Archaeological Site of Baalbek
Structural Risk Management Strategy

P. Smars*, T. Patrício†, M. Santana Quintero‡, A. Seif§

Abstract

This paper presents works done in March-July 2010, in the framework of the UNESCO programme "Capacity Building of Human Resources for Digital Documentation of World Heritage Sites Affected by 2006 War in Lebanon". The aim of the project was to develop a methodological framework for the establishment of a *Risk Preparedness Strategy* (RPS) for the World Heritage Property of Baalbek (Fig.1,2; [1, 2]).

The archaeological site is potentially exposed to various disasters, resulting from various kinds of hazards, either natural (mainly earthquakes), or human (tourism, armed conflicts, etc). It is also exposed to slower but continuous and cumulative degradations, resulting from weathering or pollution.

The present paper will focus on the *structural risks*.

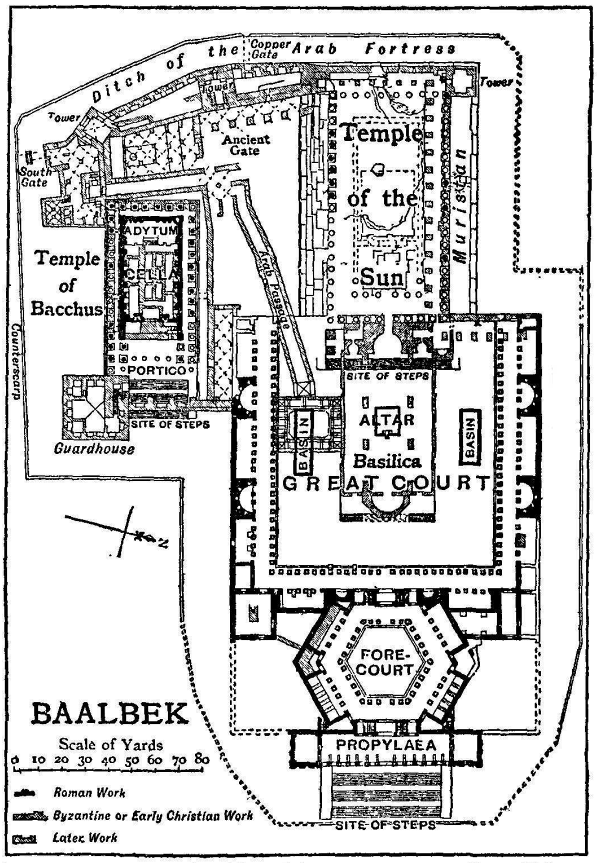
Figure 1: 360° panorama of the site from the steps of the temple of Jupiter. March 2010.

*Department & Graduate School of Cultural Heritage Conservation, National Yunlin University of Science & Technology, Dou-Liu, Taiwan, *smars@yuntech.edu.tw*

†Dr architect, Self-employed, Bruxelles, Belgium

‡R. Lemaire Centre for Conservation, K.U.Leuven, Leuven, Belgium

§Directorate General of Antiquities, Beirut, Lebanon



After Puchstein, with permission of Georg Reimer Emery Walker sc.

Figure 2: Site Plan (after Puchstein).

1 Risk Preparedness Strategy

The interest of a RPS results from the fact that resources are limited and risks are endangering the values at stake (affect the buildings and its visitors). It is therefore reasonable to prepare a strategy to maximise the effectiveness of the actions which are taken. The main outcome is the definition of priorities: where and when should the money be first spent to better protect the values at stake? A *risk map* will synthesise the key elements of decision about possible actions:

- No action; understand the risk (hopefully) and accept it.
- Structural intervention on the building (reinforcement) (with various level of intensity, from maintenance to more extreme interventions[1]).
- Non-structural mitigation: limit access (i.e. reduce vulnerability), prepare an effective disaster response...
- Improvement of knowledge.

[1] "1.7 No action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in cases where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g. after seismic damages); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way." [3]

Information about the first phase of the project (laser scanner documentation), about other aspects of the risk assessment and about structural pathology interpretation can be found elsewhere [4, 5].

2 Methodology

Conceptually, a quantitative evaluation of the risks seems possible. PEER, the *Pacific Earthquake Engineering Research Center* has for instance developed a very complete framework for a scientific evaluation of seismic performance of buildings: *performance-based earthquake engineering* (PBEE) [6, 7]. A requirement of this approach is to be able to characterise precisely hazard (earthquake occurrence), vulnerability (*structural and damage analysis*) (physical effect of a given earthquake on the building) and expected losses (consequence of a deterioration on the values).

