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A new device for stress monitoring of ancient masonry buildings: Pilot study and results

Haydee Blanco | Yosbel Boffill | Ignacio Lombillo | Luis Villegas

Department of Structural and Mechanical Engineering, Civil Engineering School, University of Cantabria, Av. Los Castros s/n, Santander 39005, Spain

Correspondence
Haydee Blanco, Department of Structural and Mechanical Engineering, Civil Engineering School, University of Cantabria, Av. Los Castros s/n, Santander 39005, Spain.
Email: haydee.blanco@unican.es

Summary

The need to obtain the mechanical characteristics for analysis and understanding of the mechanical behaviour of historic buildings is highlighted. Destructive tests and non-destructive tests are widely used for this purpose; however, they only provide a value associated with a specific instant. Structural health monitoring contributes to the monitoring of specific processes before, during, or after an intervention. Nevertheless, among the available sensors, there is a lack of devices for continuous monitoring of stress variations undergone by masonry structures. In response to this need, a new stress-measurement device for structural monitoring of masonry structures has been developed. It has the aim of determining the initial stress in masonry structural element and providing continuous control of the evolution of the stress variation. The article describes the design of the device, as well as its implementation in a historic building. Moreover, an assessment is performed of the stress variations registered in comparison with the displacements recorded in the monitored areas, as well as the influence of the thermic fluctuations on these. A good relation was confirmed between these measurements. The results demonstrate that the designed device proved to be a useful tool for monitoring structural strengthening interventions.

KEYWORDS

ancient buildings, flat jack, masonry structures, pressure pad, stress sensors, structural health monitoring

1 | INTRODUCTION

Nowadays, civil societies give an increasing importance to their historical and cultural heritage, showing a great interest in its preservation and conservation,[1] and even promoting the drafting of specific legislation for this purpose.[2]

Interventions in old constructions, given their fragility, require precision and detail in developing a rigorous previous diagnostic study.[3,4] Clearly, it must be supported by in-depth historical research and surveys on materials, structural techniques, and geological aspects of the building.[2] This provides the basis for decisions about the intervention techniques that should be adopted.

As the evaluation of the conservation state of historic buildings using destructive techniques should be avoided to preserve the integrity of the cultural heritage, the development of non-destructive techniques (NDTs) becomes of crucial importance.[1] In fact, NDTs are necessary to obtain knowledge about several properties in the analysis and understanding of the mechanical behaviour of historic constructions, as well as to validate the analysis itself.[5] These have been applied for several years to works of art and monumental buildings.[6–8]

In this context, Bisby[9] considers that NDT normally refers to a one-time assessment of the condition of materials in the structure using equipment external to the structure. However, structural health monitoring (SHM) is an engineering technique that monitors, verifies, and informs about the condition or changes in the condition of a structure so that engineers are able to obtain trustworthy information for management, decision making, and to guarantee the safety of users.[10–12] As a result, monitoring systems undoubtedly contribute to knowledge of the evolution of specific processes[13–15] before, during, or after an intervention.

In addition, SHM can be used where data are needed to guarantee reliability of new or ancient buildings. In the case of a structure nearing the end of its service life, SHM may permit its continued use for a time by providing confidence in its satisfactory performance.[9,16] Likewise, as new sensors become available, the possibility for application of improved SHM techniques is increasingly feasible.[17]

The rehabilitation of ancient buildings requires detailed knowledge of the mechanical characteristics of the material of the structure,[18,19] which play an important role in the intervention process. However, this aspect in masonry structures is not easy to deal with given their considerable heterogeneity, with rigid materials (bricks, stones, etc.) along with more deformable ones (mortar). Thus, SHM, which detects changes in the material or geometric properties of structures,[17,20] becomes essential to the safety of these masonry structures.

Therefore, the objective of this paper is to provide a device capable of, on the one hand, determining the stress level existing in a masonry structural element and, on the other hand, monitoring continuously the relative evolution of the stress level over time. Thanks to the integration of several techniques, an analysis of the structural behaviour of the building can be carried out. The device enables the examination of the building's behaviour both under serviceability conditions, during the building rehabilitation and once it has been finished.

In particular, the article focuses on a device enabling the monitoring of serviceability stresses in a masonry structure. The basics of the design, the component elements, and the application methodology are detailed. In Section 2, the background is analysed and the motivation of the research is described. Next, the adopted methodology and its application to a specific case study (Modernist Church of the Comillas Seminary, Spain) is presented. Thus, the work related to the installation of the monitoring points, the data acquisition system, and the software development is addressed. Finally, the evolution of the measurements recorded during the building rehabilitation is detailed.

2 | BACKGROUND AND MOTIVATION

The simplest approach for the determination of physical and mechanical characteristics of the structure is provided by geophysical testing methods. However, geophysical measurements can only give a qualitative evaluation of the mechanical behaviour of the structure, and in any case, the results obtained by these techniques have to be verified based on the results of direct mechanical tests.[18] In this sense, tests based on flat jacks enable the stress level and mechanical properties of a masonry structural element to be determined without removing or altering the samples themselves.

The first applications of this technique to ancient buildings clearly showed its great potential.[18] It appeared to be the only way to obtain reliable information about the main mechanical characteristics of a masonry structure: deformability, strength, and stress level.[21] Noland et al.[22] consider the double flat jack method to be unique, because it provides a direct measure of modulus of elasticity and Poisson's ratio and a masonry strength estimation. The single flat jack test provides a direct measure of the vertical stress at a point in a structure. Thus, the combination of both tests gives an indication of the safety factor in compression of the structure concerning gravity loads.

The test originates in the field of rock mechanics,[18,23,24] having been adapted for the evaluation of brick and stone masonry structures by Rossi and other researchers[18,25,26] in the 1980s. It should be added that its application over the years has enabled the evaluation of safety of structures[21] and even the use with the aim of determining whether load-bearing walls are sufficiently strong to resist new actions.[27] As well as its use in rehabilitation of historic buildings, it has been used with other types of construction such as dams, bridges, and tunnels.[19,28] Additionally, this technique has been used in concrete tunnels[29] such as the case of the civil engineering of Hauensstein in Switzerland.

Many studies have been done on the application of simple flat jack tests and the satisfactory results in the building sector.[30,31] These describe the technique as a reliable alternative to obtain information about stress in a structural element in a direction perpendicular to the flat jack. However, despite its advantages, in its application during diagnostic and intervention processes, this type of test only provides a value associated with a specific instant of time. Thus, there is a lack of a device enabling the register of the continuous evolution of the stress levels undergone by a structural element before, during, and after an intervention process (increment/modification of loads, generation of significant apertures in walls, etc.). Therefore, the necessity for a measurement instrument providing information about the evolution of stress levels in the elements affected by these interventions should be addressed.

In this context, SHM systems can, by using one of a variety of techniques, collect information about the magnitude and configuration of loads applied to a structure.[9] Using this data, engineers can determine whether the loads on a structure are as expected or are excessive. SHM can also be used to learn how the various loads are distributed within and supported by the structure.

Among the different devices used to measure these parameters, pressure cells and load cells can be highlighted. These, as the names indicate, are used to monitor the pressure in different materials or media, among others: soils, rocks, concrete structures, dams, embankments, or on the contact surface between a structure and the ground. They have basically been applied in civil infrastructures,[10,17,32–36] their use being quite scarce in the building sector, and particularly in historic buildings. In this last context, the use of load cells can be cited as a monitoring technique[37–39] for structuring monitoring during interventions. Nevertheless, outside these actuations, work related to the monitoring of the evolution over time of stress levels in masonry structures has not been found. This is an extremely important aspect given the creep phenomenon that structures can be subjected to, which occasionally has led to the collapse of historic buildings.[40–42] In this sense, diverse research has been carried out,[43–47] although the continuous monitoring of stresses has not been contemplated as a monitoring parameter.

