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Seismicity in France / *Sismicité en France*

Archaeoseismology in France: developments and new perspectives for cultural heritage preservation

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Abstract. Archaeoseismology is one of the four issues usually involved to increase the knowledge of seismic risk. The three other issues are seismic records, historical seismicity, and palaeoseismicity. Archaeoseismology was founded as a discipline in the 1980s. It was developed and methodologically defined during the 1990s and 2000s, and its new developments and perspectives are based on two procedures. First, the numerical field, with tools like the database OPUR (Outil Pour Unités de Réparation), "Tool For Reparation Units", conceived as a sort of atlas, to collect and index all the types of repairs identified in the Roman site of Pompeii, in Italy. Second, the focus on the evolution of ancient buildings and their pathologies, serves as a basis for the structural modelling, carried out by engineers. It allows to understand the behaviour of ancient buildings during seismic motion, to quantify the impact of seismic effects on cultural heritage and to propose a method of preservation. Major studies conducted in France as well as recent developments in this field are presented, in order to illustrate this collaboration between archaeoseismologists and engineers for the preservation of cultural heritage.

Keywords. Archaeoseismology, Database, Structural modelling, Seismic effects, Post-seismic repairs, Reinforcement techniques, Methodology.

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1. Introduction

Archaeoseismology is a relatively new discipline whose main objective is to recognize the effects of past earthquakes on ancient buildings or settlements. In addition, post-seismic repairs and strengthening techniques, used to improve the building resistance, are also analysed to trace past earthquakes. As a way of research on past earthquakes, archaeoseismology, emerged in France in November 1983, with the IVth International meeting of Archaeology and History of Antibes [Valbonne meeting, Helly and Pollino, 1984] titled: "Earthquakes: History and Archaeology". For the first time, not only historians and archaeologists, but also seismologists and other researchers in earth and environmental sciences, were brought together to discuss earthquakes and their effects. The investigations were mainly based on the texts produced by geographers and historians of Classical Antiquity (Herodotus, Strabo,

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Thucydides, Pliny the Elder etc.), epigraphical documents (Greek or Latin inscriptions), and architectural evidence. Helly [1984], an epigraphist working at that time on Thessalian inscriptions (North of Greece), focused on the indications concerning earthquakes and their effects on ancient constructions. Through his epigraphic studies, he was the instigator of the Valbonne meeting [Helly and Pollino, 1984] that gave birth to the discipline. In the same meeting, Adam [1984], as an architect working at Pompeii, presented his observations of post-seismic repairs on the buildings of this emblematic Italian archaeological site. Moreover, geographers, like Bousquet et al. [1984a,b] interpreted the indications of earthquakes and their effects in ancient texts: "We have, thanks to the ancient texts and epigraphy, remarkable testimonies by the precision of the specialized vocabulary and details of the circumstances and the course of the event as well as its immediate effects and more distant consequences. We can easily deduce that observational seismology existed very early in antiquity" [Bousquet and Péchoux, 1981].

2. The development of archaeoseismology in France

How did archaeoseismology gradually develop as a discipline in its own right?

Simultaneously, at the European level, the European University Centre for Cultural Heritage (CUEBC) CUEBC [2021] was created in Italy, at Ravello, in 1983. The objectives of the CUEBC are "to contribute, in connection with national and international institutions concerned, to carry out a cultural heritage policy from the point of view of expert training and specialization, scientific advice, as well as protection and promotion of cultural and historical assets". During the last days of the meeting, the international team that had gathered, among whom were Bruno Helly and Ferruccio Ferrigni [see for example Ferrigni et al., 2005], contributed to specify the main issue of "local seismic culture" and to identify "seismic pathologies" and seismic-resistant techniques: "the anomalies that protect" Ferrigni [1990]. These anomalies are illustrated by observations on traditional architecture of the town of San Lorenzello, in Italy.

With the beginning of the nuclear programme in France in the seventies, the seismologist, Agnès Levret-Albaret, from the IPSN, collaborated with the historian Jean Vogt. Together they started revising the existing earthquake catalogues, in order to have a better understanding of historical earthquakes for a period of about 1000 years in France [Vogt et al., 1979]. The result of this work was the creation of a database at first named SIRENE, which became SisFrance [2021] in the 80s. Today, this database is managed by a consortium of three organizations: IRSN, EDF and BRGM (with the work of the geographer Lambert [1997]). The purpose of the database is to record all the information concerning ancient earthquakes that have occurred in metropolitan France with a complete description of the events, from historical sources to the quantification of intensity observations [Scotti et al., 2004].

The development of a rich database like SisFrance as well as the meeting of different communities around archaeoseismology have led to the first multidisciplinary studies on the French territories in the nineties: the aqueduct of Nîmes and the Manosque 1708 earthquake (see Figure 1 for the locations of the French historical earthquakes discussed in this paper). These studies were the precursors of global archaeoseismological studies conducted later with the concept of buildings as "stone seismometers".

2.1. *The aqueduct of Nîmes*

All this scientific impulse around earthquakes and their effects on cultural heritage led to the first multidisciplinary study on archaeoseismology in France: the case study of the Nîmes Roman Aqueduct, built in the middle of the first century AD. The study of this aqueduct was first of all a founding moment for the knowledge of Roman hydraulic works and for the diffusion of a global methodological approach, crossing archaeology, architecture, geosystem and history [Fabre et al., 1991, 2000]. It led to the creation of a collective research project in 1984.

Seismic impacts were taken into account only in a second phase of the study, during the 1990s. Indeed, taking into consideration some previous evidence found by archaeologists Fabre and Fiches [1986] on the remains of the Roman aqueduct near the town of Nîmes (south of France), the CNRS "Research Group on the Nîmes Roman Aqueduct and the Pont du

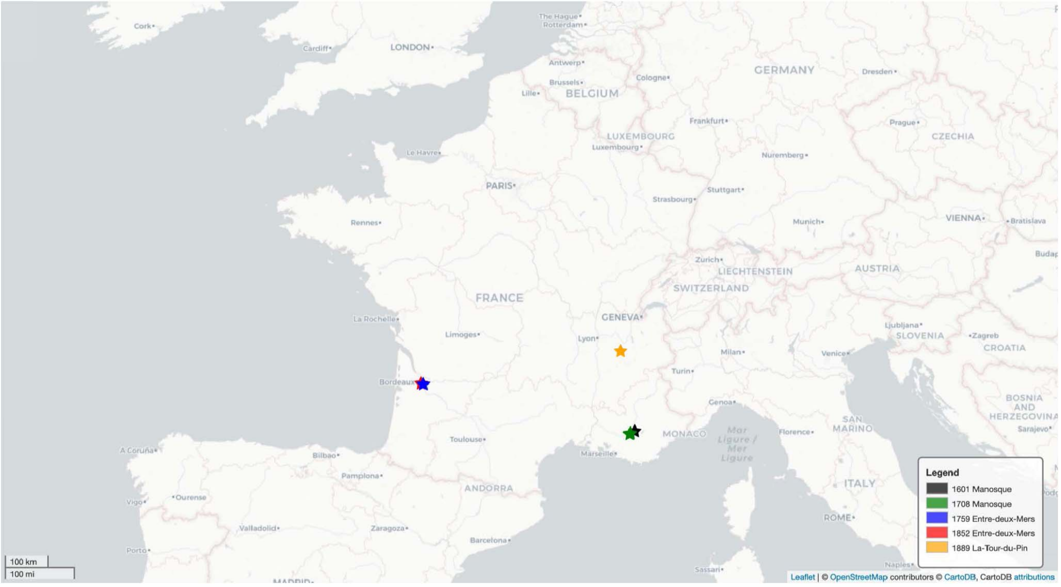


Figure 1. Location of the French historical earthquakes presented in this paper (data extracted from SisFrance [2021] database).

