

The record of the collected seismic data has been facilitated by the use of a web-site (http://perpetuate.cs.bath.ac.uk/) which permits users to: create of new architectural asset records, effectively from anywhere, draw simplified sketches of inspected façades, record damage type and damage level to structural elements and artistic assets, upload photographic records of assets and asset damage, and assess probable collapse mechanisms using the reasoning process described in the previous section. Surveys are in progress and at this stage have collected records from buildings in L'Aquila and the Casbah in Algiers. Since LOG-IDEAH will be applied to both case studies, the system will be trained first on a sample of buildings damaged by L'Aquila earthquake and then on a sample of buildings in the Casbah of Algiers that has weakness and crack patterns not necessarily caused by seismic events. Information regarding the buildings and their structural elements is stored in XML format. The XML representation is converted to AnsProlog code and passed to clingo for processing. Integration between web-site and LOG-IDEAH is currently in progress. The Figure 5-1 shows the record of the observed seismic damage and the feasible collapse mechanism of the facades 22.1e and 22.1s, which are the only facades that can be inspected since the building in question has a corner position.

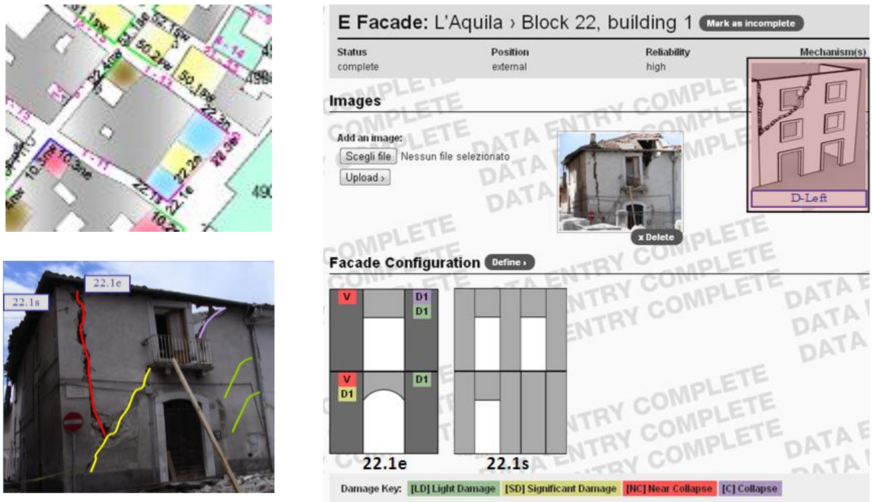

Figure 5-1 Extract from completed data entry in web browser

6. REPRESENTATION AND REASONING

6.1. Logic trees

The identification of the collapse mechanisms becomes extremely complex if uncertainties arise during the seismic damage assessment of an architectural asset. The three major uncertainties inherent to the evaluation of the structural behaviour of a building are related to: 1. inexperience of surveyors in post-earthquake assessments, 2. difficulty in the interpretation of non completely developed crack pattern, 3. incomplete surveys of architectural assets which have facades connected to other buildings.