Consequently, a novel system in the international context has been developed, having received hardly any attention in building sector, in general, and in rehabilitation of historic buildings, in particular, with the aim of monitoring over time the evolution of the stress levels in a masonry element affected by structural interventions.

3 | SYSTEM DESIGN AND CONFIGURATION: SENSOR DESIGN

3.1 | Component elements

The device developed (Figure 1) is used in a methodology involving the vertical serviceability stress of a structural masonry element (Phase 1) and its monitoring continuously over time (Phase 2). The second phase takes as a reference the working principle of a hydraulic pressure cell habitually applied in civil infrastructures.[32,33,36] The configuration considered enables the determination of the stress level in a structural element to be determined before, during, and after an intervention. Moreover, in combination with other devices, it is possible to monitor the loading of a structural strengthening applied to a construction. In this sense, it should be highlighted that the device developed enables the monitoring of vertical stresses, horizontal stresses, or can be used in another location where the direction of transmission of loads is reasonably well known.

The sensor in question is composed of the following elements (see Figure 1a): a pressure pad (1), a pressure transducer (2), and a system of hydraulic connections (3) designed to monitor the pressure of the internal fluid in the pressure pad, in relation to its deformation.

The pressure pad (1) is made up of two stainless steel plates welded along their entire perimeter, filled with deaerated oil during the test. A pad of dimensions 350 × 260 × 3.5 mm was selected (0L103352600 model, Sisgeo). One of the tubes of

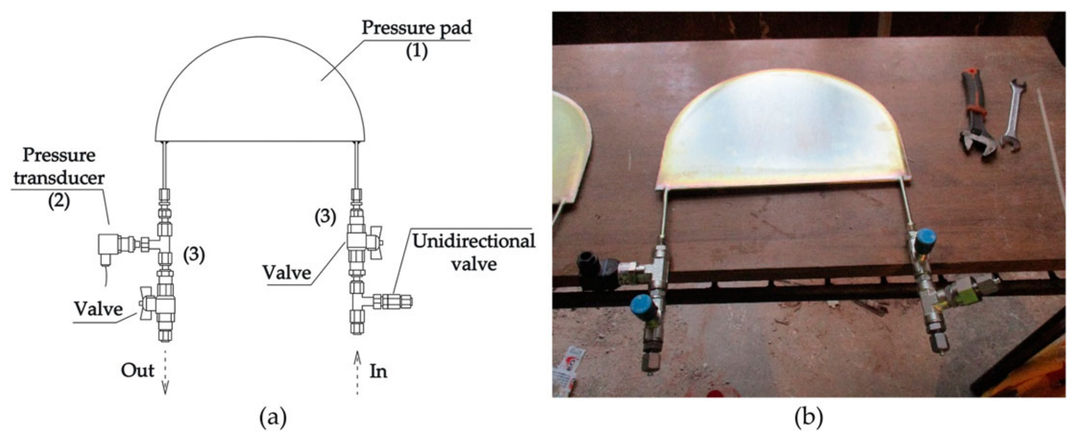


FIGURE 1 Component elements of the device for continuously monitoring stress level variation: (a) scheme and (b) prototype

the steel pressure pad (fluid input) corresponds to the connection point of the hydraulic pump. This tube contains a control valve that enables the fluid flow toward the pressure pad to be controlled, thus avoiding the fluid's return after the test (Phase 1). Additionally, and in view of a possible repressurization of the system (due to a readjustment of the masonry or of the pressure pad's own material), a unidirectional valve is included in the hydraulic system to enable the purging of the preceding connection, before the addition of new pressure to the system. This type of accessory avoids the input of air during the actuation, guaranteeing that the system does not contain air. Details can be seen in Figure 1a.

The pressure transducer is connected to the second tube (fluid output), which, through hydraulic connections, forms a closed hydraulic circuit. It is selected taking into account the foreseen stress value to be monitored in the element with the aim of guaranteeing good precision. In this study, an A-10 model pressure transducer with a range of 0 to 25 bar (Wika) was selected. The pressure acting on the pressure pad is transmitted to the pressure transducer through the deaerated oil, which transforms it into an electrical signal to be read by the data acquisition system. Its placement at the end of the circuit (selected intentionally) has the aim of smoothing the pressure peaks of the registered signal associated with the overpressures generated during the pumping process in Phase 1 of the methodology. Moreover, in the output branch of the hydraulic system, there is a control valve with the aim of regulating the output of the fluid during the process of purging the air from inside the system at the start of Phase 1.

Additionally, and in order to determine the initial stress state (existing) and later to continuously monitor it, it is necessary to have other devices to carry out the pressurization of the system: hydraulic hand pump (with pressure control, manometer) and hydraulic connections (valves, hydraulic tube, connection accessories). A hydraulic hand pump with manometer of 40 bar pressure was used.

3.2 | Application procedure

According to the whole system envisaged, the application procedure has two phases: the first, corresponding to the determination of the initial stress state of the structural element (Phase 1), followed by the continuous monitoring of stresses (Phase 2).

The determination of the vertical compressive stress in the masonry (Phase 1) is carried out using a simple flat jack test. This is based on the release of the state of stress in a small area of the masonry by a plane cut perpendicular to the surface of the structure.

After making the cut, a slim pressure pad is inserted into the cut, and once the air is purged from inside the system, the pressure is gradually increased until the previously measured closure is nullified and the state of strain is returned to the condition prevailing before the cut. Under this condition, from the internal pressure in the pressure pad, and considering two correction factors, which will be explained later, the stress existing in the masonry can be obtained.

The test methodology for estimating the stress level in masonry structures through flat jacks (Figure 2) was developed according to two norms: RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages)[48] and ASTM (American Society for Testing and Materials).[49] These norms reflect the test procedure to be followed, as can be consulted in diverse references.[5,21,31]

Taking into account the aspects mentioned before, next, the steps to be followed to determine the initial stress state (Phase 1) and the later continuous monitoring (Phase 2) are described. Some are shown in Figure 3.

1. Activities making up Phase 1:
    - Selection and preparation of the test area.

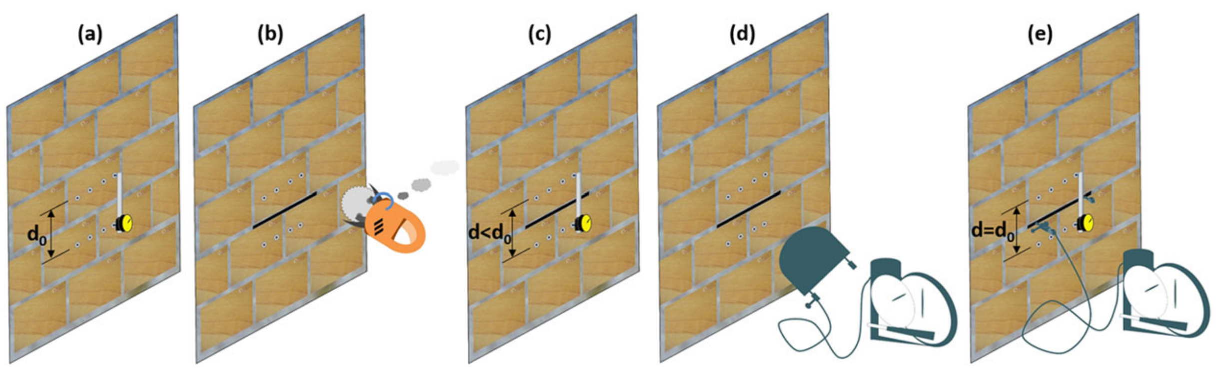


FIGURE 2 Steps followed for determining the initial stress state (existing) in the masonry