Gard", the IPSN and the CUEBC jointly organized the 9th meeting, in February 1995, for the study of this archaeological site [Fiches et al., 1997]. The objectives were to assess the effective seismic destruction of a bridge, the Pont de la Lone, a part of the aqueduct, and to define the methods for analysing seismic damage to archaeological sites, through this multidisciplinary case study [Fabre and Levret, 1999]. The results of this investigation on the Pont de la Lone site led to the validation of the seismic origin of some damage on the standing remains. The following conclusions were arrived at through the work of various specialists in architecture, seismology, engineering and earthquake modelling [Levret et al., 2005]:

(1) the endokarstic formations showed that the stalactites fell suddenly on the corresponding stalagmitic floor, then calcified again and were sealed by a second stalagmitic floor generated by the resumption of water infiltration;
(2) the cracks and deformations observed appear to be related to seismic effects;
(3) the collapse of a wall over several ten metres in the same direction could be explained by the effect of a seismic movement. The bridge was statically modified by the construction of a wall at its base which caused the collapse [see Combescure et al., 2005, Berthellot, 2000].

Unless some limitations regarding the definition of potential earthquake loading for the analysis of failure mechanisms (i.e. response spectra and registered accelerogram associated to foreign site), it should be pointed out that this study was the first attempt in France to apply earthquake engineering methods to evaluate the response of historical structures. A similar study on an ancient aqueduct, combining archaeology and seismology, was recently applied by Benjelloun et al. [2018], with the case study of the aqueduct of Iznik.

2.2. *The creation of the APS Group*

In continuity with this broad collective study on a Roman building, the APS (Archaeology, Pathology, Seismicity) Group was created in 1999 by Rémi Marichal. The first nucleus was composed mainly by Rémi Marichal, Bruno Helly, Agnès Levret and Bertrand Grellet [see for example Marichal, 1999]. In his work on the site of Ruscino, Marichal and Rébé [2003], an archaeologist of Perpignan's town, identified traces of seismic effects on ancient settlements. This discovery was the starting point for the creation of the APS group.

The APS Group brings together experts, specialists and researchers working in the fields of historical seismicity, archaeoseismicity and the effects of earthquakes on old buildings, as well as on their vulnerability and local seismic cultures. As a non-profit cultural association the APS Group regularly organizes meetings largely open not only to scientific disciplines concerned with seismological issues, but also to the professionals in the building and historical monuments sector and institutions. The objectives of the association are to develop studies aimed at identifying seismic pathologies in old buildings, to recognize and inventory the elements of local seismic culture in order to participate in reducing the vulnerability of old housing, and finally, to participate in prevention by disseminating techniques and knowledge in this field to the general public. For the APS group, the emphasis should be on a culture of vulnerability rather than a culture of risk. This multidisciplinary team works to promote archaeoseismology in France, both by international conferences and field work, and to develop the methodology of the discipline [e.g. Poursoulis, 1999].

2.3. *The Manosque 1708 earthquake*

From 2001 to 2006, a multidisciplinary team (seismologists, geologists, historians, archaeologists, architects, engineers, sociologists) worked on the emblematic case of the 1708 earthquake in Manosque (south of France, see Figure 1). The aim of this study was to characterize the Moyenne Durance fault, to determine the earthquake's intervention zone and to reassess its intensity through the recognition of its traces on historical buildings. *The seismotectonic study* allowed to clarify some parameters:

- the location of the fault in the upper part of the crust in its present activity,
- the reduced dimension of the active segment of the fault and its geometric characteristics,
- an estimation of the maximal magnitude as well as of major events return period (i.e. 100 years).

The historical investigation led to the discovery of an archive of primary importance (i.e. the report of the masons visit in the town of Manosque after the earthquake [Quenet, 2001]). This document lists the seismic damage and their distribution in the town of Manosque, and provides an exceptional set of data on the seismic impacts in the town [Quenet et al., 2005].

The archaeological study made it possible to reassess the intensity of the 1708 earthquake by recognizing its effects on the historic buildings in Manosque and in 13 surrounding villages where the effects of the earthquake are still visible [Poursoulis and Lambert, 2005]. Indeed, traces of the earthquake were found on many of the 21 buildings identified by the archaeological data among the 740 reported in the historical document: the report of the masons visit in the town after the 1708 earthquake [Poursoulis and Lambert, 2005].

The archaeological data thus made it possible to trace the earthquakes that affected the town of Manosque every 100 years. In particular, effects of the 1601 earthquake have been found on historical buildings. Indeed, this earthquake was assumed by the recurrence but unknown by the evidences, until the recognition of its traces on the Saint-Sauveur church [Poursoulis and Lambert, 2005]. First dated in 1610, the year of 1601 for this earthquake was determined by the seismologists after this work on Saint-Sauveur church.

The overall study in Manosque and the surrounding villages allowed to reevaluate the 1708 earthquake's shock intensity. The VIII (MSK) estimate in Manosque was validated as well as its superficial focal of magnitude 5.

The engineering assessment of the historical buildings, in their current state of conservation, highlighted their vulnerability, due to the lack of maintenance. Moreover, the sociological investigation carried out among the inhabitants, showed their ignorance of the seismic risk and the poor state of organization in terms of risk management.

The book by Poursoulis and Levret-Albaret [2014], which presents all the researches carried out on this 1708 earthquake, contributed to develop and disseminate the methods used in archaeoseismological studies in France.

3. New methods and explorations

The archaeoseismological studies find application in many cases. Indeed, the history of traditional masonry construction can be used to determine the seismic risk in an area, to preserve cultural heritage, and to improve the safety of the population. In this frame, the first author of the present article had the opportunity to focus on three important earthquakes in France: the 1759 and 1852 earthquakes in Bordeaux area (France) and the 1889 earthquake in Isère region (France) (see Figure 1 for the location of these earthquakes). These works were carried out using the methodology developed in the Manosque case study [Poursoulis and Levret-Albaret, 2014]. As a starting point, an analysis of the available historical documents and the context is done. If necessary, new documents are searched. It allows to clarify the context and give a better knowledge of the building's history and the earthquake mentioned in historical documents. This first phase helps in the field survey preparation in order to recognize the seismic traces on historical constructions.

3.1. *The two Bordeaux region earthquakes: recognition of traces and extent of their influence zone*

The focal location of the 1759 and 1852 earthquakes is in the southeast region of Bordeaux in the "Entre-deux-Mers" area (see Figure 1). The 1759 earthquake had an intensity evaluated at VII (MSK) and the 1852 earthquake an intensity evaluated at VI (MSK). According to the historical documents, 22 villages in the field survey area were more affected by the 1759 earthquake and nine by the 1852 earthquake. The identification of the architectural styles and the distribution of the construction phases in the visited villages, allows to chronologically surround the possible seismic intervention. During the field campaign, the seismic effects and repairs on the buildings as well as the reinforcements built to improve the building's resistance were recognized. The field of investigation has been extended to villages not mentioned in the historical documents. This additional investigation was done to assess the real extent of the earthquake's impact area. The schematic view in Figure 2 shows the different types of traces found in the villages studied.

With the exception of medieval churches, the old buildings found in the inspected area are mainly dated to the 17th and 18th centuries. Some buildings of the 16th century are preserved, and earlier buildings are very scarce. In the villages located near the focal area and with old buildings essentially dated to the 18th and 19th centuries, the buildings dated to the 16th and 17th centuries were probably damaged after the 1759 earthquake and rebuilt. This observation testifies to the importance of this seismic event. Furthermore, some of the buildings surveyed show important reconstructions of their walls (Figure 3(a)), indicating out-of-plane ruin mechanism, as well as break and shifting in structural elements like opening frames or decorative arches (Figure 3(b)), column drums etc.

These elements are representative of a quite strong earthquake, with an intensity near VII, according to the MSK scale for buildings erected in rubble masonry. The traces found by the field survey therefore attest to the importance of the 1759 seismic event.

3.2. *The 1889 La Tour du Pin Isère earthquake: the field researches*

The 1889 event epicentre is assumed to be located near La Tour du Pin (see Figure 1), with an epicentral intensity estimated at VI–VII [SisFrance, 2021 database]. The aim of the field mission was to find traces of the 1889 earthquake by investigating a large area around La Tour du Pin. The initial historical documents at disposal are secondary sources corresponding to copies of a unique record: a local newspaper giving few details of the seismic damage caused by this event. Just a few cracks in the walls and the shaking of windows are mentioned and no destruction is indicated. The study of local archival records is necessary to get more information about the real impact of this event.

