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# ARCHAEOSEISMOLOGY OF ARCHITECTURE: A NEW TOOL FOR SEISMIC RISK MITIGATION?

## Questions And Potential Of Archaeoseismological Research In Architectural Context

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**Abstract**: *Although archaeological sites have been used to investigate past earthquakes since the 1970s, only in recent years have archaeologists of building tried to extend the archaeoseismological approach to architectural contexts.*
*The innovation of such research lies in the fact that the object of investigation are not archaeological areas, but rather ancient buildings, that is to say artefacts that are not in a 'fossilized' condition but that continue to undergo anthropic actions. In terms of seismic risk mitigation these studies are interesting because they deal with two different aspects of seismic risk analysis. Firstly they provide important information on the seismic history of the area in which the object of the study is located, therefore investigating seismic hazard. Secondly, they provide a better understanding of the structural behaviour of the building in relation to seismic stress, suggesting the best method of intervention to reduce its vulnerability.*
*Although early studies in this field have achieved interesting results, we are still far from having identified an applicative method for this new kind of information. Two case studies will be presented, through which the potentials and questions that are yet to be resolved regarding this new interesting discipline will be illustrated. Future improvements will be suggested in order to make archaeseismology of architecture a new important tool in seismic risk mitigation.*

**Keywords**: archaeoseismology, archaeology of building, past seismicity, architectural heritage.

## 1. Introduction

Every time a natural disaster occurs, it displays how exposed and vulnerable human beings are. Despite all the efforts made, society still remains a step backwards. It is a well-known fact that seismic risk depends on a number of variables such as hazard, exposure and vulnerability. This paper explores the ways in which archaeoseismological research in architectural context can possibly enhance existing knowledge about seismic risk mitigation, especially concerning seismic hazard and buildings vulnerability.

Archaeosismology is not a new concept within the study of past seismicity, in fact, the effects of historical earthquakes on archaeological heritage have been investigated since the 1970s (Karcz and Kafri 1978, Ambraseys 1977; Stiros 1996; Guidoboni et Al. 2002; Galadini, Hinzen and Stiros 2006). However, the last decade has witnessed a growing interest in a new subject of study in this field: built heritage.

As opposed to similar studies conducted in the past, such a research is innovative as the subject being studied is not archaeological areas, but rather ancient buildings, i.e. artefacts that are not in a 'fossilized' condition but that continue to undergo human-induced activity.

This new subject of study is particularly relevant for those areas in respect of which no written sources are available and no archaeological remains were preserved due to their moderately recent urbanization.

The following pages illustrate a method for validating the seismic origin of a stratified damage applied to two case studies: the Sanctuary of the Saints Vittore and Corona in Feltre, a city located in a medium to high seismic risk area in the north-east of Italy and the medieval Venetian bell towers. Lastly, the potentials and limits of archaeoseismological research in

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architectural context building will be discussed to highlight pending problems and the necessary improvement of this new methodology.

## 2. The case study of the Church of Saints Vittore and Corona[2]

The Church of Saints Vittore and Corona is an ancient 11th century building perched on a rocky spur of Mount Miesna in Anzù, a hamlet of the nearby city of Feltre.

The sanctuary represents an excellent object for archaeoseismological study given its position in a medium to high seismic risk zone, the presence of significant damage already previously identified as potential seismic effects (Doglioni and Petrini 1987) and its long history.

Although the church has been studied for over a century, poor information is available about the constructive (and destructive) phases of the sanctuary. Therefore, the first step required was to identify the various construction phases of the sanctuary in order to then place the 'destructive sequence' within that timeline.

The first historical references concerning the foundation is represented by the epigraph bearing the year 1906 in which Giovanni da Vidor is defined as the fundator aulae (Alpago Novello 1974). This suggests that in 1096 A.D. the construction of the building had already started. A second element is represented by an inscription placed inside the temple, according to which the church was dedicated in 1101 A.D. (Dal Zotto 1951).

A series of stratigraphic discontinuities led us to believe, from the very start, that the original plan of the structure was considerably different from the present one and that therefore the first construction phase of the original complex corresponds to the pseudo-isodomic masonry made by large ashlar blocks that involved exclusively the lower perimeter of the hall and the "apse block", formed by the martyrium and the two bell towers to the north and the south. Thanks to some frescoes located on the south wall of the hall and probably dating back to the first half of the 12th century (Ericani 2004, page 125; Claut 2006, pages198-199), this first phase can be ascribed to the 12th-13th centuries.