(a) (b) (c) (d) (e) (f)

FIGURE 3 Determination of the initial stress level (Phase 1) and later continuous monitoring (Phase 2): (a) initial measurement of the manual monitoring points, (b) performing the cut, (c) installation of the stress sensor, (d) purging of the hydraulic system, (e) determination of the stress level in the masonry, and (f) measurement of the displacements during the repressurization process

- Placement of reference points, followed by the measurement of initial lengths between each pair of points (d_0), Figures 2a and 3a.
  The monitoring of displacements (manual or continuous) enables, after the test, the contrast of any anomaly in the evolution of the stresses in the masonry determined by the continuous stress monitoring sensors.
- Execution of the cut in the plane perpendicular to the direction of the stresses to be determined, Figures 2b and 3b.
- Record the measured slot dimensions (length and depth), carrying out a second group of measurements (d) after the readjustment of the stresses, Figure 2c.
- Installation of the device to continuously monitor stresses, Figures 2d and 3c.
  In relation to the assembly of the hydraulic connections of the sensor, it is recommended to prepare them beforehand in the laboratory to guarantee the suitable sealing of the joints, thus avoiding possible future leaks.
- Connections and purging of the system.
  The connection and purging of the system has the aim of extracting all the air from the system pumping the fluid through its in/outputs. To do so, and given the additional new hydraulic installation, after connecting the manual pump to the input tube, the valves in the input and output are opened. Once the air is extracted and a continuous output of hydraulic liquid can be observed, the valve at the output is immediately shut, Figure 3d.
- The pressure in the pressure pad is increased until the initial condition before the cut is achieved. That is, until the original distance is restored (approximately) between the monitoring points ($d = d_i$), Figures 2e and 3e.
  The pressure is continuously controlled from the start of the test with a pressure transducer connected to the data acquisition system, as a contrast to the pressure manometer available in the manual hydraulic pump.
- Determination of the stress state existing in the masonry.
  Under this condition, the pressure of the pressure pad is equal to the stress level previously existing in the masonry, provided that the correction factors are taken into account: K_m, calibration of the pressure pad, taking into account the rigidity inherent to the pad that resists the expansions when it is pressurized; and K_a, ratio between the pad area and the slot area. Taking into account the aforementioned premises, the stress state at that point of the structure is determined through Equation 1:

$$\sigma = p \cdot K_m \cdot K_a \tag{1}$$

where

- σ serviceability stress determined in situ (MPa).
- p flat jack pressure required to restore the reference points to the initial distance (MPa).
- K_m reflects the geometric properties and stiffness properties of the flat jack (calibration factor). It is determined through laboratory calibration of the flat jack ($K_m < 1$), (adimensional).
- K_a ratio of the area of the flat jack and the area of the cut ($K_a < 1$) (adimensional).

2. Activities in Phase 2:
   - Increase in pressure (overpressurization) of the system.
     Once the test to determine the initial stress level of the masonry is complete (Phase 1), the pressure of the system is increased to compensate for the possible relaxation over time of the material of the pressure pad and/or the readjustment of the surrounding masonry structure itself. Thus, it can be guaranteed that, after readjustment of the system and the structure being monitored, a hydraulic pressure is maintained in the system over that determined during the test, to avoid the stress distribution being affected due to the arch effect (local loosening of the masonry above the cut made). In this sense, it should be indicated that there are no specific recommendations in the bibliography for masonry structures, so it is proposed to adopt an increase in initial pressure of 15–20 %, a similar value to that used in hydraulic pressure cells.[50]
   - Monitoring of pressure during a period of stabilization and disconnection of the hydraulic system.
     Before disconnecting the system's hydraulic pump, it is necessary to verify that the pressure introduced is stabilized given the possible instantaneous initial readjustment of the device inserted in the masonry. For this purpose, it is recommendable to monitor this parameter for at least the first 30–60 min. The bibliography does not provide information related to this, so the period proposed is as a consequence of the experience obtained during the application of the methodology in this research. Moreover, it should be added that it will depend on the degree of homogenization and deformability of the masonry. Thus, the definitive disconnection of the hydraulic system should be done after stabilizing the pressure.
   - Continuous monitoring of stress level.
     This envisages the continuous monitoring over time of the variation of stress level of the element being monitored. This corresponds to a relative value for comparison, bearing in mind the increase in pressure introduced in the system once the test is complete. A pressure must be maintained in the system all the time over that determined in the test and under the maximum stress established.
   - Repressurization of the system.
     The repressurization of the system must be done when a variation in stress is registered around 5 % over that determined in the monitored element. Before carrying out this actuation, any possible leak from this hydraulic system must be discounted.
     The procedure includes the measurement of the displacements, at the start and finish of the repressurization, of the monitoring points installed, Figure 3f. This aspect is important given the correspondence of the displacements to the pressures in the system.
     It should also be highlighted that during the whole repressurization process, it should be verified that cracks do not appear in the monitored zone.

The procedure described has wide ranging applicability; given that the simple flat jack technique (initial phase of the methodology) can be applied in a wide range of materials and masonry structures (brickwork, rubble stone, ashlar, rammed earth, etc.).

4 | IMPLEMENTATION IN A CASE STUDY

4.1 | The building monitored: Church of the “Seminario Mayor de Comillas”

The Modernist Church of the “Seminario Mayor de Comillas” (Figure 4a) is a late 19th century building listed as a Historic-Artistic Monument.[51] Nowadays, it is one of the elements of greatest value in terms of historic, architectural, artistic, and

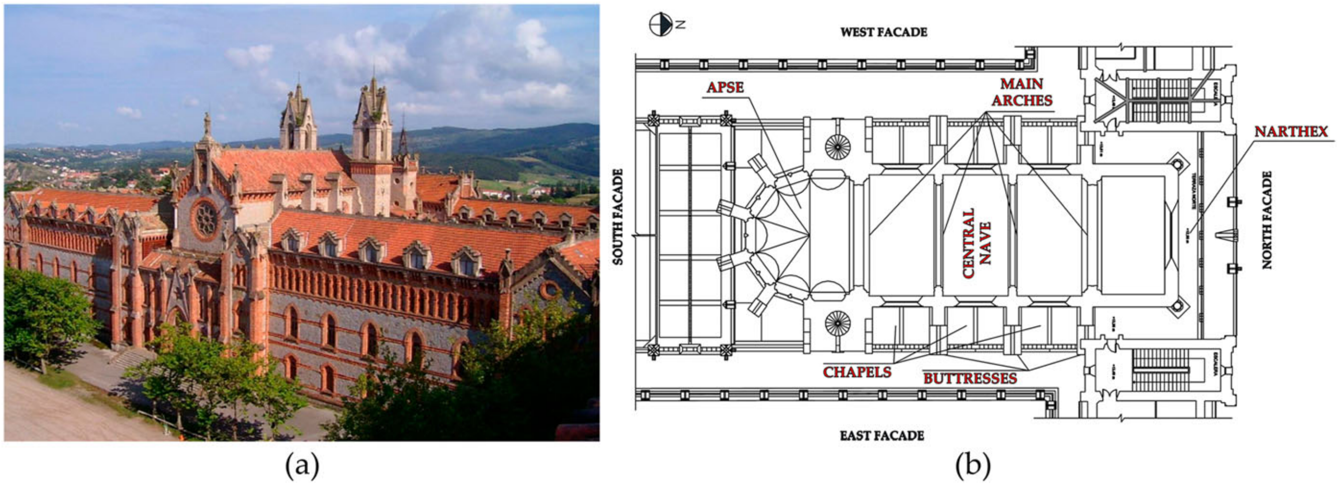


FIGURE 4 (a) General perspective of the "Seminario Mayor de Comillas" and (b) floorplan of the church

economic heritage in the region of Cantabria, Spain. The church (Figure 4b) is made up of a main body, with a central nave and two lateral naves (chapels), with an apse oriented to the south and the narthex to the north. The principal nave is formed by principal transverse arches counterbalanced by buttresses that delimit the lateral chapels. Parallel to the axis of the church, there are side arches separating the central nave from the chapels. A series of ellipsoidal solid brick domes is supported by the arches. The roof is completed by wooden trusses with iron ties and wooden studs.

