Towards a systematic diagnosis of structural damage

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ABSTRACT: Traditionally, the diagnosis of damage is largely based on the intuition and experience of the surveyor. Despite its benefits, this approach to diagnosing can be subjective, and difficult to communicate. This paper discusses the limitations of the current intuitive approach, illustrated with the results of a questionnaire, and suggests a method to increase its quality and efficiency. This method proposes a systematic description of the development of structural damage, based on a uniform vocabulary, and a syntax that distinguishes between damage patterns, the processes leading to damage, and the factors that influence course and extent of these processes. By using this approach, it is possible to share the knowledge that is currently embedded in intuition and experience, and enhance the retrievability of a diagnosis. The benefits are clear: the opportunity to learn from cases, and make this knowledge available to the profession.

1 INTRODUCTION

The assessment of a building with damage has often been compared to the approach to a patient in health care. In both professions, the most important, but at the same time most difficult phase is the diagnosis. Despite the resemblances with medicine practice, the field of building pathology still lacks an ‘encyclopedia of diseases’. Although some atlases and expert systems are available (e.g. MDDS), especially for structural damage we still miss a consistent way of describing the processes leading to this damage, including a coherent use of a well-defined terminology.

Damage is the manifestation of a lack of performance of a building. Thus, the assessment of damage can be regarded as an evaluation of the present and expected loss of performance, combined with proposals for improvement or repair. Diagnosis is an essential part of this assessment: its aim is not only to indicate what has caused the damage, but, moreover, to try and understand what initiated the damaging process (root cause) and how this process has developed in time. In medicine, this understanding of the course of a disease is indispensable for finding ways to treat symptoms, to cure a patient of his illness, and, if possible, to prevent a disease from affecting other people as well.

The process of diagnosing damage is a deductive process. It is based on the evaluation of the available data on symptoms and context of the damage, and of the investigator’s knowledge on damaging processes. This leads to the formulation of one or more hypotheses, which, subsequently, are verified until the cause of damage is diagnosed with a certain accuracy. For a sound diagnosis, the investigator needs thorough insight into all processes possibly leading to damage, and also the ability to distinguish between these processes. This is complicated by the fact that damage often results from several causes, rather than from just one. In its Recommendations, the ICOMOS International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) (2005) states: ‘This is why intuition and experience are essential components in the diagnostic process.’

A correct diagnosis of the damaging process and its root cause is necessary for the proper assessment of damage, and the importance of this correctness has even more increased since we aim at minimal interventions. Therefore, the best way to improve the assessment of damage is by improving the accuracy of the diagnosis. There are two ways to achieve this: either by improving the quantity and/or quality of the information available to the surveyor; or by improving the qualities of the surveyor in processing (analysing, interpreting, and evaluating) this information. Please note that the word ‘information’ is used here for data and knowledge in two domains. On the one hand, it refers to data on a specific case: the symptoms and the context of the damage. On the other hand, it also concerns the more general knowledge of damaging processes, which is essential for the formulation of hypotheses.

In the past decades, many studies have contributed to the improvement and facilitation of the diagnosis of
damage. We can classify these studies into five groups, according to their main goal:

- Improvement of the data on damage;
- Improvement of the knowledge on damaging processes;
- Improvement of the analysis of information;
- Improvement of the evaluation of information;
- Improvement of the exchange of information.

Many studies belong to the first group. Their aim is to improve the completeness and quality of data on the symptoms or the context of damage. These studies have resulted in new and better techniques for on-site investigation, for on-site and laboratory testing, and for monitoring. Special attention has been paid to the development of a range of non-destructive tests (Binda et al. 2000, Binda & Saisi 2002). A good overview of the techniques currently available is given in the documentation of the Onsiteformasonry project (2005).

Tragedies such as the sudden collapse of the civic tower of Pavia in 1989, the Umbria-Marche earthquake of 1997 and the Molise earthquake of 2002 have led to a second group of research projects. This group has aimed at extending our knowledge on specific causes of damage. Especially the creep behaviour of masonry and the effects of seismic actions on buildings have been investigated (Ignoul et al. 2006, Binda et al. 1992).