We can assume that once the apsidal zone was built with the martyrium and the skeleton structure of the bell towers constructed along with the external enclosure of the main body of the church, the construction works were interrupted for a significant period of time. There are some architectural incongruities that induce us to suppose that the "Greek-cross" layout visible today is the result of an unexpected change in the original project (Ganz and Doglioni 2015).

It is after this change that the sanctuary was hit by a major seismic event which caused severe damage that can be still observed as follows:

- marked detachment from the side walls and rotation/overturning of the two opposite facades located to the north and south of the transept;
- diagonal damage to the southern bell tower and widespread cuts in the northern bell tower, in stretches that originally soared above the church. These are typical cracks caused by a shear and bending stress and they are attributable to the discordant oscillation of the bell towers with respect to the main body of the building. The oscillation might have probably been accompanied by partial collapses of the cells above, later demolished;
- damage and partial failures of the north-west corner of the hall.

A third construction phase began when the Sanctuary was assigned to the Fiesolani ministers (1494) and major restoration works were carried out during their rectorate: the side walls of the hall were raised up to the "Greek cross" level, the tympanums of the transept were demolished as well as the cells of the bell towers and a two-pitched roof was made. A cloister was built closed by the southern front, also incorporating pre-existing structures and leaning against the out-of-lead church wall. A new bell tower was also built, this time on the western part of the church nearby the entrance (Alpago Novello 1974; Claut 1994).

The next step was to validate the seismic origin of the observed damage and to insert the 'destructive sequence' within the previously identified phases. The process of verifying the seismic nature of a damage, which we call "validation", is based on two complementary actions.

[2] This case study has been the object of the author M.A. thesis and it has been published in Ganz, Doglioni 2015

The first is excluding other causes of damage, both static and dynamic (explosion, wind, oscillation of the bells etc.), the second is confirming the compatibility of damage with seismic stresses.

An overview of the major parameters that characterize ancient seismic effects is proposed in tab. 1. Based on the number of criteria verified, the seismic origin of the observed damage will be (i) confirmed, (ii) persisting as hypothesis not fully verified, or (iii) denied.

| Code | Description |
|---|---|
| A | Presence of damage due to horizontal stress |
| A1 | Diagonal cracks due to shear force |
| A1a | Crossed cracks with “X” configuration |
| A1b | Cracks due to shear force with horizontal translation on the joints |
| A2 | Overturning mechanism of external walls |
| A2a | Horizontal hinge compressed outwards and stretched inwards and placed at a higher level |
| B | Symmetrical damage pattern on at least one axis of the building |
| C | Heavy damage that exceed the minimum damage threshold |
| D1 | Local cracks in correspondence with structural hinge (ashlar masonry) |
| D2 | Horizontal cracks in correspondence with structural hinge (stone and brick masonry) |
| D3 | Widespread fractures in the arch’ s ashlars |
| E1 | Damage *sealed* by a subsequent construction phase |
| E2 | Raised part built upon previous structural dislocation |
| E3 | Interruption of the crack pattern |

*Tab. 1 Criteria for the recognition of stratified earthquake damage[3].*

If we adopt the validation criteria for the Church of Saints Vittore and Corona, regarding the damage (fig. 1a, 1b, 1c) affecting the Greek-cross structure we note that the cracks on the transept fronts:

- both display horizontal translation of the joints (Tab. 1, parameter A1b);
- are related to the activation and development of an overturning mechanism, with a hinge close to the point of wall thickness reduction (Tab. 1, parameter A2a);
- are substantially opposite and symmetrical (Tab.1, parameter B);
- have laminating effects on the lower external face of Romanesque masonry, a possible effect of the horizontal hinge that triggered the overturning of the transept facades (Tab. 1, parameter D1);
- in different ways both constitute sealed damage(the marked tilting of the southern façade —over 20cm—does not affect the double porticoes cloister built in 1494; while, on the northern façade, a large part of masonry reconstruction does not seem to have been damaged by subsequent events) (Tab. 1, parameter E1);
- can be compared with damage and mechanisms in similar buildings caused by more recent earthquakes (Tab. 1, parameter F ).

[3] For the thorough description of each parameter see Ganz, Doglioni 2015.

