

Integrating Historical Sources and Infrared Thermography for Detection of Seismic Damage in Architectural Heritage

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Abstract – This article aims to illustrate a methodological approach for identifying damage scars and reconstruction interventions on monuments affected by past earthquakes. The approach draws on the combined and cross-referenced use of historical-technical sources alongside infrared thermographic surveys, allowing to piece together the chronology and extent of structural interventions over time. To try out and validate the methodology, we focus on two case studies involving churches located in two towns in the Basilicata region (Southern Italy). These sites were struck by two major seismic events in the 20th century: the 23 July 1930 Irpinia earthquake (Mw 6.7) and the 23 November 1980 Irpinia-Basilicata earthquake (Mw 6.8). By examining these examples, we aim to lay out the potential of the method to bring out hidden traces of damage and reveal insights into the repair strategies adopted in response to seismic events.

I. INTRODUCTION

It is well known that monument restoration and conservation plans require a thorough historical analysis of the building [1], aimed at reconstructing the reasons for its original conception and construction, as well as understanding the transformations it underwent over time—whether due to changes in function, deliberate human interventions, or responses to natural hazards (e.g., earthquakes, floods, landslides) over the centuries. Strategies aimed at addressing these questions rely on the integrated use of historical research and non-destructive diagnostic techniques, such as Infrared Thermography (IRT), which is widely recognized as a valuable tool in the analysis of cultural heritage [2,3]. IRT provides insights into both the surface and subsurface structures of artifacts [2, 4] by analysing how heat diffuses through the material.

IRT can pick up on anomalies linked to material alteration and degradation, detect architectural changes introduced over time through restoration or reconstruction, and bring to light original features that may have been concealed by later interventions. Because of these capabilities, IRT has been widely and successfully used to investigate large cultural heritage structures, most often through the so-called passive approach, which is grounded in the observation of surface temperature oscillations naturally induced by the diurnal cycle, as a means to infer the structure of the wall envelope's thermo-physical properties. Alternatively, IRT can be used with the active method, which involves applying a controlled thermal stimulus to the artifact to enhance thermal contrast and reveal hidden features [5].

To develop a methodology capable of detecting damage scars and reconstruction interventions on monuments following earthquakes, the use of passive infrared thermography surveys was taken into consideration in this study. Furthermore, thermographic investigations were correlated and integrated with historical data able to document the seismic effects on the investigated built heritage. In order to test the methodology, we considered two monuments located in the towns of Melfi and Atella (Basilicata Region, Southern Italy) hit by two strong earthquakes in the 20th century: the 23 July 1930 Irpinia (Mw 6.7) and 23 November 1980 Irpinia-Basilicata (Mw 6.8) earthquakes [6-8]. The proposed approach can serve as a tool in the planning of restoration and conservation interventions on monuments, as it enables a deeper understanding of the building's structural history and the extent of past damage. By revealing hidden or non-visible traces of previous seismic events and subsequent repairs, this method helps guide more informed, targeted, and historically respectful

conservation strategies. Such insight is particularly crucial when addressing the structural vulnerabilities of heritage buildings in seismic-prone areas.

II. MATERIALS AND METHODS

Selection of the buildings

The criteria followed to single out the monuments to be investigated by the combined approach were fourfold:

1) buildings that had gone through significant damage, such as major cracking or partial collapse, because of at least one earthquake. Structures reported in historical sources as having completely collapsed and rebuilt were left out of the selection process; 2) buildings featuring plastered façades, where seismic repairs may have been covered up and are not immediately visible to the naked eye; 3) buildings for which detailed and reliable documentation on earthquake effects could be drawn upon; 4) sites that were both accessible and provided sufficient open space around the monument to allow for passive solar heating and the proper execution of infrared thermographic surveys.

IRT data acquisitions

Thermal images were obtained through the passive method. In passive thermography, the component is inspected during or directly after the wall heating exposed to natural (solar) irradiation. With this technique the identification of anomalies or discontinuities in the investigated buildings is a function of the thickness, type and state of preservation of the plaster as well as the emissivity of investigated surfaces and the physical properties of building materials. The possibility to detect abnormalities or discontinuities in a wall depends on both the frequency of thermal stress and the diffusivity of the materials constituting the states nearest to the surface investigated. The selection of the suitable period for the acquisition of data was performed taking into account some basic variables such as the different boundary conditions concerning both the object of investigation and the external meteorological conditions. Images were captured (Table 1) at night on a case-by-case basis to investigate wall orientation. Some images were taken immediately after direct solar radiation exposure, and in some instances, areas were monitored at different times to assess temperature variations. This was necessary because unfavourable surface exposure often hindered the detection of the underlying wall structure.