The building, which was in a relatively good state until the 80s, suffered a progressive deterioration process since it became derelict. Consequentially, and as the years passed, several pathological processes were undergone,[52] leading to a problem with the stability of the construction. Additionally, during the rehabilitation actuations on the east cloister, some areas were opened between this building and the church, which led to a redistribution of the loads on the building.

Between 2014 and 2017, some structural consolidation actuations took place, including the injection of arches and buttresses, the strengthening of the principal arches and domes, interventions on the load-bearing walls of the church next to the both cloisters, and change of the roof that led to an increase in the load on the structure.

The building, of more than 100 years old, was built with mixed masonry of low-strength solid ceramic bricks and limestone pieces, with poor bonding. Throughout the rehabilitation work on the structure of the church, the presence of several rows of bricks with low-strength lime mortar at the lower part of the buttresses and walls of the building (Figure 5).

The characteristic strength values of the component materials of the buttresses (petrous irregular masonry made with lime mortar, among which there are interspersed rows of low-quality bricks), were obtained in Villegas and Lombillo[52] corresponding to 2.4 MPa for the brick masonry and 6.1 MPa for the stone masonry. Consequently, the stresses acting could not surpass the strength corresponding to the brick masonry.

Bearing in mind what was mentioned previously, as well as the intervention process on the building, it was necessary to verify the structural safety of the load-bearing elements with the aim of not increasing the serviceability stress levels existing in the masonry structure. To analyse the serviceability stresses, a calculation model was used to model the structural elements through shell-type finite elements. This considers each lamina as an elastic, lineal, homogeneous, and isotropic continuous material. The resulting values were analysed in a typical central buttress, considering it as the most unfavourable element undergoing the largest part of the load. The maximum serviceability stresses and the average ones at the base of the buttress were 2.15 and 1.02 MPa, respectively, reaching a safety coefficient around 1 for the case of maximum stresses.

For these reasons, the structural solution for the east load-bearing wall included the passive strengthening consisting of a framework of reinforced concrete, partially closing the aforementioned gaps, connected to the buttresses, with the idea of favouring the transmission of loads between these and the framework (Figure 6a). The intervention devised in the west wall consisted of the opening of gaps on the ground floor to facilitate the communication between the west cloister and the church. On this occasion, and bearing in mind the previous analysis, the transfer of loads in the plane of the wall was guaranteed by constructing some reinforced concrete columns (Figure 6b), which along with an upper lintel and a lower continuous footing guaranteed a uniform transmission of loads.

(a) (b)

FIGURE 5 Rows of solid brick with lime mortar detected at different heights of the buttresses and walls: (a) detail of the lower part of the buttresses and (b) rows of brick detected in buttresses and west load-bearing walls at the floor level of the church

In the case of the east wall, the possible redistribution of loads between the buttresses and the passive strengthening must be analysed. Consequently, the behaviour of these elements must be monitored, before, during, and after the intervention. A loading of the strengthening means a reduction in the stress in the buttresses. As for the west wall, the evolution of stress levels was monitored in the buttresses during the work of cutting the wall and the later installation of the concrete columns.

Given the extent of the intervention processes devised in the building and taking into account the mechanical characteristics of the existing masonry, the necessity was considered of developing an instrumentation system that enabled the continuous monitoring of the stress level in the buttresses during the structural interventions.

4.2 | Instrumentation and data acquisition

Taking into account the interventions proposed, and after analysing the characteristics of the materials involved and the working method of the masonry structure, an effective location for the stress sensors was selected. The central Buttresses 2 and 3 were chosen, as these were the most loaded elements (Figure 7). Additionally, to monitor the

(a)

(b)

FIGURE 6 Sequence of actuation on the longitudinal load-bearing walls of the building: (a) execution of the passive reinforcement in the east wall to partially close the gaps created between buttresses and (b) work to open the gaps per phase (batache) on the ground floor of the west wall

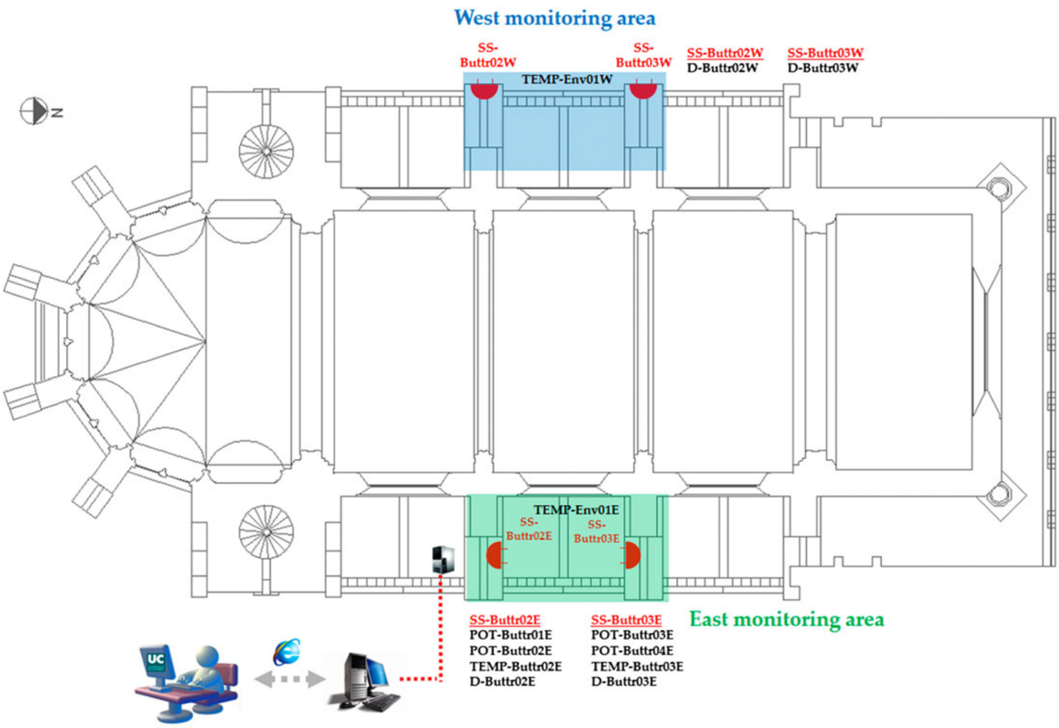


FIGURE 7 Scheme of distribution on the floorplan of the sensors installed in the monitoring areas

interventions on the building, further devices were installed whose description and location can be consulted in Blanco et al.,[53] and which are not the aim of this article.

The monitoring was done continuously using electronic sensors, as well as manual monitoring points. A total of 16 control elements were installed, monitoring the following parameters and structural elements.