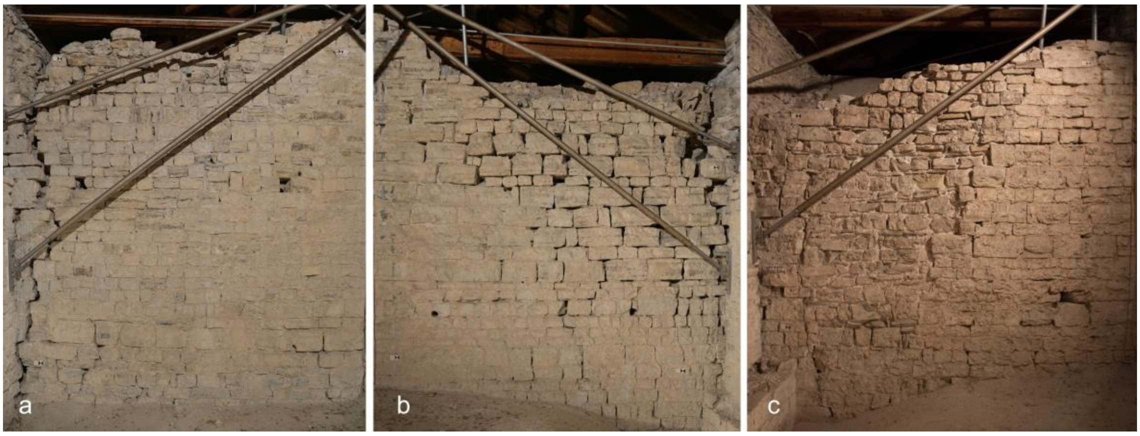


*Fig. 1a, 1b, 1c, - Damage on the north and south facades of the transept. Please note in picture 1c the rebuilt part with a later crack on the left side (author).*

The cracks observed on the surviving parts of the ancient bell towers (fig. 2a, 2b):

- both present horizontal translation of the joints (Tab. 1, parameter A1b);
- are both related to the activation and development of typical shear and bending stress (Tab. 1, parameter A) and they are attributable to the discordant oscillation of the bell towers in relation to the main body of the building. These cracks may be considered 'sealed' damage (Tab.1, parameter E1) because this configuration is only possible while the soaring bell towers were standing);
- are substantially opposite and symmetrical (Tab. 1, parameter B) even if there is a significant difference. In fact, on the southern bell tower seismic action insisted on an old construction phase which represents a weak point in the overall structural behaviour so the crack pattern for this façade consists just in a unique diagonal split (Fig. 2b), while on the northern bell tower the crack pattern is expressed by lots of minor cracks (Fig. 2a)


*Fig. 2a 2b – The cracks observed on the surviving parts of the ancient bell towers(author).*

The research presented here aimed to examine the sequence of destruction purposely avoiding associating the crack pattern with any specific seismic event(s). Only after validating the seismic origin of the observed damage were attempts made to ascribe the observed damages to one or more known seismic event(s).

Available seismic catalogues (CTPI 2004; Guidoboni 2018) record two damaging seismic events in the area contemporary with the construction and occupation phases of the sanctuary. These are the Treviso earthquake of 1268 (Guidoboni 2018) and the Belluno earthquake of 1405 (Guidoboni 2018). In addition, between these two events, the 1348 Carinthian earthquake occurred (Guidoboni and Comastri 2005, 403-434). Although there is no data relating to the impact of this earthquake on the city of Feltre, it is very likely that damage was also felt here. Therefore, it is possible that the complex suffered seismic damage as a result of earthquakes in 1268, 1348 and 1405. In addition, further uncatalogued events cannot be ruled out.

From the architectural evidence, it is clear that a strong seismic event struck the church during its Greek-cross phase between the early 13th century and before the construction of the double portico-ed cloister (after 1496). There are two main phases of fresco painting during this time. One is found on the walls of the northern semi-transept depicting the Passion of the Saints Vittore and Corona (Coden 2004) which has been roughly dated to a period from the 1340s (Coden 1996; Ericani 2004, 2008) to about 1360 (D'Arcais 1996; Lucco 1986). The second group, located on the wall of the martyrium, depicts the Fathers of the Church (Minella 2000) and is thought to date to a slightly later period—around the sixth decade of the 14th century (D'Arcais 1996; Ericani 2004, 2008). It has been speculated that this group was made for the visit of Emperor Charles IV to the sanctuary in 1354 (Doriguzzi 1984). The dating of the frescos is based on stylistic analysis, and the restricted chronological sequence this provides is not detailed enough to discriminate the damaging events which affected the church of San Vittore with certainty. However, in historic photographs taken before their restoration, both groups of frescos display seismic damage comparable with that observed in the external façade of the transept—thus providing a general terminus post quem for the occurrence of the seismic event(s). On the basis of these considerations, it is possible to confirm that the two earthquakes which affected the church occurred between 1340 (the earliest date for the frescos in the northern semi-transept) and 1496 (when the cloister which sealed the tilted southern wall of the church was constructed). Therefore, a likely hypothesis is that San Vittore was first affected by the strong 1348 Carinthia earthquake and later, after some substantial restoration had already been carried out, by the seismic event which occurred in 1405, which had a much more localised impact.