The third group of studies has focused on the development of techniques to help the investigator to analyse the present behaviour of a structure and interpret the way damage has occurred. The growing possibilities in computation have led to a range of methods and strategies such as various methods for numerical modelling (Lourenço 2002). For the analysis of collapse mechanisms due to seismic action, the macro-element approach has commonly been used (Doglioni et al. 1994). One of the applications of this approach can be found in the digital, didactic handbook MEDEA (Manuale di Esercitazioni sul Danno Ed Agibilità), which gives an overview of damage patterns in masonry and concrete structures that have suffered from an earthquake (Papa & Zuccaro 2004).

Furthermore, a fourth group has proposed methods to facilitate the evaluation of information. One major aspect in this is the evaluation of the vulnerability of structures, with the aim to predict their future behaviour and the related risks (Augusti et al. 2001, Speranza et al. 2006). The Multi-Hazard Assessment of Vulnerability method (MHAV (historic buildings)) uses the macro-element approach to link building typologies to their characteristic vulnerabilities to natural hazards such as earthquakes, storms, and floods. The method evaluates the expected loss of both material and cultural significance (D’Ayala et al. 2006).

Finally, a fifth, smaller group of studies has focused on the improvement of information exchange. These studies point out that a basic need is still to be fulfilled: the need for better communication between all parties involved in a restoration project. Suggestions have been made to improve the exchange of data by using a consistent terminology and standardised survey forms (Van Balen 2001, Kelley & Sparks 2006).

The difficulties in information exchange mentioned above are part of a larger problem: they show the limitations that are inherent to our traditional diagnostic process. The development of new techniques and methods for data collection, analysis and evaluation has certainly contributed to the improvement of diagnosis. However, less attention has been paid to the improvement of the diagnostic process itself and to a more efficient, practicable distribution of knowledge. This paper discusses the limitations of the current intuitive approach, and suggests a method to increase its quality and efficiency.

2 DIAGNOSING DAMAGE: LIMITATIONS OF EXPERIENCE AND INTUITION

The current approach to diagnosing damage is, for most experts, an intuitive one. The deduction is a mental process that strongly depends on the intuition and the experience of the investigator. These abilities are highly valued, but the subjectivity of the approach also brings about some inherent limitations.

Our brains are fast processors, and they are well-trained in finding references. When diagnosing damage, we use this ability to evaluate and compare a new situation with our personal experience. It helps us to judge and weigh different types of information, and it makes us capable of readily formulating the most probable hypothesis.

However, despite its benefits, this method has some disadvantages. First of all, we select our references more or less at random. This is a quick way to retrieve our knowledge, but it is also subjective, irreproducible, and sometimes inconsistent.

Then, experience can also make us biased. It could make us jump to a conclusion by paying more attention to facts that support our initial ideas, while we overlook facts that are contrary. In this way, we would fail to notice alternative hypotheses that could explain the type of damage as well.

Moreover, our intuitive approach may keep us unaware of the assumptions we make during the deduction, unwittingly and unwittingly. Because communicating this approach is difficult, the facts and suppositions on which the diagnosis is based may remain veiled to others. This makes it hard to judge the reliability of a diagnosis, since the conditions under which the deduction is valid are insufficiently clear.

To support and improve the diagnostic process, we need to understand how the process of diagnosing works. Therefore, a questionnaire was held among
This questionnaire contained pictures of four buildings with visible damage, and for each case the experts were asked to answer the following questions:

- What could be the cause of this damage?
- On what information do you base this hypothesis?
- What data would you need to be able to verify your hypothesis?
- If no initial hypothesis could be established on the basis of the photograph(s), what would be the next step(s) in the investigation process?

The results of this questionnaire were surprising. On the basis of a first impression, the experts have found different clues, made different assumptions, and suggested a range of possible causes. In the next paragraphs, the results of two of these cases are discussed (Figs 1–5).