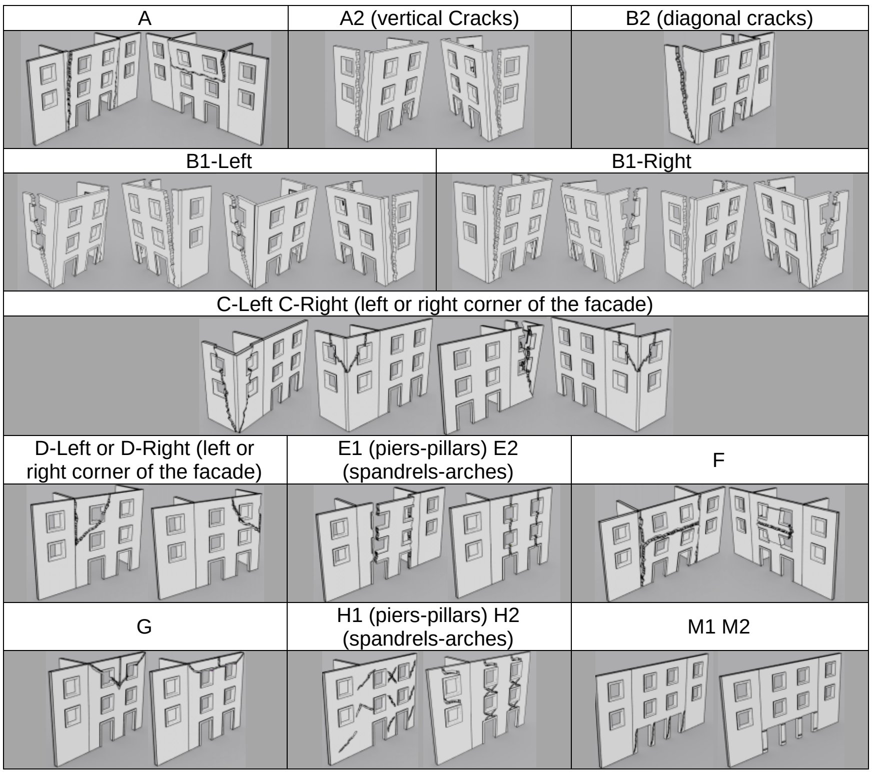

Figure 6-1 Collapse mechanisms

Therefore, by considering the numerous situations in which inspectors require a support for better understanding the seismic behaviour of an architectural asset, 19 possible collapse mechanisms of an AA, see Figure 6-1, have been identified and described by their associated crack patterns. Afterwards, this declarative description of the failure modes has been used for the implementation of logic trees, which identify the collapse mechanisms by matching the observed crack pattern with the failure modes of Figure 6-1. The rules developed in the logic trees for the pattern recognition are in some cases mutually exclusive, in some cases possible alternatives. Indeed, once the procedure has chosen to recognise or not to recognise a specific pattern as a mechanism of collapse, it is left to the operator to validate the choice. Therefore, when the mechanism has been identified, the operator has the following options: accept the mechanism of collapse proposed by the logic tree or reject the mechanism of collapse proposed by the logic tree and research another mechanism of collapse by enriching the data selected at the beginning of the procedure with more information already collected on site or by pictures, or adding new information. Once the procedure has found the feasible mechanisms, it is also estimated whether the mechanisms has:

HIGH PROBABILITY of occurrence: this means that the failure mode has been recognised on the basis of a clear crack pattern observed on one or more facades of the building under consideration;

LOW PROBABILITY of occurrence: this means that the failure mode has been recognised on the basis of a crack pattern which describes only a partial development of the identified mechanism;

LOW POSSIBILITY of occurrence: this means that the failure mode has been recognised on the basis of an incomplete survey due to denied access to the building for lack of safety after an earthquake or denied access to a facade which is connected to another building.

This approach, in order to be used as a post-earthquake assessment tool at territorial scale, requires to be implemented in a procedural programming approach. Given the declarative description of the logic trees (De Vos et al. 2012), the collapse mechanism inference procedure have been implemented in answer set program (Gelfond and Lifschitz 1988; Gelfond and Lifschitz 1991) with AnsProlog as implementation language (Baral 2003).

6.2. Applications of the LOG-IDEAH

By way of example the procedure is applied to identify the feasible collapse mechanisms for the building 22.1 introduced in section 5. To illustrate how the uncertainties affects the output, this is presented first for the facade 22.1e and then for both facades 22.1e and 22.1s. In order to identify the feasible failure modes, the procedure extrapolates the following information from the XML files created in uploading the data to the web interface: total number of inspected façades, total number of floors per façade, total number of piers and spandrels per floor, description of damage type, damage level and damage position, as it is highlighted in Figure 6-2 In case a) where the only inspected facade of the building is the 22.1e, the most severe cracks are the diagonal crack in yellow and violet and the vertical crack in red, highlighted in Figure 6-3. The two cracks describe the formation of a hinge at the bottom of 22.1e, which determines an overturning of the facade. By analysing the collected data of 22.1e with LOG-IDEAH, the procedure identifies the collapse mechanism D1-left which coincides with the collapse mechanism observed on site and recorded in the web browser. The identified failure mode by LOG-IDEAH has a HIGH PROBABILITY of occurrence, since this failure mode has been identified on the basis of a clear crack pattern (yellow, violet and red cracks) which describes an out of plane of the entire façade (from the floor 2 to the floor 1 as the system shows in Figure 6-2). However in case b) the data collected for both facades 22.1e and 22.1s are analysed and LOG-IDEAH identifies not only the collapse mechanisms D1-Left for the façade of 22.1e but also B1-Right for the façade 22.1s, see Figure 6-2b, that has not been recognised on site. As in the previous analysis, D1-Left occurs with HIGH PROBAILITY for the reasons mentioned above, while B1-Right occurs with LOW POSSIBILITY because it derives from an incomplete survey, since for the facade 22.1w, see Figure 6-3 connected to the adjacent building, the seismic damage has not been collected. Therefore, even thought the mechanism B1-Right derives from a bad connection between 22.1s and 22.1e and good connection between 22.1s and 22.1w, which has not been surveyed, the logic of the system is able to capture this failure.