This is an excellent direction to follow but a difficult one. In the reality of Baalbek (and actually of many other sites or buildings), difficulties arise. Quantitative evaluations are tainted by uncertainties: *random uncertainties* (which can be dealt by probability methods and PBEE) but also *epistemic uncertainties* (related to insufficient knowledge on the process involved, to the choice of models. . .). In the case of the structures of the archaeological site of Baalbek, there are two problems:

- At this stage, data is too scarce to characterise random uncertainties (precisely enough to lead to useful estimates).
- They are numerous epistemic uncertainties (models used in the past to evaluate some of the structure of the site were clearly not sophisticate enough to provide reliable estimates of the vulnerability; to study the seismic vulnerability of large block masonry structures is not a trivial task) (the conservation objectives needs to be clarified).

This type of situation is not unique. Klinke and Rena [8] categorise risks, assigning them to six specific classes characterised by the (a) the expected extend of damage, (b) the probability of occurrence and (c) the level of knowledge (the uncertainties on *a* and *b*). For each class, they recommend a specific strategy. They argue for instance that a "risk-based" approach (example: *PBEE*) is not the most suitable when the level of knowledge is low[2]. A decision tree is given to assist risk managers in making their choices. Five central questions have to be answered.

1. *Is the risk potential known?* In the case of Baalbek, the main risks are those affecting the persons (mainly the visitors) and the structures (their values). Both are identified but not quantified: the vulnerabilities are not yet estimated and data necessary to compute reliable estimates is lacking. The hazard should be evaluated (local

[2] "The adoption of partial factors, or the possibility of probabilistic model factors discussed in section 6.4 of the core document may not be realistically applicable to heritage structures.

In such cases, additional evidence obtained from complementary activities (comparative analysis, analysis of historical information) may, through engineering judgement, reduce the uncertainty.

Engineering judgement may take into consideration the comparative approach and historical approach." [9]

Figure 3: Left: Columns of the temple of Jupiter (foreground) and temple of Bacchus (background). Right: column of the propylaea. March 2010.

definition of the seismic hazard), the materials and construction techniques should be investigated, visitor statistics and habits should be measured. In similar situation, Klinke and Rena recommend three strategies:

a) *To make a "quick and dirty" screening on the risks.* In Baalbek, priorities could be given to the most valuable structures who experienced damages in the past: the columns of the *temple of Jupiter* and the *temple of Bacchus* (Fig.3-Left). Those priorities could be calrified on the base of structural pathology interpretation of the existing structures (see Section 3, [5]).

b) *To fund research projects aimed at improving knowledge.* In Baalbek, that would mean gather new data and estimate key vulnerabilities. Collaborations with Universities could be stimulated, especially if access to data is facilitated.

c) *To take precautions and design resilience measures.* In Baalbek, the laser scanner survey of the site can be seen as an "insurance" which would facilitate repair in case of the collapse of one of the structures (discussed further below in the discussion of the concept of *reversibility*). So would be the training of the personnel (capacity building) to identify risks, respond efficiently to disasters and to coordinate their actions [10].

Figure 4: Left and Right: Northern perimeter wall of the great court. March 2010.

2. *Is the threshold on criteria exceeded?*. Without quantitative measures of the risks, it is difficult to answer unambiguously to this question. It is nevertheless possible to look at what happened in the past and assume that similar effects could happen again (comparative approach [11]). Following the earthquake of 1759, a significant number of structures collapsed or were damaged. Since then, some of them were repaired. They may be weaker than in the past (lost integrity) or stronger (added steel and reinforced concrete... if their effect is positive). At this stage, those past interventions were not documented but the situation raises sufficient concern to answer positively to the question.

3. *Is the damage potential known?* In the case of Baalbek, the damage potential is not precisely known. As a matter of fact, it may be important first to precise what should be intended by *damage*. We conjecture that damages on structures should be evaluated in reference to their multiple values and not only in their capacity to remain standing. For new structures, the eurocodes [12, 13] require that *ultimate limit states* (concerning the safety of people and structures; possibly of their content) should not be reached during their *design working life*. But, in the case of archaeological sites, both the ideas of ultimate limit state and of working life may

be misleading or possibly altogether inappropriate[3]. A debate among stakeholders (i.e. those who have something to gain or loose in the matter) is necessary to identify and prioritise the values to protect [14, 10] in order to eliminate any ambiguity. Indeed, reinforcements measures may sometime endanger key heritage values (the "character defining elements" of [9]) for the sake of stability at all cost (see Fig.3-Right). This debate, called *participatory discourse* by Klinke and Rena [8] is part of the *Discourse-based Management* strategy. It is also related to the question of *reversibility* discussed below.