At this point, archaeometric research targeting, for example, the dating of the different mortars used within the structure could help improve the resolution of the structure's chronology. On the architectural side, quantitative analysis of failure mechanisms (Acito 2014) could enable estimations of the forces that produced them.

## 3. The medieval Venetian bell towers case study.

The Venetian bell towers have been the subject of an accurate analysis carried out ten years ago by the IUAV University in collaboration with the Superintendence of Venice (Lionello 2011). The research aimed to verify the static condition and seismic vulnerability of the bell towers. The final result of this work was the ranking of these bell towers by their structural failure level, starting from the highest to the lowest.

One of the most remarkable result revealed by that classification was that the medieval bell towers were by far the most compromised. This can be reasonably ascribed to factors such as the natural degradation of materials and the greater transformations undergone over time. Moreover, the medieval bell towers showed widespread reuse of construction material the inhomogeneous property of which impoverished the overall masonry quality.

However, the structural analysis showed that the oldest bell towers presented the following recurrent elements in the crack pattern:

- tilted or sub-vertical cracks (60-70°);
- cracks with horizontal or parallel sections;
- cracks with "spindle" structure that open and close in a short space;
- cracks with "C" shape near the angled sections.

This type of crack pattern is compatible with seismic action, although other causes cannot be excluded. Although Venice is based in a low seismic hazard area, in the past it was struck by several strong earthquakes, in particular the Carinthian earthquake of 1348 A.D. and the Slovenian earthquake of 1511 A.D.. Comparing the western front of the medieval bell towers built before and after 1348 it was possible to appreciate a clear distinction between their crack patterns: the ones related to bell tower built before the first half of 14th century are articulated and complex, whereas the ones related to bell tower built just a decade after that period are much linear and easy to explain (fig. 3).

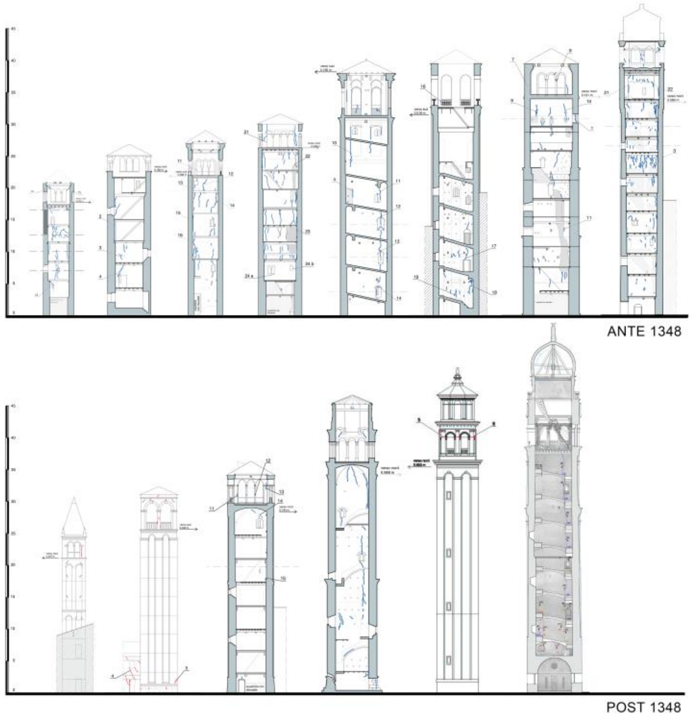


*Fig. 3 Comparison between the western facades of some Venetian bell towers realised ante and post 1348 (Lionello 2011).*

The bell tower of St. Giacomo dall'Orio (1225 A.D.) was studied in depth (Doglioni and Squassina 2011), but other bell towers were worth further investigation so they are the subject of the ongoing author's Ph.D. thesis. Even if the final outcomes are yet to be achieved, preliminary considerations are still possible.