The thermographic images were taken using FLIR SC660 detector FPA (Focal Plane Array) uncooled microbolometer that operates in the spectral band between 7.5 and 13-14 microns. The spatial resolution of the acquisition system is given by a matrix of sensitive elements of size 640x480 pixels. This acquisition system offers, in addition to a remarkable handiness, a spatial resolution that allows to investigate an area of 14.0 x 13.7 mm of dimensions at a shooting distance of 10 meters.

Church	Detect ed portion	Expositi on oh the wall	Time of image capture	Survey Date	Temperat ure and relative humidity
San Benedetto (Atella)	Lateral façade	South	Since 7 pm	28/10/2013	26,6°C 88% RU
Santa Maria ad Nives (Melfi)	Main façade	Southwest	Since 7 pm	26/09/2013	26,6°C 88% RU

Table 1. Main IRT acquisition features

Historical data

To identify seismic damage, it is essential to back up the evidence revealed by thermographic surveys (TSs) with historical data on the earthquakes that may have impacted the monument under investigation. Once the target monuments were selected, we looked into the seismic history of the respective municipalities and examined the effects of both historical and recent earthquakes on local buildings. Our goal was to match up the damage patterns recorded in historical sources with the anomalies detected through thermographic analysis. Specifically, we analysed the impact of the 23 November 1980 Irpinia-Basilicata earthquake (Mw 6.8) on a church in the municipality of Atella (VII MCS), and the consequences of the 23 July 1930 Irpinia earthquake (Mw 6.7) on a church in Rionero in Vulture (VIII MCS). Both municipalities are located in the Basilicata region (Southern Italy).

In order to identify the effects caused by the two earthquakes on the buildings surveyed, we performed an analysis on unpublished technical and administrative primary documentation jointly with the study of some published data.

The main source of data about the damage caused by the 1980 seismic event was Proietti (1994) [9]. This work includes detailed damage effects caused by the earthquake to the cultural heritage located in the two main regions involved in the earthquakes (Basilicata and Campania). These data were integrated with other documents such as unpublished photos preserved in the archive of the Superintendence of the Architectural Heritage of Potenza (chief-town of the Basilicata Region).

Analysing the 1930 earthquake, the survey cards compiled in the aftermath the seismic event allowed to get a brief overview of the information on the damage suffered by the building. To gather the detailed knowledge about the parts of the buildings involved, the entity, typology and extension of damage it was necessary to consider the restoration projects, usually including the damage survey. The church restoration projects were compiled by the Pontifical Office for Religious Works and later reviewed and validated by the Civil Engineering Department. We conducted a cross-analysis using data from both documents.

III. RESULTS AND DISCUSSION

San Benedetto (Atella) church

The first nucleus of the building complex of San Benedetto church dates from the mid of the XIV century. The church has a single nave with a barrel vault and lunettes at the sides of the windows. During the 23 November 1980 earthquake there was the collapse of the front gable damaged, the collapse of portions of the side walls of the roof and part of the bell tower (Figure 1).

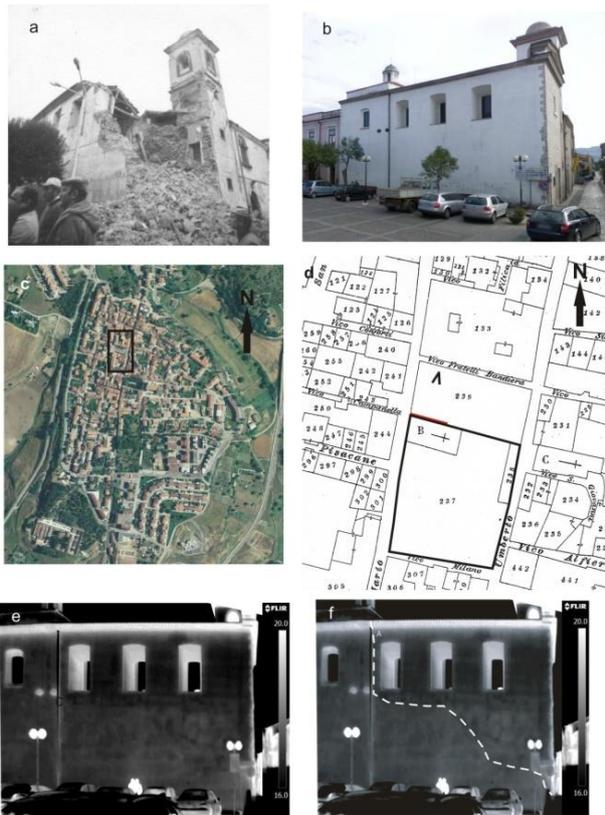


Figure 1 - San Benedetto church: historical image of the lateral side immediately after the 1980 earthquake (a) actual image of the lateral side (b) localization of the building (c) and localization of the investigated walls (d) heat map of the lateral side (c) and limit/line of reconstruction (dotted line A)