The damage in the sidewall of building A, as shown in Figure 1, forms a typical damage pattern. Most experts immediately referred to the classic ‘back-of-an-envelope’ yield line pattern, which is the failure mode of a rectangular slab, supported around its perimeter, and uniformly loaded perpendicular to its plane. The crack pattern, thus, gives a clear indication of the collapse mechanism. In accordance to the plate bending mode, the loading must have been horizontal, out-of-plane, and directed outwards. In this way, the symptoms of the damage led to hypotheses such as wind load (wind suction) and horizontal impact load (explosion), but also hindered volume changes of a concrete floor incorporated into the wall.

The experts used the context of the damage to exclude some specific causes. The local character of the damage and its distance to the ground led them to omit the possibility of settlement as initiator. Furthermore, some experts (correctly) assumed the building to be located in the Netherlands, which made them conclude that an earthquake would be a less likely cause.

Figure 2 gives an overview of the different hypotheses and anti-hypotheses that were brought forward by the participants. It also shows the arguments and the assumptions that the experts used to frame and support their hypotheses. It appears that, despite the typicality of the damage pattern, the cause of damage is not so obvious. Therefore, in response to the third question, experts asked for more data on the properties of the building, on its construction history, on the nature of the location, and on the characteristics and distribution of the damage.

The damage in building B is less evident than the damage in building A. It can be described as an in-plane deformation of the façade (Fig. 3). The skewing
of the windows at the first floor, visible in Figure 4, is accompanied by severe crack development in the lintels and sills of the windows, and in the arch above the door opening. The edges of the cracks show displacements and demonstrate that the parts on either side of the fracture have undergone a clockwise rotation.

Concerning the information on the context of the damage, the participants particularly focused on the construction of the building. For example, they pointed out the difference between the timber-framed construction of the sidewall, and the stonework façade. In addition, the relatively large openings in the façade, the apparent age of the building, and speculations on the adjacent building on the left side and the open area on the right side led them to the assumption that building B may have little or no lateral stability. This assumption helped them to explain the lateral displacements in the façade.

Figure 5 shows that, in this case, both the symptoms and the context of the damage were used to formulate hypotheses. These hypotheses vary from environment-related processes such as differential settlement, to overloading due to a lack of horizontal restraint, and hindered volume changes due to corrosion of the anchors. The hypothesis of differential settlement appears to be supported by many arguments and assumptions. Nevertheless, its root cause remains unclear, although several options were expressed.

Summarising, the results of this questionnaire demonstrate the benefits of our current approach. Even on the basis of only some photographs, experts have shown that their skill and experience make them able to formulate a hypothesis that could explain the damage.

The use of photographs in this questionnaire did hinder the evaluation of damage and context. Nevertheless, this method has been chosen with precisely this goal: It forced the participants to be more aware of the facts on which they based their hypotheses. In this way, the responses also show the limitations of the intuitive approach.

One of these limitations is that experience can sometimes make experts biased. This could be overcome by joining our experience, as the range of alternative hypotheses resulting from the combination of the responses shows.

Furthermore, the results emphasize that our line of reasoning is influenced by unconscious assumptions. For example, most experts interpreted the damage in building A as caused by out-of-plane loading of a slab supported around its perimeter. Apparently, they assumed that the perimeter of the crack pattern matches with the borders of a room behind the wall. Yet, in reality the floor lies at the level of the horizontal crack, which omits the possibility of wind suction and explosions as a cause, and increases the likeliness of hindered volume changes of the floor itself as a hypothesis. It is clear that assumptions like these should be mentioned explicitly when formulating a hypothesis.

Based on the results of the questionnaire, we can now make some suggestions to improve the current approach to diagnosing:

– Pay more attention to alternative hypotheses;
– Place more emphasis on explicitly mentioning the facts and assumptions on which the diagnosis is based;
– Find ways to join and share our experience; and
– To obtain these goals, our knowledge needs to be accessible, retrievable, and communicable.