Despite its high masonry quality, the upper part of the 12th century bell tower of St. Nicolò dei Mendicoli shows an extensive reconstruction associated with a lesion interrupted by the reconstruction. Thanks to the ancient workmanship of the rebuilt part in which altinelle bricks were used, it is possible to assume that the ancient damage occurred before the 15th century. The sudden interruption of a crack with a subsequent reconstruction is an evidence of a strong and rapid action that broke the masonry provoking the collapse of the upper part[4]. In fact, it cannot be related to progressive failure cause it doesn't affected the rebuilt part. This type of damage is compatible with seismic action but other dynamic causes are still valid.

Also the St. Aponal bell tower presents a sealed damage. According to the commemorative epigraph, the cell was rebuilt in 1407. Just below the reconstruction line there are cracks compatible with seismic actions that were repaired with cocciopesto mortar, whose ancient workmanship is clearly identifiable, with no apparent subsequent resentment. Furthermore, on the lower part of the western façade there is an extensive sub-vertical lesion that includes also the window's archivolts, likewise in the Gesuiti (12th century) and the St. Salvador (1206 A.D.) bell towers. The particular configuration of this crack is comparable to the ones observed on ancient masonry following recent earthquakes.

On the contrary, the medieval bell tower of the church of St. Polo (1361 A.D.) as well as the bell tower of the church of St. Alvise (1388 A.D.) do not show visible damage. The reason could be the general improvement of materials and technique but the possibility that they were not affected by the same violent event cannot be excluded.

Obviously, the foregoing is not exhaustive to confirm the starting hypothesis but it is sufficient to legitimize a deeper analysis on this topic. Further efforts must be made in order to validate the seismic origin of the damage observed. In particular, other dynamic actions such as the oscillation of the bells must be excluded.

[4] It could be also an induced collapse in order to level the damaged wall and rebuild on the survived masonry.

## 4. Potentials and limits of archaeoseismological research in architectural context.

The underlying concept of archaeoseismological research is the following: strong earthquakes leave traces in the buildings they affect. When it is possible to identify these effects these structural clues become material records of past seismicity. Two factors facilitate archaeoseismological research in architectural contexts: (i) the application of archaeological methods to the study of standing buildings—eg stratigraphic analysis—and (ii) the occurrence of high magnitude earthquakes in recent times allowing architects and engineers the opportunity to study the behaviour of historical structures affected by seismic stress (Doglioni 1994,1998; Cangi 2009).

The studies presented above have, in the main, the same purpose as traditional archaeoseismological research (Ambraseys 1977; Galadini et al 2006; Guidoboni et al 2002; Karcz and Kafri 1978; Noller 2001; Santoro and Bianchi 1996) and can be considered as an extension of the analysis from archaeological sites to standing buildings. But what is the boundary between traditional and more innovative approaches to archaeoseismology?
Rather than the chronology or typology, the state of preservation of the structure, artefact or site is the factor which determines the appropriate methodology. Standard archaeological techniques are applicable if the structure or remains are in a 'fossilized' condition whilst light archaeology or building archaeology are applicable to structures which continue to undergo human-induced activity.

This improvement allows the chronological period under investigation to be extended from the threshold of instrumental seismology (late 19th century).10 This is particularly true for areas with few archaeological remains (Caputo and Helly 2008). Secondly, an in-depth analysis of the historical built heritage in a seismic area allows a deeper knowledge of its structural behaviour under seismic stress. More suitable anti-seismic measures can, therefore, be found to reduce building vulnerability. In some cases, the buildings represent tangible proofs of the local seismic culture of historic communities presenting phases of destruction and subsequent restoration that suggest the most suitable anti-seismic solutions.

Finally, a potential that is still largely to be defined is represented by the possibility of classifying an earthquake starting from the observable damage. In recent years, programmes which aim to model and verify damage patterns in masonry structures have been conducted (Galassi 2014; Modena 2009), in some cases in archaeological contexts (Hinzen et al 2011, with bibliography discussed here) or contemporary post-seismic scenarios (Acito et al 2014). The main problem regarding structural modelling of ancient buildings in a pre-seismic scenario is the amount of uncertainties related to the mechanical characteristics of historical materials and to the exact conformation of the structure before earthquake occurrence. Quantitative information about a past earthquake starting from the observable damage would be possible if those uncertainties could be limited. Nonetheless it may be possible to apply a process to contexts affected by recent earthquakes where the uncertainty on the exact conformation of the building is minimal. Obviously, the more we go back in time the more errors in modelling are likely to occur.