Additional archival research on 1456 historical buildings in the study area provided precise knowledge on the building types and the associated construction periods. The studied area is mainly rural, with a majority of farms made of mud, with the cob technique. This type of building features very few traces of destruction, as it is very easy to rebuilt a mud wall after damage. The majority of the identified traces have been collected on stone buildings, like churches, administrative and industrial buildings. Figure 4 presents the different building periods determined in the surveyed area.

This schematic view shows that a majority of villages present a building frame dating from the 18th

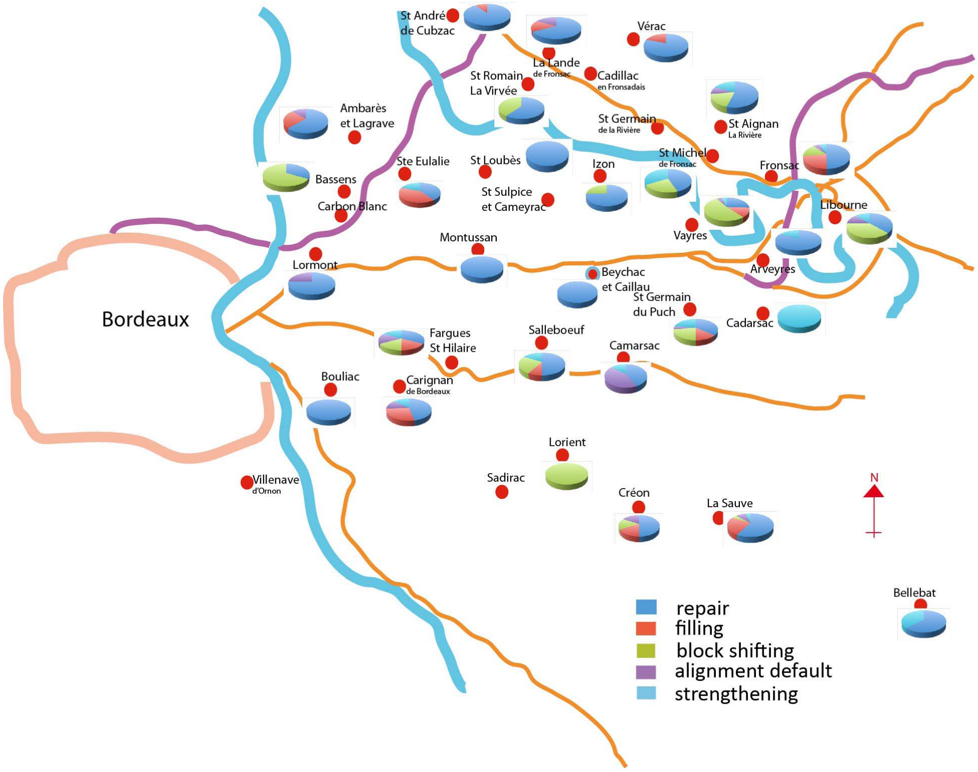


Figure 2. Schematic view of the different seismic traces found in the surveyed villages [Poursoulis, 2013].

(a) (b)

Figure 3. (a) Beauregard Castle (18th century) in Targon village masonry repair after face wall partial collapse and metallic ties in the wall. (b) Vayres village, 18th century tomb showing break and shifting of the decorative stone blocks [Poursoulis, 2013].

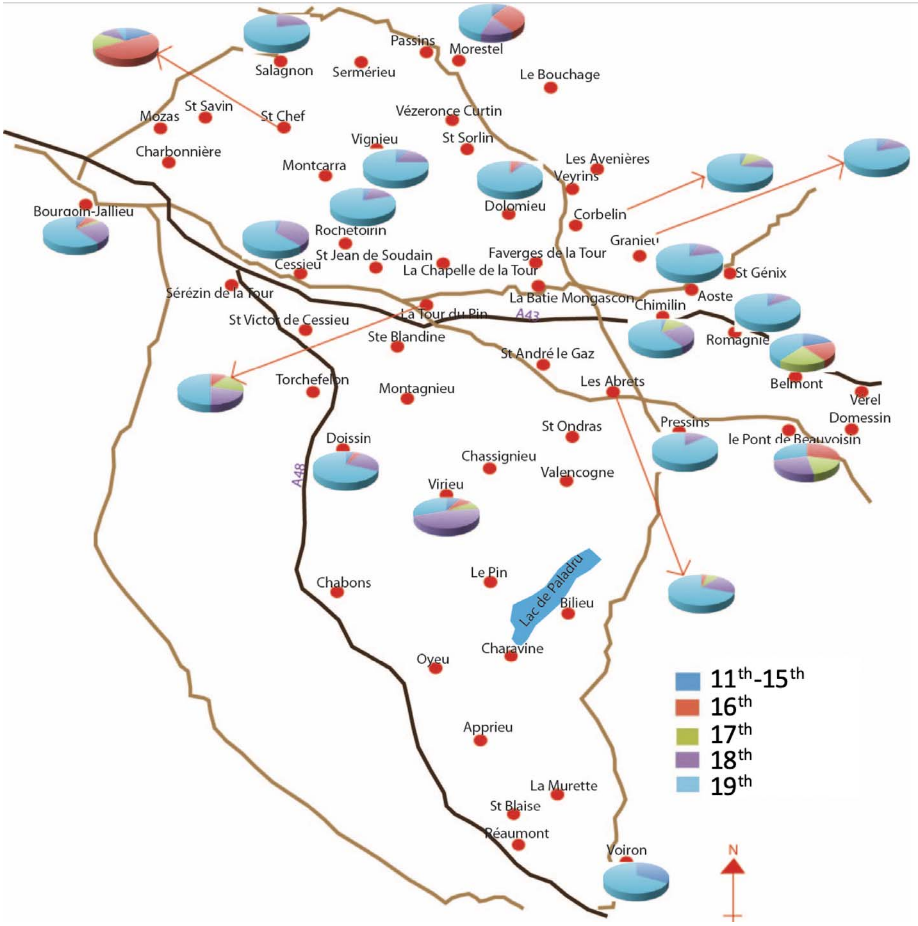


Figure 4. Schematic view of the surveyed area with the age distribution of the buildings. Each color gives the century corresponding to the building period [Poursoulis, 2017].

and 19th centuries. The identified traces are essentially reconstructions (Figure 5(a)), and wall corners have been rebuilt. There are also evidence of broken and displaced lintels, broken and shifted barrels of stairs (Figure 5(b)), and partial collapse of walls, as in Figure 5(a).

The field survey resulted in a schematic view illustrating the different types of traces found in the constructions from the 11th to 18th centuries and for the 19th century in the villages of the area (Figure 6).

One can observe that there are more traces on the buildings of the 11th to 18th centuries than on those of the 19th century (in brown). Furthermore, the traces on buildings of the 11th to 18th centuries are more diversified, and are the result of more violent effects.

The effects are mainly concentrated in the northern sector of the study area. The whole area seems to be crossed by a horizontal band at the Paladru lake level, in which no trace is detected. Below this delimitation other traces are found in the southern part of the surveyed area. In conclusion, the northern and southern traces are probably the result of two distinct events.

3.3. *The post-seismic AFPS [2021] (French Association of Earthquake Engineering) missions and the understanding of seismic effects for better risk prevention*

The Aquila mission in 2009 [Juster-Lermitte et al., 2009, 2011]. The Aquila Earthquake in 2009 in Italy

(a) (b)

Figure 5. (a) House in the town of La Tour du Pin, reconstructions marked in the red circles, filled cracks indicated by the red lines, an opening reduced in central part of the wall, and a reconstruction with small bricks at the upper part between the two windows. (b) The "Dolphin House" (16th century) at La Tour du Pin, the stair's barrel broken and shifted, with the loss of vertical alignment as shown by the red line [Poursoulis, 2017].