Concerning the evaluation of the physical vulnerability of the structures, the importance of the modelling strategy has to be stressed out. Crude models can be used to filter out low-risk situations but should not be used to justify and design interventions[4]. The high cultural value of the structures, the complexity of their behaviour, the requirement of minimum intervention [11], and the respect for public money should prompt the analyst to use models fitting the reality as well as it is achievable today[5]. As a minimum requirement, models should give a measure of the vulnerability [3]. Linear elastic models cannot provide such a measure. In some precise circumstances, they can be used to safely design new constructions (because such constructions follow typical models and use materials & techniques respecting standards [12, 13]). But this is not the case for masonry made of large blocks (like in Baalbek) whose behaviour under dynamic actions is largely *rocking* (and not flexure like for most modern constructions) [16, p.326]. A good survey of available methods is given by DeJong [17].

4. *Is the disaster potential high?* The high cultural importance of the site means that any loss of value is to be considered as serious. In this case, Klinke and Rena recommend three different strategies in function of the level of uncertainty of occurrence of a disaster. If the probability of occurrence is not well known, they recommend to improve knowledge. If it is low, a *risk-based* strategy should be followed and the vulnerabilities should possibly be reduced. If the probability of occurrence is high but not perceived as such (because of its remoteness in time, think about the long return period of the earthquakes), a *discourse-baseed* strategy should be followed, awareness should be raised and clear conservation objectives should be set.

An intermediate conclusion (if one is ultimately targeting a PBEE type approach, a *risk-based approach* following Klinke and Rena) is that a RPS should not be static: the approach is likely to be mainly qualitative and discourse-based at first and to acquire progressively more quantitative elements[6].

[3]"Heritage structures do not have a defined working life and therefore the approach recommended by section 7.2 of the core document is inappropriate. Conservation should therefore be regarded as a continuous or incremental activity." [9]

[4]"An examination that suggests that the structure does not satisfy safety requirements does not necessarily mean that safety conditions are lacking" [15]

[5]A perfect fit will never be possible [16, p.321]

[6]This is a usual structural assessment strategy. "2.2 Data and information should first be processed

- New research could help providing better estimates of the random uncertainties (a local evaluation of the seismic hazard – taking into account the geological situation of the site, investigations on the materials, . . .).
- Research on the construction techniques and on the inner constitution of the structures (survey and non destructive techniques) can reduce epistemic uncertainties.

Some debate is also going to be necessary to eliminate ambiguities on the values (see above).

3 Qualitative Informations

For the safety evaluation of heritage buildings, it is rarely possible to rely exclusively on quantitative structural analysis (mathematical models). Other sources of informations (possibly more qualitative[7]), can also be used to give useful clues for a better modelling and more assurance to a diagnostic:

- The time dimension should be considered.
- Historical information (Fig. 5). Many structures of the sites still keep the traces of past earthquakes (the last important one occurred in 1759) and previous interventions. Analysing them can help us to understand the behaviour of the structures and also to evaluate the effects to be expected in case of a new occurrence [16, p.326-333] [15].
- Changes should be monitored [3]. The implementation of the "risk map" will allow an easy comparison of the situation at different period.
- Structural pathology analysis. A good understanding of the existing pathologies and of their evolution greatly facilitates the evaluation of risks. Fig 6 is an example of interpretation maps prepared using data gathered by a laser scanner [4]. Guidelines for such analysis are given elsewhere [5].

4 Guiding Concepts

The concepts of *value*, *reversibility* and *ubiquity* are now discussed as they are important to assess the losses resulting from potential disasters (or critical events).