On the contrary, the main critical points can be summarized as follows:

1. Timing and accessibility.
   Archaeoseismological research in architectural contexts takes a considerable amount of time as seismic damage on historical buildings is often not clearly visible as, for example, in the case of a settlement abandoned following an earthquake. As stratified seismic damage is linked to the chronology and biography of a structure, archival research along with field survey are required. Construction phases, modifications and interventions must be identified in order to fully understand a building's current configuration. In addition, as the object of study are buildings which are still in use researchers must rely on the, often limited, availability of users, owners, or institutions depending on the ownership and function of the buildings.
2. Conscious identification of damage.
   If we consider how simple it is to hide older layers by simply plastering over them, we can easily understand that the identification of ancient cracks can be a challenging task. This is just the beginning as, after the recognition of damage, its seismic origin must also be assessed. As mentioned earlier in this script the validation of the seismic origin of the observable damage is based on two actions: the confirmation that the observable damage

is coherent with seismic loads and the exclusion of any other possible explanations for the damage (such as foundation failure, landslide, explosion, wind, bell oscillation). Especially the second one is a difficult task as some of the characteristic evidences of earthquakes might be deleted in occasion of later restoration or modification. Therefore the evidences that left might be attributable also to other cause of damage. This is what happens, for instance, in the second case regarding the damage observed on the North-West front of Saints Vittore and Corona church (Figure 5.3) that was compatible with seismic action but in absence of further information neither foundation failure nor other cause could be excluded. This means that the restorer should be prepared to recognize seismic damage. Ancient seismic damage is both a weak element in the structural behaviour that must be secured and a data of past seismicity that must be preserved. Only through conscious interventions is it possible to mitigate the vulnerable element without erasing historical data. In the case of the sanctuary of the Church of SS Vittore and Corona the research benefitted from the survival of historic photographs recording the original state of the structure before restorations were carried out.

3. Relative and absolute dating.
   Issues of dating are connected to the problem described above. Through a stratigraphic sequence it is possible to date observable damage relatively—the accuracy of which depends on how many markers ante quem or post quem can be found. Archaeometric methods, such as dendrochronology, radiometric dating and OSL dating, offer the potential to provide more accurate dating in certain contexts (Bailiff 2007). However, besides being costly, these analyses are often not feasible with the difficulty of finding the proper quantity and quality of raw material required for analysis are considered.

4. Methodology.
   The innovative aspect of an architectural approach to archaeoseismology is evident as if we considered all the archaeoseismological methodologies developed so far we would notice that they largely ignore the architectural context.
   Take for example The logic tree for archaeoseismology scheme proposed by Sintubin and Steward (2008)[5]. The aim of the logic-tree formalism is to offer "the potential of a standardized procedure to compile, categorize, and evaluate archaeoseismological information in a form that might, with refinement from wider earthquake archaeology studies, be appropriate for seismic-hazard analysis."(Sintubin and Steward 2008, p. 2209). A more in-depth analysis of the proposed method would show that, as far as the 'technical' field is concerned, the architectonical part turns out to be almost absent, in particular regarding the estimation of the QWF (quality weight factor) of the Dating of Earthquake-Related Damage in which only archaeological context is considered. Due to its very recent development, the lack of architecture in the archaeoseismology approach is not surprising, though the upgrade of existing methodology could be the starting point towards a complete acceptance of architecture as an archaeoseismology discipline.

This paper has investigated the archaeoseismological potential of architectural context. Even if unresolved issues seem to prevail over uncertain results, the case studies illustrated herein prove that the architectural contribution in archaeoseismology is not only possible, but even indispensable when the written sources are silent or not available.

As far as seismic risk mitigation is concerned, it is possible to conclude by saying that archaeoseismological data provided by the architectural heritage are very interesting because they deal with both seismic hazard and vulnerability. At present this data can be defined just as what Zenely (2006, p. 7) calls information:

*"Information, as a description of action, may be difficult to measure – it has no tangible outcome per se. The value of information is intangible, unless it becomes an input into measurable action, i.e., knowledge".*

Therefore, greater efforts must be made to convert information into knowledge, starting from the solution of pending problems and the improvement of research methods. These are the steps required to make archaeoseismology of architecture a tool for seismic risk mitigation.

[5] For further archaeoseismological methodologies see: (KARCZ KAFRI1978); (RAPP 1982); (NIKONOV 1988); (STIROS 1996); (GALADINI et al. 2006); (RODRÍGUEZ PASCUA 2011).

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