- Continuous monitoring of stresses. Two points were monitored on the *east wall* of the building (SS-Buttr02E and SS-Buttr03E), installed on the central buttresses of the building. In the same way, the stress variations in the two opposing buttresses of the *west wall* of the church were monitored too (SS-Buttr02W and SS-Buttr03W). In this respect, it should be said that, to monitor the stress level of the buttresses, sensors were installed, as far as possible, in the zones with greatest stresses and as close as possible to the foundations of the buttresses.
  The control of the pressures of the stress sensors was done using a pressure transducer with a maximum range of 25 bar. This monitoring interval was chosen bearing in mind the characteristic strength obtained in the brick masonry (the weakest material among the components of the buttresses), 2.4 MPa. This had the aim of guaranteeing a suitable precision of the registers.
- Monitoring of displacements, manually and continuously, in the zone of the location of the stress sensors. The monitored displacements were vertical, parallel to the direction of the stresses. This was to evaluate the relationship between the stress variations and the displacements. This control was done through two procedures, one discrete manual measurement and another with continuous registration. The first was done in both monitoring areas (east and west) making use of the Demountable Mechanical (DEMEC) strain gauge, with a measurement range of 200 mm and a precision of 1 μm (to the east: D-Buttr02E and D-Buttr03E, and to the west: D-Buttr02W and D-Buttr03W). The continuous monitoring was done using four potentiometric transducers (POT-Buttr01E, POT-Buttr02E, POT-Buttr03E, and POT-Buttr04E) installed in the east monitoring area. The use of the systems considered (manual and continuous) enabled the contrast of the results obtained with the two methodologies.
- Monitoring of the thermic variations around the stress sensors and ambient temperature in the test areas. The first had the aim of monitoring the temperature around the fluid contained in the inside of the sensors, to analyse the possible influence of the ambient temperature on the registers of the stress sensors. Thus, two temperature monitoring units were installed on the stress sensors located to the east of the building (TEMP-Buttr02E and TEMP-Buttr03E). In the same way, another two devices were installed in each of the areas monitored (TEMP-Env01E and TEMP-Env01W) for the control of the ambient temperature.

Table 1 lists the sensors used, whereas Figure 8 shows some of them placed in situ.

Data management and data acquisition were carried out using two systems. The first one corresponded to a portable acquisition and registration system (a 16-channel SARP MK2 of, which houses an IMC Cronos SL-2 datalogger, Figure 9a), used for the determination of the initial stress level of the buttresses. This enabled the conditioning and rapid configuration of the direct connection of the stress sensor used. The second consisted of a monitoring and control system based on remote data management through an application developed in JavaFX. This included a novel integration of systems of electronic instrumentation, data acquisition, and ad hoc software development.[54–56] This integration was based on the implementation of remote terminal unit (RTU) architecture on an industrial PC (Figure 9b) that acted as master unit (master terminal unit, MTU[57]). This, along with data acquisition cards suitable for each type of sensor, performed uninterrupted data collection. In addition, two 12 V and 244 Ah lead batteries were available that allowed a continuous supply of current for a period of 7 days in case of any incidence.

TABLE 1 Sensors installed in the monitoring areas

Location	Monitoring element	Quantity	Model	Abbreviation
East monitoring area	Stress sensor	2	In-house design	SS-Buttr
	Potentiometric displacement transducers	4	RS Pro LM10/3M295K0M TO ES AW	POT-Buttr
	Surface temperature sensor	2	Thermocouple type T	TEMP-Buttr
	Ambient temperature sensor	1	Thermo-Hygrometer PCE-P18	TEMP-Env
	Manual displacement monitors[a]	2	Deformometer DEMEC and reference discs of 6.3 mm diameter	D-Buttr
West monitoring area	Stress sensor	2	In-house design	SS-Buttr
	Ambient temperature sensor	1	Thermo-Hygrometer PCE-P18	TEMP-Env
	Manual displacement monitors[a]	2	Deformometer DEMEC and reference discs of 6.3 mm diameter	D-Buttr

[a]Each monitoring area was composed of four pairs of reference points.

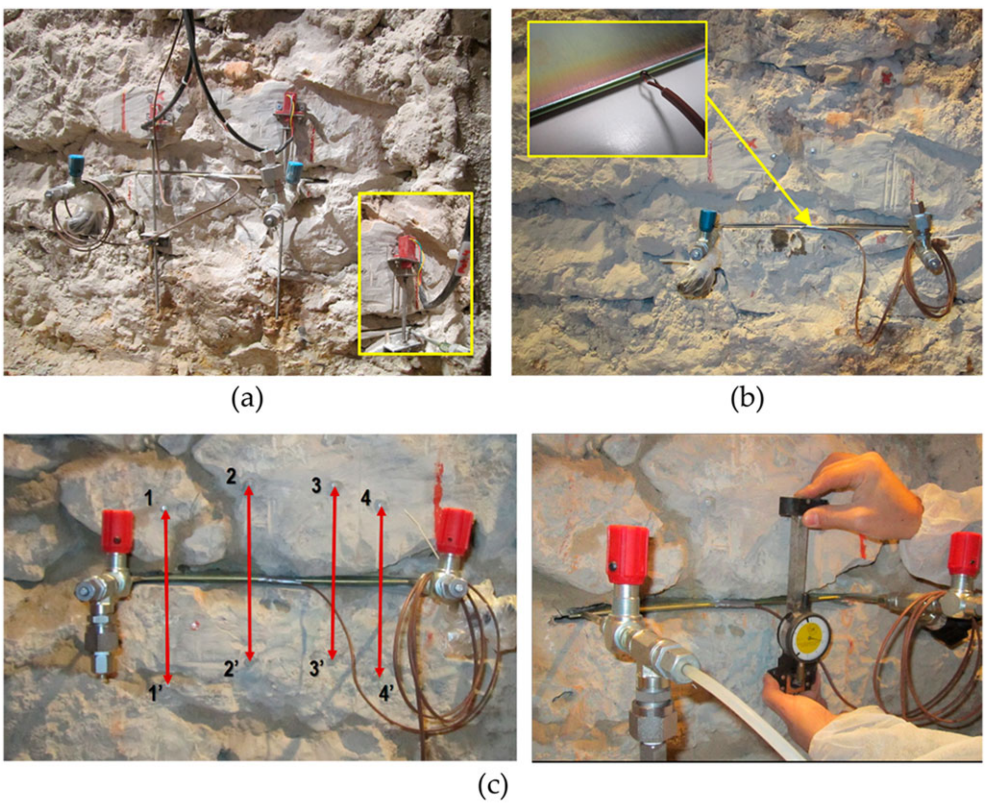
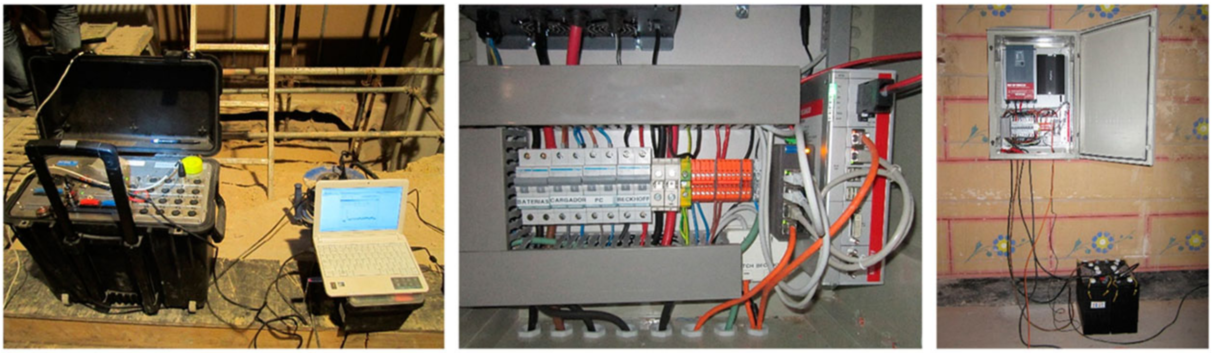