Values

All architectural elements do not have the same value. If a part of a structure collapses during an earthquake, it may be an original remain, undisturbed, or it may be an original

approximately, to establish a more comprehensive plan of activities in proportion to the real problems of the structures." [3]

[7] "2.5 Diagnosis is based on historical, qualitative and quantitative approaches; the qualitative approach being mainly based on direct observation of the structural damage and material decay as well as historical and archaeological research, and the quantitative approach mainly on material and structural tests, monitoring and structural analysis." [3, 11]. See also [15]

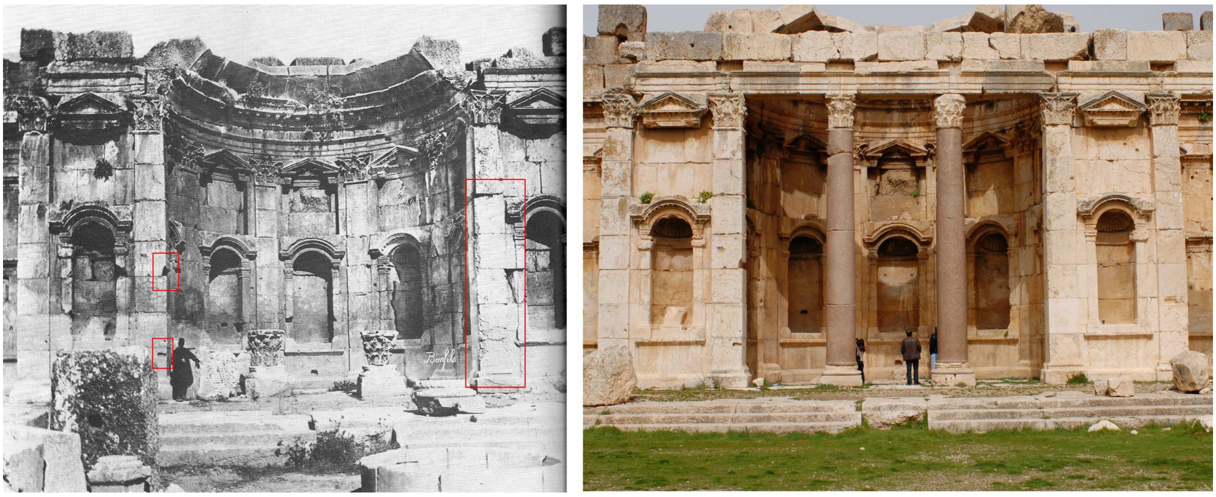


Figure 5: Left: semi-circular chamber of the great court in 1900. Right: same semi-circular chamber in March 2010. The parts encircled in red rectangles show areas which did not change (left) and where stones where replaced (right).

remain that suffered previous interventions (displacements, addition of new stone blocks, reinforced concrete), or it may be a new element. The integrity of these parts is different. The five standing columns of the Jupiter temple (one of the iconic highlights of the site), even if restored with reinforced concrete, have undoubtedly a higher value/significance than the restored columns of the Great Court. A systematic inventory and cartography of those values would help defining objectives to achieve and provide data necessary to quantify the potential losses (and consequently the risks) [18, 14].

The precise definition of the values and of the events/actions which may endanger them was also discussed above and will require *participatory debates*. The concept of *reversibility* now presented can help clarifying the situation.

Reversibility

In the context of conservation, reversibility usually refers to the reversibility of an intervention. But it could also denote the possibility to repair a damaged structure. In the case of destructive events, reversibility (in this second sense) is often not achievable and in some instances not applicable. *Stricto sensu*, all destructive events are indeed irreversible. It is not possible to cancel an event, to forget the past. Nevertheless, in some circumstances it is possible to recover an important proportion of the value. There is a clear difference between the following situations: 1) A block falls down from the structure. Later, the block, nearly intact is replaced on the structure. 2) A monolithic column fall down, it breaks in two parts. Later, the column is reassembled and put back in its original place. 3) A stone element with decorative value is stolen. 4) A decorative element is so weathered that the reversibility is not achievable.

Some constructive characteristics have also to be considered. In Baalbek, most of the masonry elements are large stone blocks. To prevent the possibility of occurrence of certain events (toppling or sliding of a block for instance) would require interventions which also have a heavy cost on the cultural value of the fabric[8] (Fig.4). This without considering the costs and potential technical problems (alteration of the original structural behaviour, prevention of friction damping, risk of corrosion. . .)

Ubiquity

Ubiquity is related to the extend of a particular type of damage. It refers to the fact that losses cannot be calculated by simple arithmetic: to loose everything is much worst than to loose one half (more than two times worst). In the evaluation of the risk, it is therefore important to evaluate how likely it is for all specimen of particular type of architectural elements to be damaged by a given event. To take a specific examples, it is very likely that, if one of the remaining columns of the temple of Jupiter falls down, the other will suffer the same fate.