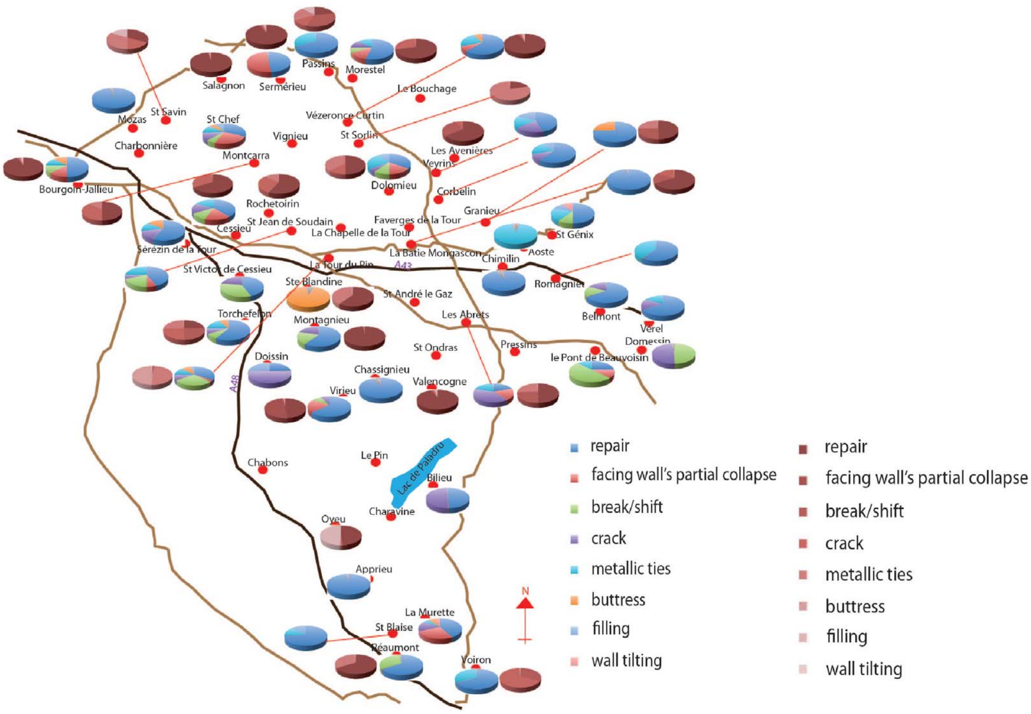


Figure 6. Schematic view of the different type of traces found in the surveyed area: in blue on the 11th to 18th centuries buildings, in brown on the 19th century buildings [Poursoulis, 2017].

happened in an area with an important 800 years of architectural heritage, similar to the heritage visible in France. For this reason, the damage caused by the earthquake to historical buildings, and the recent renovations and reinforcements carried out by the authorities, can be instructive for the future. The archaeoseismological observations made during the AFPS mission at l'Aquila are described in Poursoulis

[2012]. In this paper, the different damage mechanisms on the historical buildings, churches, houses, administrative monuments, etc., are presented. The archaeoseismological traces like the different historical repairs and strengthening methods used and which still are visible on the buildings are also listed. Furthermore, some examples of strengthening works made by the architects of the Italian Monuments Conservation Services are detailed.

The Teil mission in 2019 [Taillefer et al., 2021]. The Teil earthquake in 2019 occurred in an area of moderate seismicity, with past earthquakes mentioned in the French seismic database SisFrance. Earthquakes are known in this area from the 16th century. From the 18th century the area of North and East Tricastin plane has been the location of seismic sequences of low intensity, particularly in 1773, 1873, 1933–1936, 2002–2009. The most important damage testified were generated during the sequence of 1773 and 1873 with an intensity of VII (identified damage on numerous buildings, MSK scale). Some of the places affected by the 1873 earthquake were also affected in 2019 by the Teil earthquake. From the archaeosismological point of view, the context of the Teil earthquake is an opportunity to benchmark methods developed for past earthquakes. Indeed, the region affected by the earthquake shows more than hundred historical structures like castles, churches, houses etc. (Figure 7). Severe damage observed in historical structures like the Castle of Saint-Tomé and the Saint-Etienne of Melas church (Figure 8) can be correlated to the vertical component of the earthquake.

3.4. *The OPUR database and the RECAP [2018] programme: first digital catalogue of seismic damage and repairs in Pompeii*

The RECAP [2018] programme ("Reconstruire après un séisme. Expériences antiques et innovations et à Pompéi»; Rebuilding after an earthquake. Ancient experiments and innovations in Pompeii"), funded by the Agence Nationale de la Recherche, focuses on Roman post-earthquake reconstructions and repairs in the paradigmatic site of Pompeii. Indeed, this small town in Campania is a unique laboratory, as it suffered several earthquakes in quick succession at short intervals in the twenty years prior to the eruption of Vesuvius in 79 AD. The reconstruction work necessitated by the successive seismic episodes was brutally interrupted by the final eruption of Vesuvius. An exceptional "snapshot" of the rebuilding processes can thus be examined. Thanks to the exceptional state of conservation and sheer extent of the remains, the site of Pompeii is particularly suited for a systematic archaeosismological investigation. This is true both on the small scale, with a focus on specific construction sites as case studies, and on the large scale, taking a complete overview of the management of building processes in the ancient town. On the small scale, the project chose to focus on two complementary case studies: firstly, priority urban services revealed by the water network as well as through the extra-urban aqueduct [Filocamo et al., 2018] and the 15 public urban water towers; and secondly, the private building strategies attested to by a vast aristocratic residence—namely, the Villa of Diomedes [Dessales, 2020]. On the large scale, the project applied a systematic approach to an extended area of Pompeii, visualizing all the post-seismic repairs. The Regio VII was selected, with its ten blocks, to the east of the forum (5 ha, around 15 percent of the discovered site), as a representative area that comprises public and religious buildings, houses, shops, and industries. In this manner, the reconstruction conditions were compared in the various functional categories of the city (Dessales, forthcoming). In the field, the pluridisciplinary approach was based on the OPUR database ("Outil pour Unités de Réparation"; Tools for Repair Units) (see Figure 9), which was conceived in order to characterize the post-seismic repairs [Dessales and Tricoche, 2018] and associated to a GIS. The description and analysis of each repair follow four main steps: identity and location of the repair, identification of the damage, nature of repair, chronological relations between the different repairs, and characterization of the different building techniques [Dessales and Tricoche, 2018]. The database was used to list all the repairs visible in the Regio VII, through a field survey of three weeks during 2017. In this area, 255 repairs were finally registered, and more than 1500 photos of the repairs made on the site were added to the database. The OPUR database presents, in its final version, an index and a system of analysis for each repair (see Figure 10 for an example of unit identification), in French, English and Italian; the database is free and publicly available [ANR RECAP, 2018].

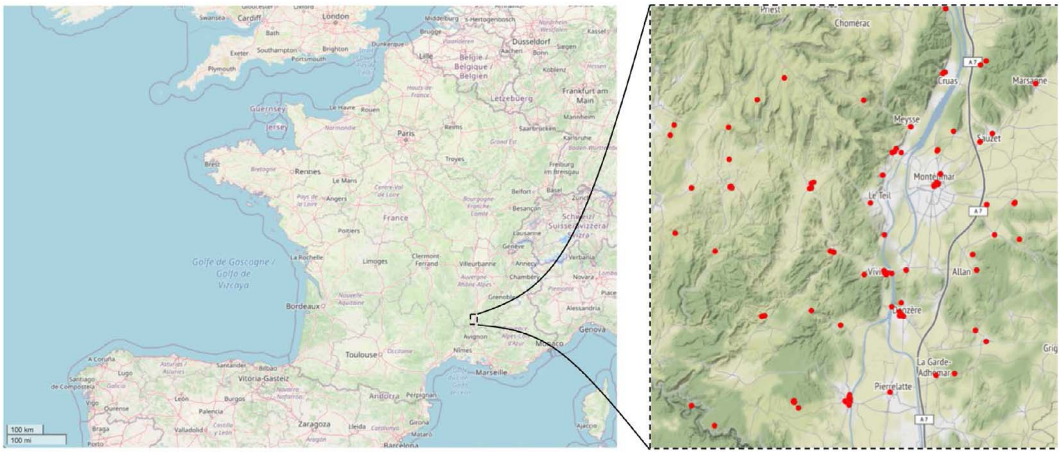


Figure 7. Localization of historical structures (red dot) in the Teil region.

(a) (b)

Figure 8. (a) Saint-Etienne of Melas church (assumed construction date: 11th century): degradation of the cover of the baptistery in the red ellipsoid, cracks in the bell tower indicated by the red lines. (b) Castel of Saint-Tomé (assumed construction date: 14th century), broken lintel.

4. Perspectives and developments in the discipline

Currently, the discipline evolves following two different ways of development in collaboration with engineers and seismologists on one side, and through the numerical database elaboration on the other.