3 DATA ACCESS

To improve the accessibility of our knowledge on damaging processes, we should examine how our experience-based reference system could be supported by a more systematic way of data cataloguing. A possibility is the use of knowledge-based systems. These systems are not a new phenomenon: They are widely used in health care, and also for building pathology some systems do exist. Knowledge-based systems consist of a framework to contain data, and a tool to make these data accessible. This tool could be an index, but also a deduction function: a set of rules composing a ‘wizard’ that guides a user through a list of questions, to determine which specific information is asked for, or to find a solution to a specific problem. In building
pathology, a knowledge-based system could contain an overview of damaging processes, including clear selection criteria how to distinguish between them. The benefits of such a system are obvious: It supports the investigator in the framing of a hypothesis, while the systematic approach makes the method unambiguous and, therefore, communicable. Prerequisite is a consistent use of terminology, to make the stored knowledge retrievable and suitable for exchange.

An example of a knowledge-based system is the expert system and decision support tool MDDS (Monument Damage Diagnostic System, successor of the Masonry Damage Diagnostic System). This system aims to facilitate a minimal intervention approach, by offering a structured, transparent and consistent method for analysing and diagnosing damage. MDDS helps to collect and order all relevant data on symptoms and context, and supports the interpretation of these data by offering background information on damage types and patterns, damaging processes and methods of testing (van Hees et al. 2005).

Until recently, MDDS mainly contained information on damage related to the interaction between materials and environmental factors. To fill this gap, a module on structural damage is now being developed. In the next section, it is explained why a diagnostic instrument for structural damage should be based on a clear distinction between processes and factors, and on the use of a consistent terminology.
DISTINGUISHING BETWEEN DAMAGES

In accordance with the suggestions made in the previous sections, an instrument for supporting the diagnosis of structural damage should consist of two databases. We need a knowledge base, in which we can store our combined knowledge on damage and damaging processes. And then we need a rule base to make this knowledge accessible and retrievable.

The framework of both databases should provide the diagnostic instrument with three types of use. First, it should allow for a passive use: The knowledge base should serve as a reference, as an encyclopaedia on structural damage, made accessible with a traditional index. A more active use is possible by supplying a search function, so that the encyclopaedia can also be searched by criteria other than the ones mentioned in the index. Similarly, hyperlinks between related articles can help improving the retrievability of information.

These passive and active uses help to retrieve specific information. However, we may miss essential facts, if we do not specifically ask for it. To establish a diagnosis, it is not only necessary to verify the most probable hypothesis; we also need to be aware of alternative hypotheses that could explain the damage as well. The diagnostic instrument can be particularly important to overcome this problem by offering interactive support.

When using this interactive function, the system should evaluate the data entered by the user, by applying the inference rules stored in the rule base. The input data are used as arguments, from which the diagnostic instrument tries to derive conclusions on the nature and cause of the damage. In this deduction, the instrument should first check the possibility that a certain process could have led (or contributed) to the damage under investigation. Next, it should rank all possible processes on the probability that they could have taken place. In this way, the interactive function can supply the user with a hierarchical overview of alternative hypotheses.

To allow for a passive, active and interactive use of the diagnostic tool, all information on damaging processes should be classified and presented in a systematic and structured way. Therefore, all data contained in the knowledge base need to be of uniform language, in vocabulary and in syntax. This asks for clear definitions of damage, and for a logical way of describing damaging processes. These issues are discussed in the following two sections.

4.1 Uniform vocabulary: clear definitions of damage and damage patterns

The consistent use of a clear terminology is a prerequisite for communication without misunderstandings. Several glossaries on damage and deterioration exist next to each other. However, especially for databases, a uniform vocabulary is essential. For instance, MDDS has a built-in dictionary of damage terms. It would be profitable to compare and combine these individual glossaries into one.