FIGURE 8 Examples of sensors deployed for the supervision of the actuations: (a) potentiometric displacement transducers, (b) thermocouple installed in the stress sensor, and (c) monitoring of the displacements manually in one of the monitoring areas



(a) (b)

FIGURE 9 (a) Portable 16-channel SARP MK2 datalogger and (b) industrial PC for C6920 distribution box along with lead batteries

Additionally, along with the installation of an application server, which periodically communicates with the system, real-time access was available to the data, which were stored in a database. The system designed also incorporates actuation protocols that systematically evaluate through a computer the sensor registers, defining automatic alarms if the monitored magnitudes exceed prefixed limits. Thus, in the case of a register outside the range being received, an alarm was instantly sent via email to the assigned addresses. Finally, a web server made the data available through an application developed in JavaFX, which constituted a novel platform for developing enriched applications for internet.

5 | MONITORING AND EVALUATION

In order to illustrate the potentialities of the designed system, next the evolution of the registers related to the stresses, displacements (obtained through discrete in situ monitoring and by continuous remote monitoring), and the correlation between the two parameters (stress and displacement) and the influence of the thermal gradients on the stress measurements.

It should be borne in mind that this article considers the continuous evolution of the stresses in Buttresses 2 and 3 on both sides of the building (east and west) after obtaining the serviceability stress level existing (Table 2). The reader is referred to Blanco et al.[58] to consult information on the process followed for the in situ determination (simple flat jack test).

5.1 | On the monitoring of stresses

Figure 10 shows the evolution of stresses in the east buttresses of the building during 19 months of monitoring (SS-Buttr02E and SS-Buttr03E). During this period, passive strengthening interventions took place in the east load-bearing wall and the monitoring of this area before, during, and after these. In addition, by means of a discontinuous constant reference, the stress value determined in the masonry in Phase 1 of the methodology (SS-Buttr02E-I and SS-Buttr03E-I) is included.

The difference between the continuous initial stress and the stress value determined in Phase 1 corresponds to the tasks of overpressurizing the pressure pad. After this actuation, the behaviour of these in the first stages registered a slight decreasing slope. This was associated with a readjustment of the system "pressure pad-masonry structure" under

TABLE 2 Initial stress state determined in the buttresses

Location		Nomenclature	Initial stress state, σ (MPa)	Correction factors K_m	K_a
East area	Buttress 2	SS-Buttr02E-I	1.21	0.903	0.929
	Buttress 3	SS-Buttr03E-I	0.87	0.855	0.881
West area	Buttress 2	SS-Buttr02W-I	1.05	0.885	0.848
	Buttress 3	SS-Buttr03W-I	0.94	0.885	0.773

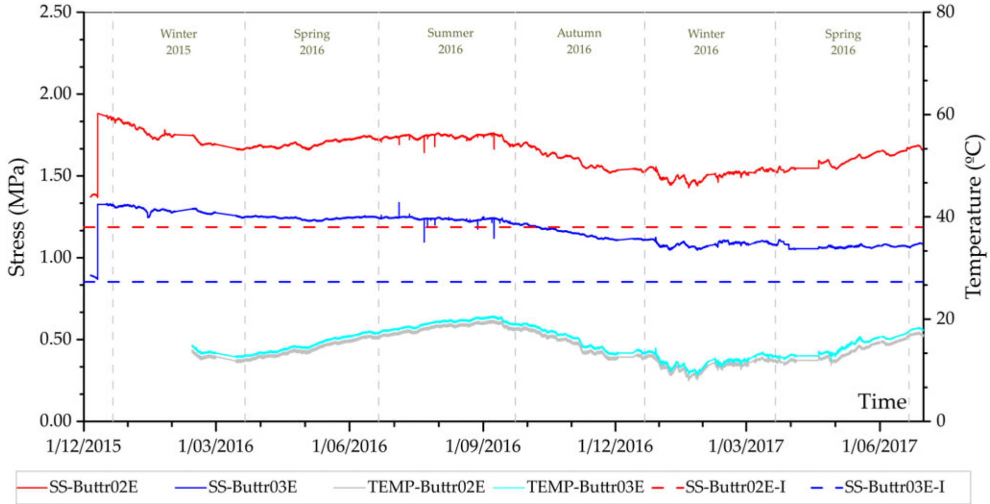


FIGURE 10 Graph of stress evolution in the monitored areas of the building's east buttresses (SS-Buttr02E and SS-Buttr03E), the constant discontinuous reference stress value determined in Phase 1 (SS-Buttr02E-I y SS-Buttr03E-I). In addition, the temperature was recorded with the aim of assessing the influence of temperature variations on the measurements

maintained pressure. Thus, the initial pressure value introduced into the system in December 2015 was 1.88 MPa for SS-Buttr02E and 1.33 MPa for SS-Buttr03E (values after initial overpressurizing of the system, see Section 3.2), corresponding to 1.75 and 1.28 MPa, respectively, at the end of January 2016.

In relation to the evolution of the pressures during the monitored period, it should be indicated that the variations registered were not significant and were influenced, to a great extent, by the thermal environmental changes undergone by the building. Figure 10 illustrates, in addition to the evolution of the stresses, the values recorded by the thermocouples installed in the sensors (TEMP-Buttr02E and TEMP-Buttr03E). Behaviour related to the seasonal variations can be observed, decreasing values of the stresses as temperatures decreases, and vice versa. In the period from December 2015 to June 2017, the variations recorded ranged from 1.43 to 1.88 MPa in the sensor installed on Buttress 2 (SS-Buttr02E) and 1.05 to 1.33 MPa in the other one on Buttress 3 (SS-Buttr03E). Thus, the maximum values were reached in summer 2016 and the minimum ones in winter 2016. These variations may be related to the influence that the ambient temperature exerts on the internal density of the liquid in the pressure pad,[58] which in turn influences the pressure of the system.

Thermal fluctuations have also been reflected in the registers of the stress sensors installed in the west of the building (Figure 11). It should be noted that these are influenced to a greater extent by the diurnal and nocturnal cycles (daily cycles) because they are located outside and above the finished floor level (FFL + 0.45 m), Figure 12a. Meanwhile, the devices installed on the east side are inside the building and below the finished floor level (FFL - 0.75 m), which leads to a lower thermal fluctuation (Figure 12b). Moreover, it should be noted that, due to its location, there is a direct influence of the sun on the monitored area to the west. This fact is also reflected in the behaviour of the sensors.

As for the evolution of the stresses, initial behaviour similar to its counterparts can be observed. This can be considered normal behaviour in this type of devices, the result being related to readjustment and stabilization of the sensors and the masonry itself, given the heterogeneity of the material and possible presence of isolated areas of voids in the wall, after the test. In particular, the stress sensors installed on the west buttresses (SS-Buttr02W and SS-Buttr03W) began their registration on October 20, 2016 with a relative value of 1.39 and 1.33 MPa, respectively (value after initial overpressurizing of the system, see Section 3.2).