4.1. *The engineering contribution*

From the observation of a structure (shape, building techniques, materials, etc.), archaeosismology tends to determine the correlation between the observed degradation and the history and characteristics of its environmental seismicity. In order to characterize more precisely the environmental effects at the origins of the degradation or no degradation of a structure, quantitative methods should be used. For the analysis of a large set of structures, a classification by typology, degree of damage and statistical analysis allows to develop an isoseismal map for earthquakes like the SisFrance database [Scotti et al., 2004] for the definition of historical earthquakes in France. From this information, methodologies are proposed in the literature to characterize the location and magnitude of the earthquake [see for example: Levret et al., 1994, Traversa et al., 2018, etc.]. In this derivation of the earthquake characteristics, the observations or

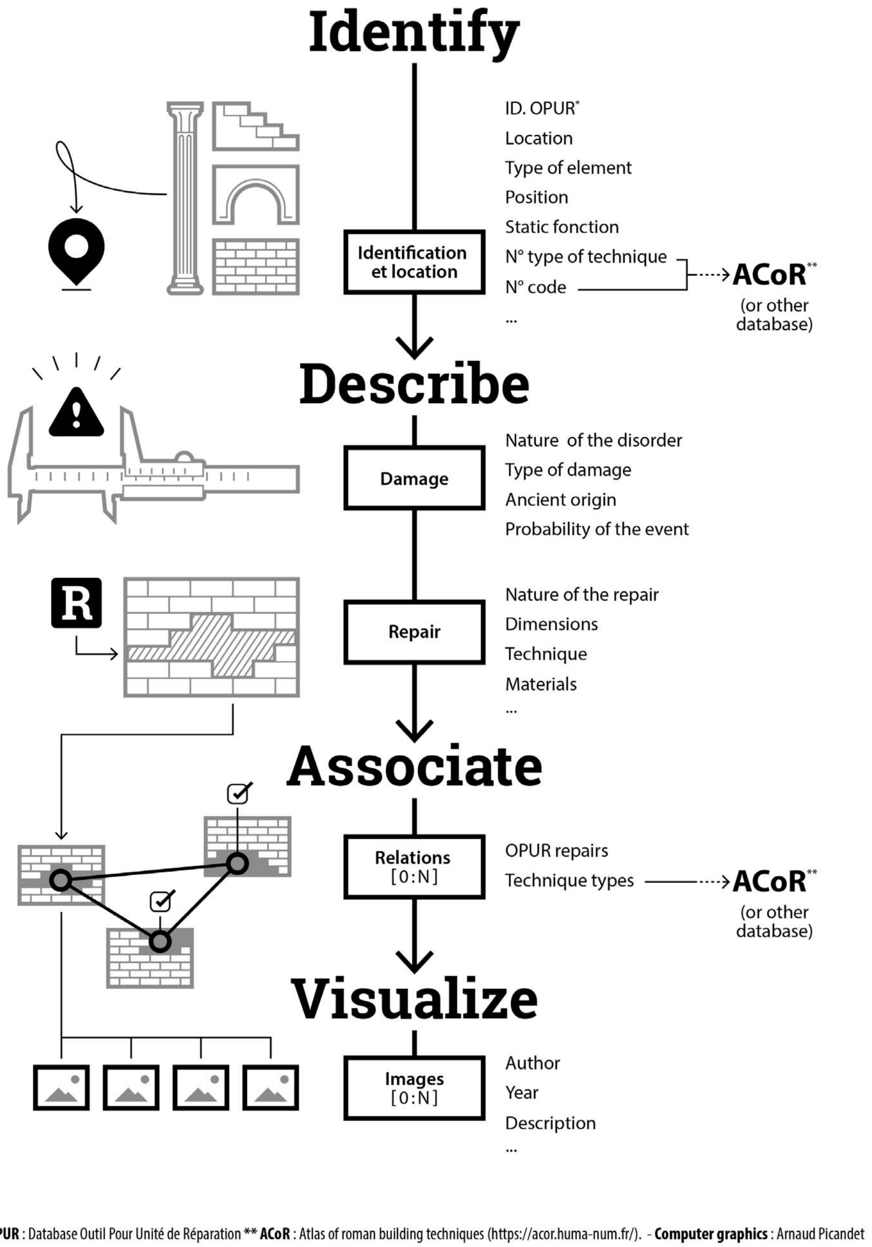


Figure 9. Diagram of the organization of the OPUR database [Dessales and Tricoche, 2018].

testimonies of the structural state are generally directly transcribed into intensity data points and combined with intensity predictive attenuation models to get an estimation of the magnitude and location of an earthquake. The process does not require the use of numerical models for the structure. For isolated buildings in an area (church, castle, aqueduct, etc.) or for more precise information on a specific typology, the use of structural analysis allows to provide more detailed data and to consider more deeply the observations on a structure. The masonry structures represent the largest part of the building patrimony in France and, as such, are the privileged witnesses of past earthquakes. In order to evaluate the response of

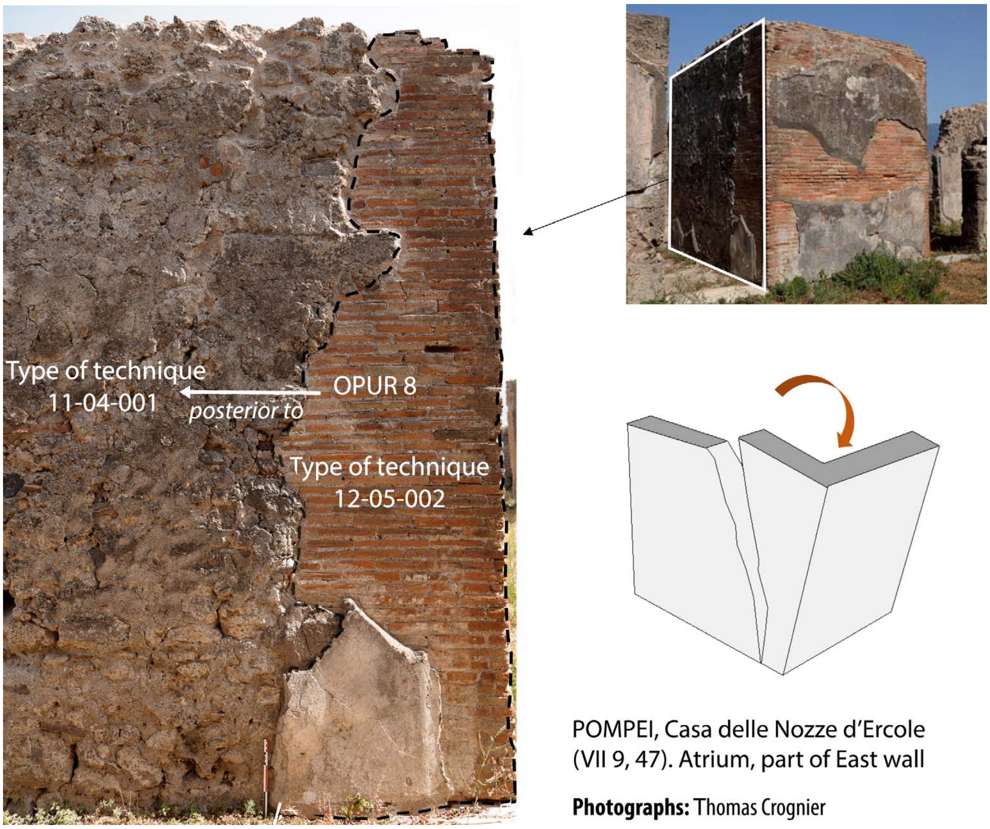


Figure 10. Example of an OPUR unit identification (Casa delle Nozze d'Ercole, VII 9, 47, Atrium, part of the east wall): repair consecutive to a corner overturning, OPUR unit no. 8 [Dessales and Tricoche, 2018].

these structures, dedicated numerical strategies are needed [for a review see Ghiassi and Milani, 2019] like the ones illustrated on Figure 11. Macroelement models are robust and numerically efficient models for quick evaluation of a large number of structures but they fail to address complex structural behaviour and are generally limited to the description of in-plane behaviour. They are dedicated to the description of simple old structures like house or small regular buildings. Furthermore, they describe the nonlinear behaviour at a macroscale and do not provide local quantities such as cracking. In order to get a direct description of cracking or indirect quantification (i.e. by post-treatment method), block-based model or continuum models are preferred. In the following sub-sections, the main aspects of classical modelling methods are explained with a focus on the archaeological data needed to build an efficient numerical model. Examples are shown to illustrate the use of these models to evaluate the response of historical structures.