In the process of diagnosing, we should also be aware of the objectivity of our word choice. Our description of damage should be independent from the presumed cause, to prevent preliminary assumptions. For instance, we should be cautious when using the terms ‘material decay’ and ‘structural damage’ before a diagnosis is established, as these terms imply the cause of damage. Therefore, we need an unbiased typology of damages. A proposal for a neutral description of structural damage patterns can be found in Naldini et al. (2007).

4.2 Uniform syntax: clear distinction between processes and factors, and between symptoms and context

Damage often results from several contributory causes. Hence, insight into the whole process leading to damage is indispensable for diagnosing. This
insight is particularly important when aiming at minimal intervention. To be able to evaluate an intervention on its effects on the performance of a building in time, we need to know how the damage occurred, how it evolved, and under what circumstances. Thus, rather than on the root cause alone, we should focus on the development of damaging processes.

To describe damaging processes, we need a clear vocabulary, but also a uniform syntax. The syntax suggested in this paper reflects the relations between the different phases of the processes. This concept of a structural failure mechanism has two general rules (de Vent & Hobbelman 2007a, b).

In the first place, the structural failure mechanism divides each damaging process into four steps: event, impact, effect on the structure, and damage pattern (Fig. 6). These steps describe the course of a damaging process. The arrangement allows for an easy comparison between the various processes.

Secondly, the structural failure mechanism clearly distinguishes between processes and factors. The damaging processes lead to damage, while the factors influence the course of a process and/or the extent of its effects. Each factor can affect a transition between two of the steps, and is related to the scale on which this part of the damaging process takes place. Therefore, the factors of influence can be separated into three main categories: environmental variables, geometric variables, and material variables (Fig. 6).

This systematic description will help improve the diagnosing by giving insight into both the possibility that a certain process has led to damage, and into the probability that this process has taken place. In this way, it will give insight into the time path of the occurrence of damage. This will help to choose an optimal intervention.

5 EXAMPLE: PRELIMINARY OVERVIEW OF STRUCTURAL FAILURE MECHANISMS

The knowledge base of the diagnostic instrument should contain an as complete as possible description of all damaging processes including their factors of influence. A study of literature has resulted in a preliminary overview of structural failure mechanisms. A condensed version of this overview is shown in Figure 7.

For clarity reasons, the structural failure mechanisms have been subdivided into three main groups of causes: differential settlement, overloading, and hindered volume changes. As can be seen in the first three columns, differential settlement of the foundations can be caused either directly by variations in loading or in bearing capacity, or it can be induced by differential settlement of the soil, due to local variations in the subsoil or changes in the underground (e.g. construction works).

Each category of causes has been linked to typical damage patterns, as illustrated in the last column. The overview in Figure 7 only mentions the damage patterns related to differential settlement. A more comprehensive discussion of damage patterns can be found in Naldini et al. (2007).

This preliminary overview of structural failure mechanisms needs further organising to make it applicable in a computerised knowledge-based system. Principles of mechanics will be used to streamline it to a greater extent.

More work still needs to be done on the rule base, which should contain the inference rules meant to distinguish between processes. These rules will be based on the factors of influence. A preliminary list of the factors related to differential settlement is given between the four columns of Figure 7.
Like in medicine, understanding the course of damaging processes is indispensable for finding ways to treat and prevent structural defects in buildings. The results of the questionnaire have shown that, although intuition and experience allow us to readily analyse damage and formulate a hypothesis, we should be aware that our current approach to diagnosing can be subjective and difficult to communicate.

To improve this diagnostic process, this paper has presented a method of describing damaging processes in such a way that it allows for a systematic overview of all alternative hypotheses that could be formulated in such a way that it allows for a systematic overview presented a method of describing damaging processes subjective and difficult to communicate. Such an expert system would help to make a diagnosis more explicit, so that it is easier to communicate. Such an expert system would be applicable in practice, both as a learning tool for novice surveyors, and as a support tool for experts. Moreover, it should help in sharing knowledge among all professionals.

REFERENCES

vulnerability of monumental buildings. Structural Safety
23(3): 253–274.