The device designed enabled the supervision of the interventions, providing information at all times to the agents involved about any event that arose. Figure 11 shows several moments in which the actuations were manifested in the registers of the sensors, by way of example:

- Actuation 1: Start of the work related to opening of gaps toward the west cloister on the 4th of November. A variation of abrupt stress of 0.04 MPa in west Buttress 02 (SS-Buttr02W) was detected. At the same time, there was a sudden decrease in temperatures recorded during the following days that was reflected in the behaviour of the sensors.

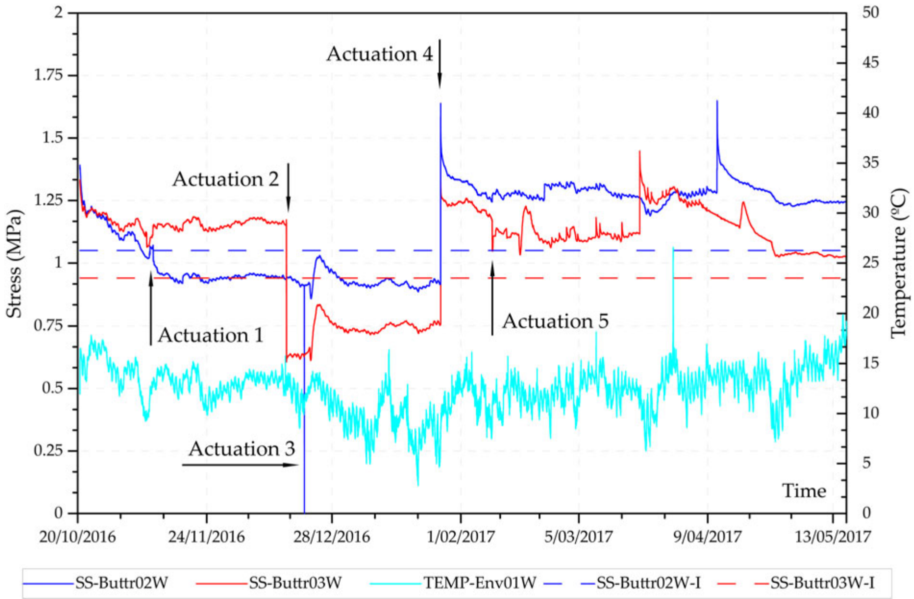
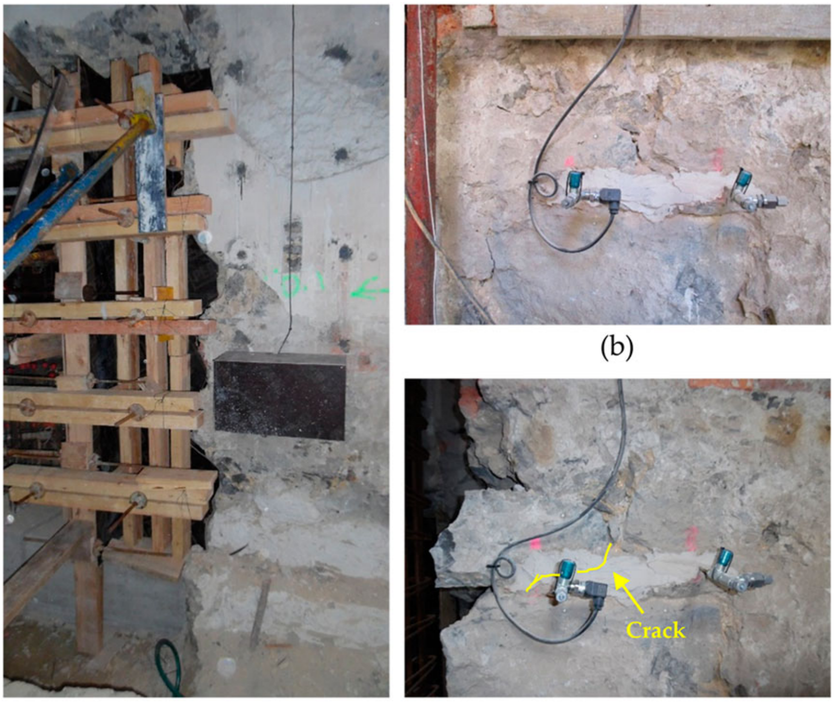


FIGURE 11 Graph of evolution of stresses (7 months) in the monitoring points of the west buttresses of the church (SS-Buttr02W and SS-Buttr03W) and discontinuous constant reference of the stress value determined in Phase 1 (SS-Buttr02W-I and SS-Buttr03W-I). In addition, the temperature was recorded with the aim of assessing the influence of temperature variations on the measurements

FIGURE 12 (a) West load-bearing wall on which the sensors were installed: open space outside and incidence of the sun and (b) location of the devices to the east inside the church and under the finished floor level (FFL)

- Actuation 2: Start of the work of opening the gap adjacent to device SS-Buttr03W on west Buttress 03. An abrupt and significant drop in the stress (from 1.17 to 0.61 MPa) was registered. This behaviour was a consequence of the process of perforation near to the sensor installed on that buttress and placement of the structural steel of the adjacent column (see Figure 13). The appearance of a crack is initially detected at the sensor level after the process of cutting the wall, which later induced a loss of section around it, and in consequence, the piece located in the upper left side became relatively loose.
  Additionally, the proximity of the sensor to the zone where the gap was opened should be highlighted. To guarantee the correct function of the device, it is recommendable to install it at a minimum distance of 1½ pad lengths from wall openings or ends.[49] This could not be guaranteed in this actuation given the instability of the masonry that led to the aforementioned incidences.
- Actuation 3: Test carried out on sensor SS-Buttr02W consisting in disconnecting it for some seconds on December 20, 2016. An instantaneous variation was detected in the readings of the device installed in west Buttress 02 (SS-Buttr02W).
- Actuation 4: Repressurization of the hydraulic system of the sensors installed to the west (Figure 14a). This was done in response to the loss of pressure registered in the sensor installed on Buttress 03 (SS-Buttr03W). This actuation was



(a) (b) (c)

FIGURE 13 Images taken during the actuations adjacent to west Buttress 03: (a) process of installation of the structural steel, (b) state of the wall after the first cutting works when a crack was detected at the height of sensor SS-Buttr03W, and (c) conditions of the wall during the work making the columns

done in the two sensors. This led the sensors to change their registers from 0.92 and 0.76 MPa to 1.62 and 1.31 MPa in west Buttresses 02 and 03, respectively. As for the later evolution of these devices, it should be said that in the following 3 days after repressurization, a new readjustment of the sensors in the masonry took place, registering after this period values around 1.35 and 1.23 MPa in Buttresses 02 and 03, respectively.

- Actuation 5: Cutting works in the wall adjacent to the south face of Buttress 03 on 9th February (Figure 14b). These were also reflected in the registers of the sensor (SS-Buttr03W) leading to a slight fall in the stress (from 1.17 to 1.05 MPa).

5.2 | Correlation between displacements determined manually and continuously

As previously mentioned, in addition to the continuous stress monitoring points, the evolution of the displacements in the monitored areas was monitored by two methodologies (manual and continuous). The aim of these registers was to verify the evolution of the stresses in the masonry, while verifying the appropriate adjustment between them. In relation to the last aspect, the displacements in the buttresses were monitored through the manual reference points (D-Buttr02E

(a) (b)

FIGURE 14 (a) Repressurization of the sensors installed on the west buttresses (SS-Buttr02W and SS-Buttr03W) and (b) photo taken during the cutting process on the west load-bearing wall near Buttress 03 using a diamond wire cutting machine and D-Buttr03E), composed of four pairs of reference points each; and displacement transducers (POT01-Buttr02E and POT02-Buttr02E installed on Buttress 2, whereas POT03-Buttr03E and POT04-Buttr03E were installed on Buttress 3).