Block-based models. For block-based models, the masonry is described as a discrete medium with blocks interacting with each other thanks to contact and friction laws. Among the block-based model, the non-smooth contact dynamics (NSCD) method has shown its capacity to describe the response of complex structures. This method is implemented for instance in LMGC90 [Dubois and Jean, 2003]. The interactions are described thanks to two models (Signori conditions and Mohr-Coulomb model) summarized by,

$$g \geq 0, \quad r_n \geq 0, \quad g \cdot r_n = 0 \tag{1}$$

$$\begin{cases} \text{if} \quad \|\mathbf{u}_t\| = 0, \quad \|\mathbf{u}_t\| \leq \mu r_n \\ \text{if} \quad \|\mathbf{u}_t\| \neq 0, \quad \|\mathbf{u}_t\| = \mu r_n \end{cases} \tag{2}$$

g is a gap to the normal reaction, r_n and $\mathbf{r}_t$ are the normal and tangential forces to the contact surface,

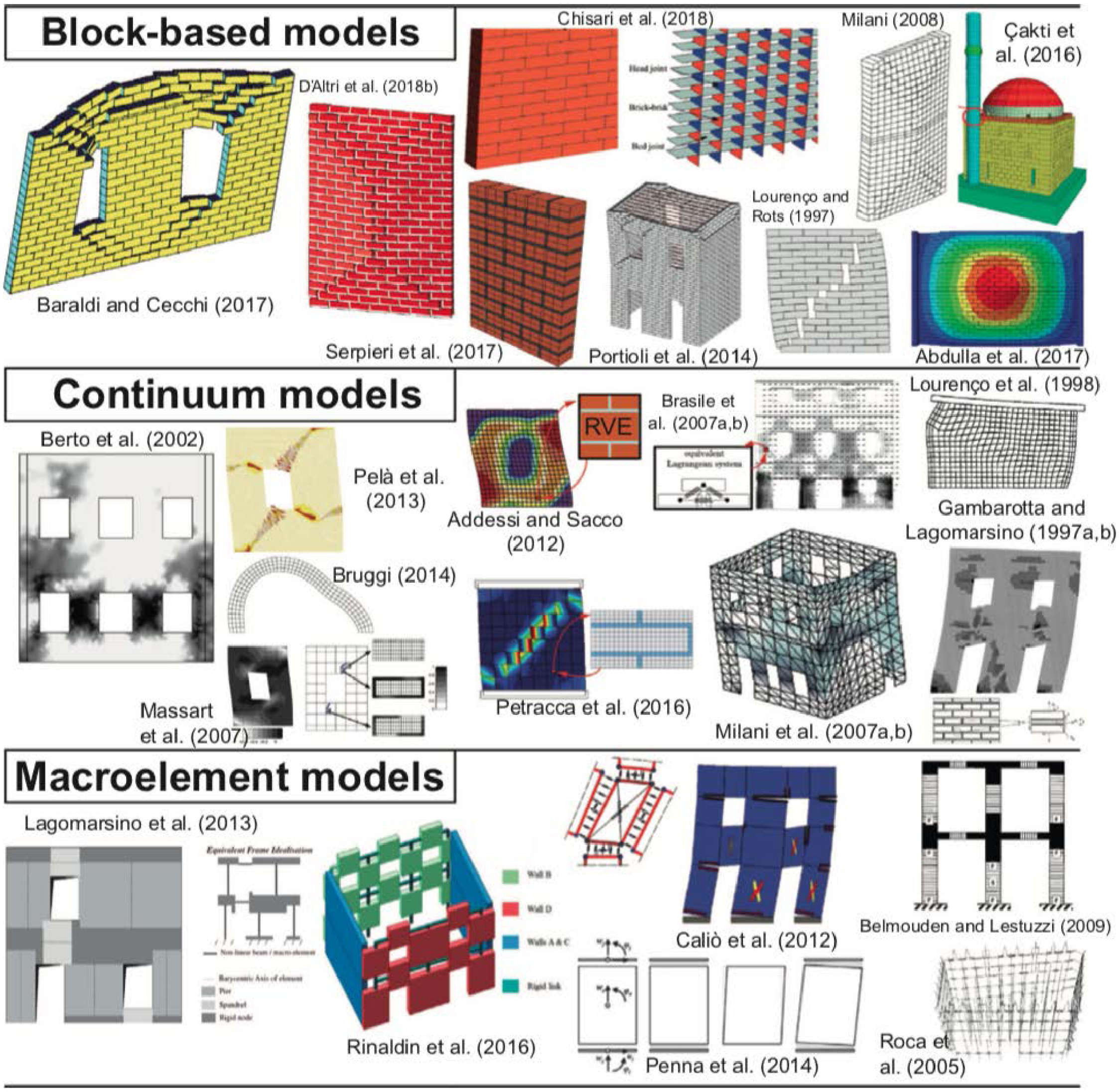


Figure 11. Numerical strategies for masonry structures (extracted from Ghiassi and Milani [2019]).

u_n and $\mathbf{u}_t$ are the normal and tangential displacements to the contact surface. The only material parameters necessary in this interaction model is the friction coefficient μ. In order to describe the behaviour of the blocks, isotropic elastic constitutive model is classically used, thereby introducing two additional parameters to identify for the modelling (i.e. the Young modulus E and the Poisson ratio ν). Finally, to manage dynamic analysis, the density ρ of the material is needed. One can see that the number of material parameters to identify are limited and may be relatively easy to obtain from archaeological expertise and local material testing. Nevertheless, it should be pointed out that one of the main influent parameters in the response of the structure is the shape of the block elements. Indeed, the response of the structure is driven by the surfaces in contact. From an archaeological point of view, this requires the knowledge of the techniques used to obtain the block and to assemble those blocks in order to create the whole structure. A visual inspection or photogrammetric technique can only provide the shape

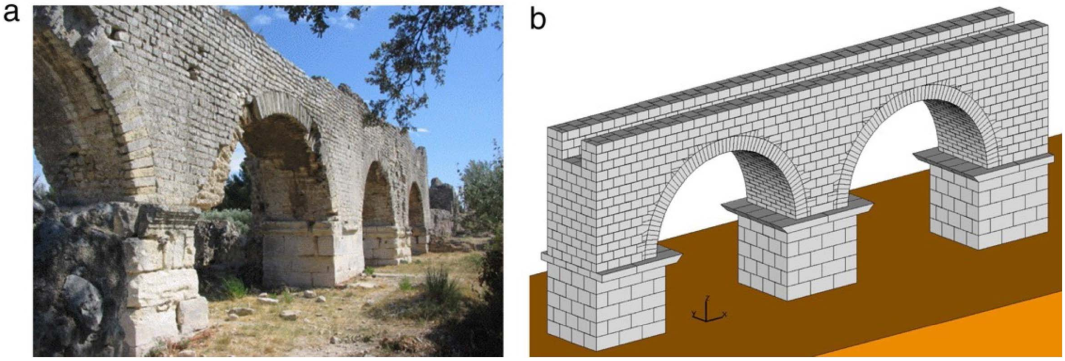


Figure 12. Arles aqueduct (a) arches showing large stone course pillars, (b) 3D model for LMGC90 (from Rafiee et al. [2008]).