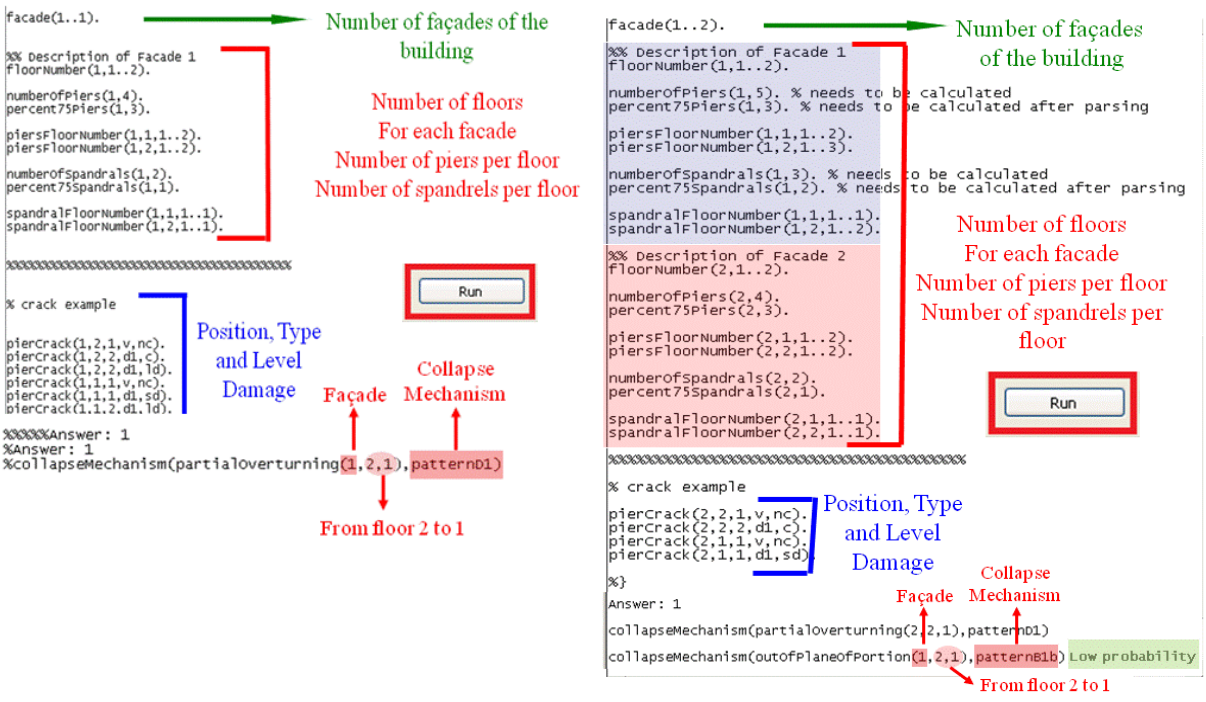

Figure 6-2: LOG-IDEAH applied a) on the façade 22.1e and b)on both facades 22.1e and 221s

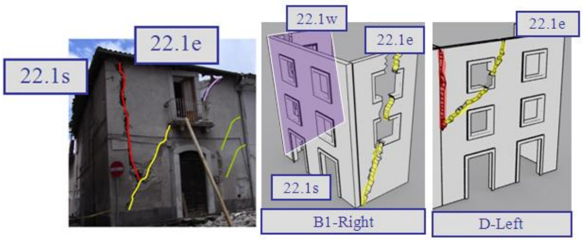

Figure 6-3: LOG-IDEAH Output applied to the façade 22.1e and façade 22.1s

7. DISCUSSION AND FUTURE WORK

In this paper, LOG-IDEAH an expert system able to identify the global seismic behaviour of an architectural asset on the basis of the seismic damage collected on site or by pictures has been introduced. In order to identify the failure mode, logic trees able to interpret the local seismic damage first at level of the macroelements and then at level of the architectural assets, have been implemented as a logic procedure. Since in case of an earthquake it is usually required to assess large amount of buildings, the logic trees have been written in answer set programs to automate the procedure.