Binda, L., Gatti, G., Mangano, G., Poggi, C. & Sacchi
Landiani, G. 1992. The collapse of the civic tower of
Pavia: a survey of the materials and structure. Masonry

procedures for the diagnosis of historic masonries. Cons-

Binda, L. & Saisi, A. 2002. State of the art of research on
historic structures in Italy. ARIADNE 11 Workshop ‘His-
toric structures’ – programme of the EC 5th Framework
activities, Praha, Dejvice, 20-26/05/2002.

model for multi-hazard assessment of the vulnerability of
historic buildings. In P.B. Lourenço et al. (eds), Proc. 5th
Int. Conf. Structural Analysis of Historical Constructions,
New Delhi, India: 121–140. Delhi: Macmillan India Ltd.

Doglioni, F., Moretti, A. & Petrini, V. 1994. Le chiese e il
terremoto. Trieste: Edizioni LINT.

system for analysis of damage to plasters due to salt
and moisture. Proc. Sem. Soluble salts in the walls of old
buildings, Damages, processes and solutions, Lisbon:
16.1–16.11.

ICOMOS ISCARSAH 2005. Recommendations for the anal-
ysis, conservation and structural restoration of architec-
tural heritage. Istanbul: Maya Basin Yayı̇n.

2006. Creep behaviour of masonry structures – Failure
prediction based on a rheological model and labora-
tory tests. In P.B. Lourenço et al. (eds), Proc. 5th Int.
Conf. Structural Analysis of Historical Constructions,
New Delhi, India: 913–920. Delhi: Macmillan India Ltd.

Kelley, S.J. & Sparks, S.P. 2006. The challenges of struc-
tural stabilization following the hurricane Katrina disaster.
In P.B. Lourenço et al. (eds), Proc. 5th Int. Conf. Struc-
tural Analysis of Historical Constructions; Possibilities
of Numerical and Experimental Techniques, New Delhi,
India: 261–268. Delhi: Macmillan India Ltd.

Lourenço, P.B. 2002. Computations on historic masonry
structures. Progress in Structural Engineering and Mate-

Naldini, S., Vent, I.A.E. de, Hees, R.P.J. van & Binda, L.
2007. Definitie van constructieve schadepatronen; De
MDDS constructieve schadeatlas. In J.M. van der Veen
(ed.), Praktijkboek Instandhouding Monumenten; Deel II-

In Dutch, English article in preparation.

Onteiformasonry 2005. Results and research methodologies
of Onsiteformasonry; On-site investigation techniques for
the structural evaluation of historic masonry build-
ings. Berlin: Federal Instititue for Materials Research and

and didactic handbook for seismic damage evaluation.
In M. Garcia-Fernández & A.B. Walker (eds), Proc.
XXIX General Assembly of the European Seismological
Commission, Potsdam, Germany.

Speranza, E., Viskovic, A. & Sepe, V. 2006. Integrated method for
the assessment of the structural vulnerability of his-
toric towers. In P.B. Lourenço et al. (eds), Proc. 5th
Int. Conf. Structural Analysis of Historical Constructions,
New Delhi, India: 651–658. Delhi: Macmillan India Ltd.

Van Balen, K.E.P. 2001. Learning from damage of masonry
structures, expert systems can help! In P.B. Lourenço &
P. Roca (eds), Historical Constructions 2001, Possibilities
of Numerical and Experimental Techniques, Proc. 3rd Int.
Seminar at Guiamares, Portugal, University of Minho:

Vent, I.A.E. de & Hobbelman, G.J. 2007a. Failure mech-
anism as a method for the assessment of structural
damage. In C.A. Brebía (ed.), Structural Studies, Repairs
Southampton: WIT Press.

Vent, I.A.E. de & Hobbelman, G.J. 2007b. Determining the-
etorical failure mechanisms for structural damage. In
A. Zingoni (ed.), Proc. 3rd Int. Conf. Structural Engineer-
ing, Mechanics and Computation: 219–220, full version