The photograph taken shortly after the earthquake clearly reveals the collapse of the south and east walls of the building (Figure 1a). When this historical image is compared with the more recent thermal image (Figure 1e), a quite distinct boundary becomes visible on the southern façade, delineating the area of reconstruction carried out following the seismic event (Figure 1f). Notably, the extent of the reconstruction appears to be broader than the portion of the wall that visibly collapsed in the immediate aftermath. This discrepancy can likely be attributed to the fact that, although some segments of the southern wall

(particularly those located beneath the windows) did not completely collapse, they nonetheless sustained extensive structural damage. The severity of this damage rendered the remaining sections unstable, necessitating their subsequent demolition and replacement as part of a broader restoration effort. The thermal imagery thus not only highlights the physical boundaries of post-earthquake interventions but also provides insight into the decision-making process regarding structural safety and the scope of reconstruction beyond what was immediately apparent from the visible damage.

Santa Maria ad Nives (Melfi) church

The Santa Maria ad Nives church was built in 1570. It is made up of a single nave, barrel vaults and lunettes. The main façade faces south-west orientation, while the side walls to the northwest and southeast (Figure 2).

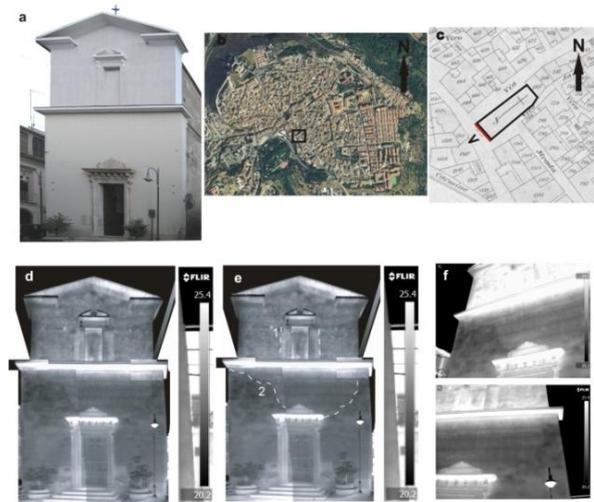


Figure 2 - Santa Maria ad Nives church: current image of front facade (a) localization of the building (b), and of the investigated wall (c) Heat map of the facade (d) and indication of the reconstruction elements (dotted lines 1-2) (e); details of thermal maps with lines of reconstruction

As a result of the 1930 earthquake, damage was recorded to the lateral walls, the front façade, and the front wall of the tympanum. Furthermore, the building suffered partial collapse of the roof and damage to the inner vaults and the bell tower. After the 1980 earthquake the church was affected only by slight damage on the right lateral wall. A comparison between the documented repair works carried out after the 1930 earthquake and the infrared images highlights the likely starting point of the reconstruction process. In particular, the thermal image of the main façade reveals a boundary with an irregular trajectory, extending from the lateral section of the façade to the architrave above the main entrance (Figure 2d-f).

This thermal signature corresponds with the area described in the historical and technical documentation as having undergone repair. The irregular shape of the detected boundary can suggest a non-uniform reconstruction effort, possibly influenced by varying degrees of structural damage sustained during the earthquake.

IV. CONCLUSIONS

The combined use of historical research into earthquake-related damage and infrared surveys has been relied upon to help identify and date failures in monuments. By drawing on both archival records and thermographic imaging, the approach shed light on the sequence and extent of past damage, providing valuable insights into the building's historical development.

To setup the methodology two case studies have been summarized in this article. Looking ahead, the methodology will be further tested and expanded through additional applications, considering a wider range of building typologies and construction materials. The goal is to weigh up the strengths and limitations of the approach in varied architectural settings. Ultimately, this method can serve as a valuable tool in deepening our understanding of a monument's history, an essential step to be carried out prior to any intervention, particularly those aimed at reducing seismic vulnerability and ensuring long-term structural resilience.

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