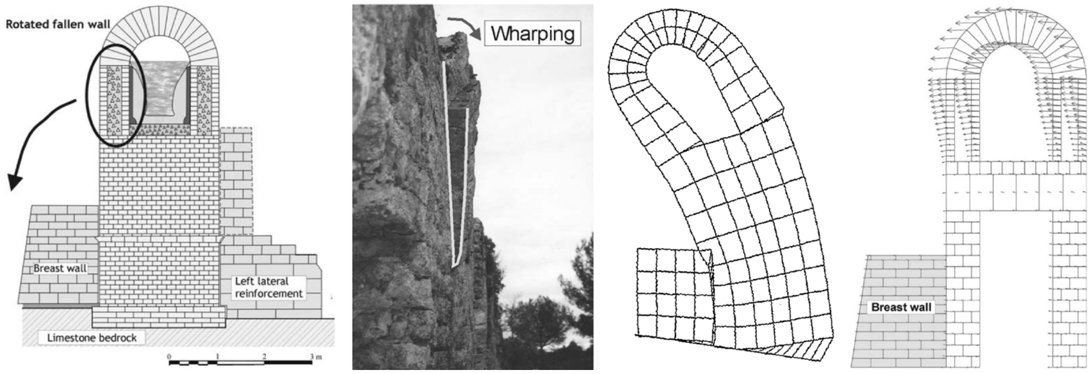
of the blocks at the surface [see Acary et al., 1999 for an application of this technique]. In the context of archaeoseismicity, this type of modelling has been used to analyse the dynamic response of the Arles aqueduct and identify some correlation between the actual state of the structure and earthquake loadings by Rafiee et al. [2008] (Figure 12). Unfortunately, due to the lack of *in situ* quantitative information or testimonies, the results obtained stay qualitative and the authors can only conclude a past earthquake can be at the origin of a failure of the Arles aqueduct.

Continuum models. For continuum models, the masonry is described as a continuous medium. Furthermore, at the structural scale, homogeneous description is generally adopted with more or less complex constitutive behaviour (e.g. elasticity, damage, plasticity, etc.). The homogenized masonry model can be defined in a general form,

$$\boldsymbol{\sigma} = \mathscr{F}(\boldsymbol{\varepsilon}, V_i), \tag{3}$$

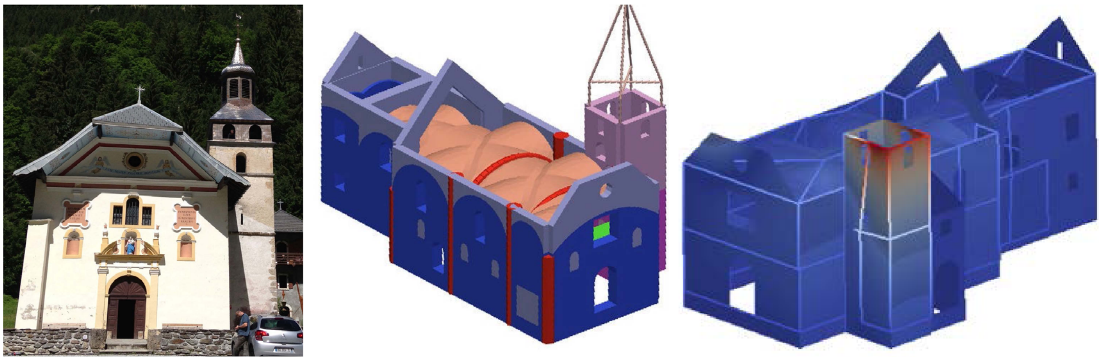
where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\boldsymbol{\varepsilon}$ is the strain tensor (small perturbations hypothesis) and V_i are internal variables used to describe the nonlinear mechanisms. $\mathscr{F}$ is the masonry model. The number of parameters depends on the complexity of the model. It can go from only two parameters for isotropic elasticity to several tens of parameters for orthotropic elasticity with coupled damage and plasticity. For the identification, a multidisciplinary approach is strongly desired to identify the characteristics and nature of joints and blocks, the arrangement of the masonry, etc. These data can be also useful to perform virtual testing to identify the parameters of the homogenized model of masonry [see Giry et al., 2017, as an example]. From a numerical point of view, the finite element method (FEM) is classically used to approximate the displacement field of the structure. Examples of FEM code used for archaeoseismological studies in France are: Cast3M [2021], code_aster [2021], etc. Only the global shape of the structure needs to be defined without describing explicitly the blocks and joints. In the context of archaeoseismology, this type of modelling has been used for the aqueduct of Nîmes study [Volant et al., 2009]. The authors perform a 2D analysis of the cross section of the Pont de la Lône with FEM with nonlinear joints using Cast3M [2021] code and with distinct elements methods (DEM) using UDEC [2021] (Figure 13). This last method is close to the one described in the previous sub-section.

With this simple 2D modelling, the authors are able to illustrate the fact that the breast wall at the bottom left induces a large stress state at the base of the canal wall where the failure has occurred and a larger magnitude than the one originally defined (i.e. M6 earthquake at 10 km distance) is needed to obtain an overturning of the canal wall. An additional study is proposed in Volant et al. [2009] to illustrate the fact that a magnitude larger than 6 should be considered for historical earthquakes in the region. It uses one advantage of the FEM model compared to simple block models, its capacity to perform classical modal analysis with the identification of eigenfrequencies and associated mode shapes. The modal analysis is not possible for block models without superposing a



(a) (b) (c) (d)

Figure 13. Analysis of the Pont de Lône. (a) Cross section, (b) picture of the failure mechanism, (c) FEM modelling with Cast3M [2021] and (d) DEM modelling with UDEC [2021] ((a), (b) and (d) are extracted from Volant et al. [2009] and (c) from [Berthellot, 2000]).



(a) (b) (c)

Figure 14. Structural analysis of the Notre-Dame-de-la-Gorge church, (a) picture of the church, (b) numerical model with the substructures decomposition and (c) shape of the third mode (3D model with Cast3M [2021] and lines 3D plot from Operational Modal Analysis) (extracted from Limoge [2016]).

lattice model due to the nonlinear behaviour of the contact (i.e. unilateral response). The modal analysis allows the use of simplified analysis derived from earthquake engineering (spectral analysis) by considering response spectrum to describe earthquake loadings.

Perspectives and challenges for the use of numerical strategies. The numerical analyses performed in the framework of archaeoseismology generally consider a virgin structure and an isolated event. In a seismic region, the structure shows generally complex history with different construction phases, repair, etc. These traces that archaeological science can identify [see for instance Montabert et al., 2020] play a major role in the evaluation of the structural response and the potential activation of specific local vibrations. Indeed, repairs and modification of the structure may induce a different response from the one obtained for a homogeneous distribution of the masonry properties over the entire structure. Limoge [2016] shows the necessity to decompose a complex structure like a church in homogeneous substructures that have seen the same shaking history in order to retrieve structural properties like the eigenfrequencies and mode shapes (Figure 14). The environmental conditions may also induce modification and degradation of the mechanical properties of the masonry. Kržan et al. [2015] have studied ageing and moisture problems of Kolizej palace in Ljubljana and their influence on the vulnerability of the structure. From simple consideration of reduction of the mechanical properties according to in situ and laboratory tests, they obtain a drop off for the maximum shear base force close to 50% of the one obtained for normal environmental condition. For continuum models, multiphysical phenomena can be considered in the same framework as the one used to derive a constitutive model. From a thermodynamical formulation of the constitutive model [Lemaitre et al., 2020], it leads to the introduction of additional state variables to describe additional physics and their interactions like in the following equation,

$$\boldsymbol{\sigma} = \mathscr{F}(\boldsymbol{\varepsilon}, V_i, T, RH, t), \tag{4}$$

where T is the temperature, RH is the relative humidity and t is the time. An example of multiphysical model for the study of ageing effect on old masonry structures can be found in Oñate et al. [1996]. A continuum framework was considered to describe the response of the masonry. The effect of ageing through physical–chemical–biological effects is considered thanks to a variable that tends to introduce a pre-damage state of the structure prior to the evaluation of its response to severe loading like earthquake.