At the moment buildings are assumed to be relatively regular for the purpose of continuous cracks. Piers and spandrels on different floors have similar size, lined-up are consecutive. The next version of the model and software will relax this constraint by using (structural) element as the basic component of a building rather pier or spandrel. In this way, wider piers can conceptually be encoded as three elements of type pier to allow for elements on several floors to be lined up.

The current model in Answer Set Program does not take into account facades for which no information is available, either because data was not available or because it is connected to another building. Once this included in the model, it will also be able to start reporting possible and probable collapse mechanisms.

REFERENCES

Applied Technology Council, - Procedures for postearthquake safety evaluation of buildings, ATC-20, Redwood City, CA, 1989

AIS, (2003). Asociacion Colombiana de Ingegneria sismica, Manual de Campo para Inspecion De Edificio Despues de un Sismo. Manizales, Colombia.

Applied Technology Council, Users manual: Mobile postearthquake building safety evaluation data acquisition system (Version 1.0), ATC-20i. Redwood City, California, 2003.

Baral, C. (2003). Knowledge Representation, Reasoning, and Declarative Problem Solving. Cambridge University Press, Cambridge, England.

Cadei M., Lazzari M., Salvaneschi P. (1990). Safety management of civil structures using knowledge based systems. In Proceedings of the third international conference on Industrial and engineering applications of artificial intelligence and expert systems - Volume 2 (IEA/AIE '90) , 1990

Carreno M.L.,Cardona O. D and Barbat A. H. (2004). Expert system feor building damage evaluation in case of earthquake. 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada, August 1-6, 2004, Paper No. 3047

D'Ayala D., Speranza E. (2003). Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings. Earthquake Spectra Vol.19, August, pp. 479-509.

D'Ayala D. (2005) "Force and Displacement Based Vulnerability Assessment for Traditional Buildings." Bulletin of Earthquake Engineering, Vol.3, Springer, pp. 235-265.

D'Ayala D., Paganoni S. (2011). Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009. Bulletin of Earthquake Engineering, Vol.9, Number 1, pp. 81-104.

D.P.C.M. 23 February 2006 (G.U. 7.3.2006, n. 55)

De Vos M., Padget J., Novelli V., D'Ayala D. (2012). LOG-IDEAH: ASP for Architectural Asset Preservation. 28th International Conference on Logic Programming

Dovers, SR, Handmer, JW. (1995). Ignorance, the precautionary principle, and sustainability. Ambio Stockholm [AMBIO]. Vol. 24, no. 2, pp. 92-97.

Gelfond, M. and Lifschitz, V. (1988). The stable model semantics for logic programming. In Proceedings of the 5th International Conference and Symposium on Logic Programming. MIT Press, 1070{1080

Gelfond, M. and Lifschitz, V. (1991). Classical negation in logic programs and disjunctive databases. New Generation Computing 9, 3-4, 365, 386.

Melchor-Lucero O. and Ferregut C. (1995). Toward an expert system for damage assessment of structural concrete elements. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 9 pp. 401–418

Novelli, V. and D'Ayala, D. (2011). Seismic damage identification of cultural heritage assets. Conference of Seismic protection of Cultural heritage, Antalya, Turkey.

Ogawa H. and Fu K. S., (1985). An inexact inference for damage assessment of existing structures. Int. J. Man-Machine Studies, vol. 22, pp. 295–306, 1985.

Centro Nacional de Prevención de Desastres (CENAPRED). Norma para la Evaluación del Nivel de Daño por Sismo en Estructuras y Guía Técnica de Rehabilitación (Estructuras de Concreto Reforzado). Cuadernos de Investigación, Número 37, México, 1996