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[8]"1.3 The value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time." [3], [11]

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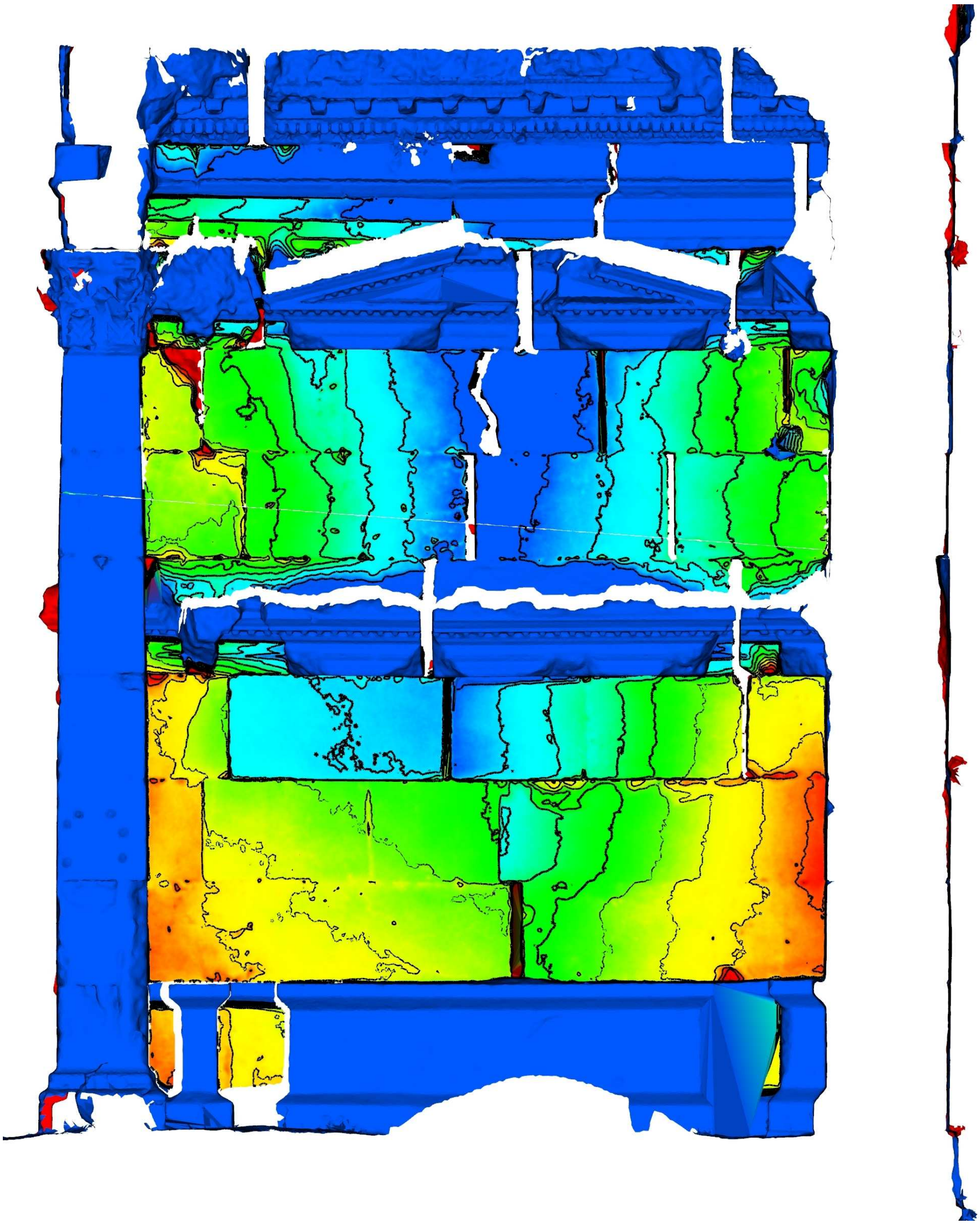

Figure 6: Eastern Wall Elevation of the semi-circular chamber of the great court (1/100). Colours indicate the distance between the surface of the wall and a vertical reference plane fitting the wall (distance from red to blue: 10 cm, blue is closer). They show that the wall is broken (along a roughly vertical hinge line clearly marked by cracks). Variations of colours indicate also that the precise deformation of the structure is more complex. Isolines (interval: 1 cm) help a quantitative interpretation.