4.2. *An Italian multidisciplinary case study: Sant'Agatha del Mugello and the multidisciplinary strategy experimented [Montabert et al., 2020]*

After the APS group multidisciplinary work example in Manosque, an interdisciplinary strategy based on: innovative techniques to identify damage associated with past earthquakes from the inventory of repairs introduced in the building archaeology [ANR-RECAP, 2018]; realistic seismic input signals consistent with the seismotectonic context; digital building models implementing realistic geometry and construction materials as well as robust modelling of masonry behaviour was at the core of the work performed by Montabert et al. [2020] in Sant'Agata del Mugello, a medieval church located in the Mugello alluvial basin in Tuscany (Central Italy). The seismic history of the church is traced by collecting historical sources, archaeological stratigraphic analysis, information on the historical seismicity of the region, and structural engineering analysis. The Mugello is an intramontane basin located in central Apennines bounded by two main fault systems. The region experimented several moderate earthquakes among which are the M_{mw} (macroseismic moment magnitude) = 6 (1542 seismic event), the M_{mw} = 5.1 (1611 seismic event) and the M_{mw} = 6.4 (1919 seismic event) seismic events [see Rovida et al., 2019 for the magnitudes]. Applying the RECAP [2018] method used in Pompeii through the OPUR database [Dessales and Tricoche, 2018], the authors identified 80 repair units, characterized by 13 building techniques. Crossing the archaeological analysis and information coming from historical records, each repair has been associated with events like earthquakes or routine maintenance/restructuring. The information is summarized in a building timeline tracing the evolution of the building through the centuries (Figure 15). Finally, structural engineering analysis has been conducted on the repairs corresponding to the occurrence of earthquake, allowing to retrieve the associated damage mechanisms. On the basis of these elements the authors conclude that the church was deeply affected by the 1542 seismic event (deduced magnitude 6.02) which resulted in the collapse of the upper part of the bell tower and the two lateral chapels as well as the overturning of the front wall and of the two lateral walls of the nave. The 1611 seismic event damaged the upper part of the bell tower as described in historical records (Figure 15). Finally, the 1919 seismic event produced only small cracks in the church. But, in spite of the confirmed occurrence of seismic events in the area from the middle of the 17th century and the beginning of the 20th century, no information relating seismic damage of the church has been found either in historical records or in the stratigraphic analysis.

This work opens a new perspective to characterize the seismic ground motion induced by historical earthquakes in a quantitative manner, as the stratigraphic description of the damage induced by historical earthquakes can be reproduced numerically. From the comparison of the observed and reproduced damage, it is thus possible to retrieve the historical ground motion features. However, to achieve this goal two further steps should be accomplished: the definition of the digital building model of the existing masonry structure, and the definition of ground motions to be used as input for

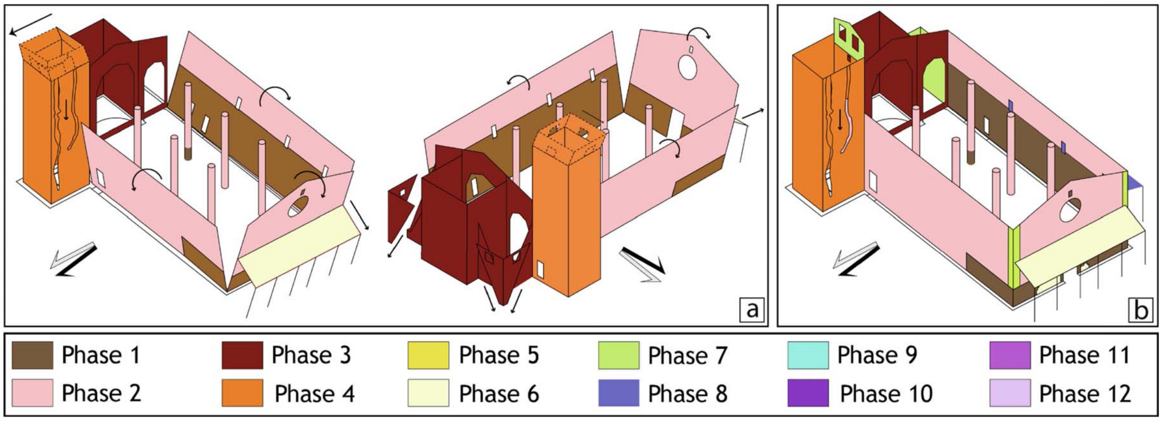


Figure 15. Sketches of the damage mechanisms identified for both 1542 and 1611 seismic event from Montabert et al. [2020].

the building dynamic analysis. The definition of the digital building model can be split in two stages, the definition of geometrical and mechanical models of the building (Section 4.1), and the definition of the modelling strategy. The geometry is usually constrained by identifying the load bearing system, by using high definition orthophotos, or when available 3D laser scanner [for example Arrighetti, 2019]. The definition of mechanical properties is indeed a difficult point especially for historical monuments for which non-invasive approach must be implemented to guarantee the building integrity. In the recent work by Limoge [2016] and Limoge-Schraen et al. [2016] on several churches located in Haute-Savoie (France), the linear dynamic behaviour of the buildings is constrained by operational modal analysis (OMA), a non-invasive approach aimed at characterizing building fundamental frequencies, modal shapes and damping ratio using ambient vibration records. The next step of the Mugello basin study is the carrying out of the ACROSS [2021] Project with future applications in France.

5. Conclusions and perspectives

Historical buildings record natural catastrophes in their walls [Caputo and Helly, 2008]. For this reason, they can be considered as “stone seismometers”, allowing to retrieve the seismic ground motions required to explain building repairs, structural disorders, or their absence. According to the archaeoseismological method, past events can be traced by studying the standing remains of historical buildings. In France, the experience led by the multidisciplinary team of APS Group brings the methodological bases, and develops the discipline, by associating the historical and archaeological knowledge of the structures to earth sciences and engineering models. The new perspectives of the discipline depend on the collaboration of the different fields like in many new projects like the Teil, Vienne, Pompeii, and the ACROSS [2021] project, the next step of the Mugello basin seismicity study.

Just after the Teil earthquake, the instrumentation of historical buildings in the region around the Teil has been proposed [see Cornou et al., 2021, as an example]: the Vivier cathedral Tower, the Castles of Saint-Tomé. The data recorded by the seismometers will give a better knowledge of the dynamic behaviour of these buildings, their vulnerability factors, their response to seismic aftershocks and the possible amplifications due to site effects.

Another future project linked to archaeoseismology in France is focused on the Chauvet cave and the town of Vienne (France) [Helly et al., 2017]: RESHIST [2021] (AURA project). This town was occupied from the Gallic period and represents an important Roman economic centre. The Roman Temple of August and Livia presents some seismic effects of an unknown event which happened during the Imperial time, near 37 AD (end of Tiber’s reign/start of Caligula’s one). Numerous destructions, reconstructions, repairs and reuses of materials are visible on the buildings still standing and give information about a probable earthquake at that time. In order to find the potential seismic fault responsible for this damage and to determine the resistance capacity of the historical buildings, the project RESHIST [2021] will study the architectural, geological, historical, seismological and other available data in the area of Vienne. This project is an important part of the work to reassess the seismic risk in the Rhodanian basin.

The development of new multidisciplinary approach for archaeoseismology is the main objective of the ACROSS [2021] project. In this project, the whole methodology, spanning from archaeology to earthquake engineering will be developed and applied to several monumental buildings located in the Mugello basin, using the OPUR database for archaeological data acquisition, and the geometrical and mechanical modelling methods for knowledge acquisition of the structural behaviour under seismic motion. Information on the historical seismic movement will thus be characterized at different locations in the basin. The richness and completeness of historical archives over eight centuries, the advanced knowledge of the seismotectonic context and of the historical seismicity (at least from the XVI century) led to the choice of this site. The experience developed with the ACROSS [2021] project will be applied in the French context in a site giving the same quality of information and knowledge, like Manosque, for which the APS Group work provided a fertile multidisciplinary base for further studies.

A next step would be the creation of an international network, which would bring together the different research groups, the Italian teams already mentioned [Arrighetti, 2015], and other centres already specialized in this topic, for example, in Leuven [Sintubin, 2011, Jusseret and Sintubin, 2017], or in Cologne [Hinzen et al., 2013]. Shared protocols for recording of data in case of excavation or building analysis would be very useful. Initiating a common reflection between the different laboratories and disciplines represents a very stimulating perspective of development for archaeoseismology.

Acronyms

AFPS	Association Française du Génie Parasismique
APS	Archéologie, Pathologies, Sismicité
BRGM	Bureau de Recherches Géologiques et Minières
CNRS	Centre National de la Recherche Scientifique
CEA	Commissariat à l'Energie Atomique
CUEBC	Centre Universitaire Européen pour les Biens Culturels
EDF	Electricité de France
IRSN	Institut de Radioprotection et de Surêté Nucléaire
IPSN	Institut de Protection et de Surêté Nucléaire
SIRENE	Système d'Information et de Rassemblement des Evènements Naturels Existants

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