Figure 15 illustrates, by way of example, the evolution of the movements registered by the control points installed on east Buttress 2 (D-Buttr02E) throughout the monitored period. In this sense, it should be noted that, given the posterior installation of the displacement transducers, only three of the four pairs of points in the two east buttresses (Points 2, 3, and 4) could be monitored. The results showed that the values recorded were insignificant and remained around the origin (initial value measured after the end of the test to determine the stress level). The greatest increase was recorded by Point 2-2′ on August 29, 2016 with a value of 0.10 mm.

In relation to the correlation between the displacements registered by the two methodologies, the evolution of the movements between the manual monitoring point of area D-Buttr02E and the displacement transducers POT01-Buttr02E and POT02-Buttr02E can be seen in Figure 16a. It can be verified that in this period (7 months), the fit of the measurements is very good. The best correlation was between Point 4-4′ and POT02-Buttr02E, a logical result considering the proximity between the two control elements (Figure 16b). Moreover, despite being slightly separated, the displacements recorded by Point 2-2′ and POT01-Buttr02E showed a good fit.

On the other hand, it should be noted that Point 3-3′ showed a lower aperture in relation to the rest, which should have been higher considering its position in relation to the geometric deformation of the pad. These results were associated with the impossibility of placing the deformometer totally perpendicular when carrying out the readings, as a consequence of the installation of the adjacent continuous sensor, thus being able to influence the readings. In this sense, note that the small differences registered may be associated with the difference of precision that exists between the two monitoring systems.

Therefore, the results can validate the goodness of the electronic system used.

5.3 | Correlation between stresses and displacements

The good correlation between the measurements of the manual and continuous displacements makes it possible to contrast the evolution of the stresses in the buttresses of both sides of the church. By way of example, Figure 17 illustrates the behaviour of the stresses and displacements registered by the transducers in east Buttress 2. An analogous behaviour can be seen in the registers of the two parameters. As an increase in stress occurs, there is an increase in the separation distance of the pairs of manual monitoring points (opening of the slot in which the pressure pad is inserted). For example, between the 24th April and June 14, 2016, for an increase in pressure of 0.39 MPa, a variation of 0.06 mm was recorded. As a consequence, the good agreement between the measurements makes it possible to provide an additional monitoring element in order to detect possible measurement errors and/or pressure loss problems that may occur during the continuous monitoring of the stresses.

Figure 18 illustrates the monitoring of manually registered displacements in control areas located on the west buttresses of the building (D-Buttr02W and D-Buttr03W). It can be seen that the values mostly register small variations over time and values close to the origin. For example, in west Buttress 2 (Figure 18a), the greatest value recorded was 0.10 mm on April 11, 2017 by Point 4-4′. The significant specific variations shown by the manual monitoring points are associated with the actuations carried out around the stress sensors, thus verifying the relationship between the evolution of the displacements and the stresses.

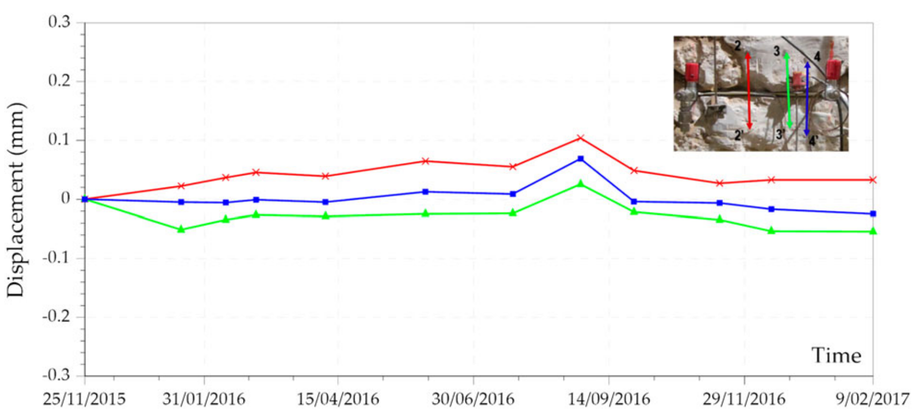


FIGURE 15 Graph of evolution of the displacements registered by the pairs of manual monitoring points on east Buttress 2 (D-Buttr02E)

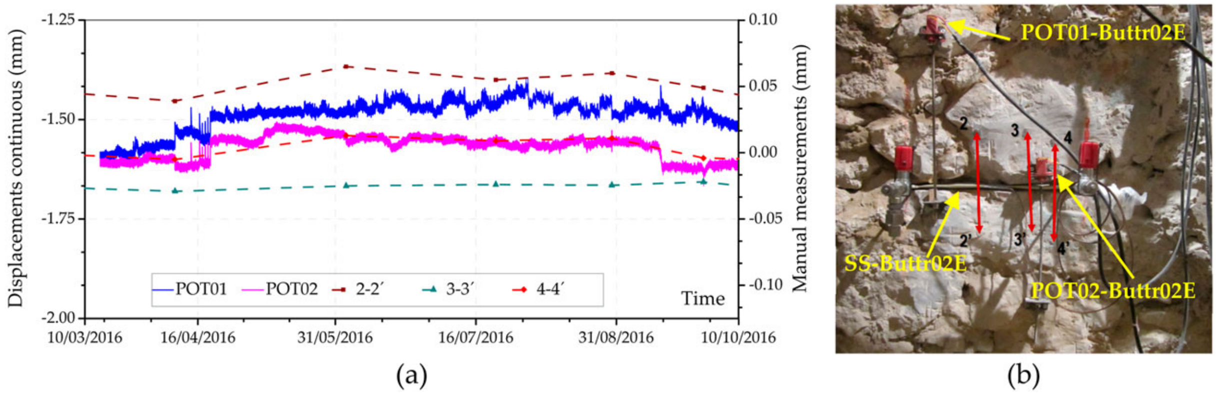


FIGURE 16 (a) Examples of evolution graphs registered by the continuous displacement sensors and the comparison with the manually obtained measures between 10/03/2016 and 10/10/2016, (b) location of the manual monitoring points (D-Buttr02E) and potentiometers (POT01-Buttr02E and POT02-Buttr02E) on east Buttress 2

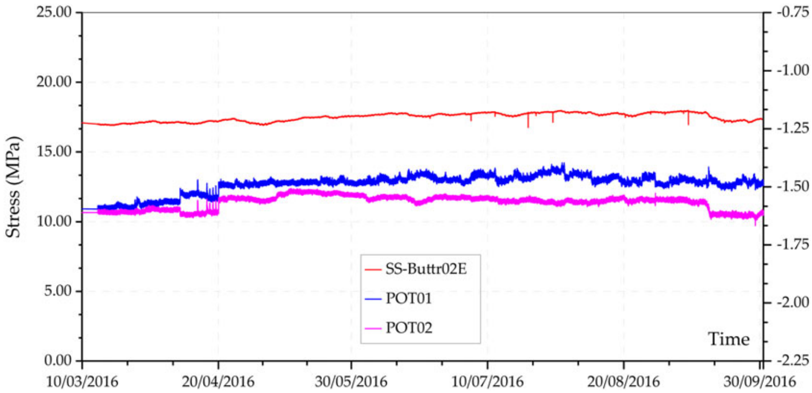


FIGURE 17 Evolution of the stresses (SS-Buttr02E) and displacements (POT01-Buttr02E and POT02-Buttr02E) in the monitoring area on east Buttress 2 ("+": increase in monitoring distance and increase in stress)

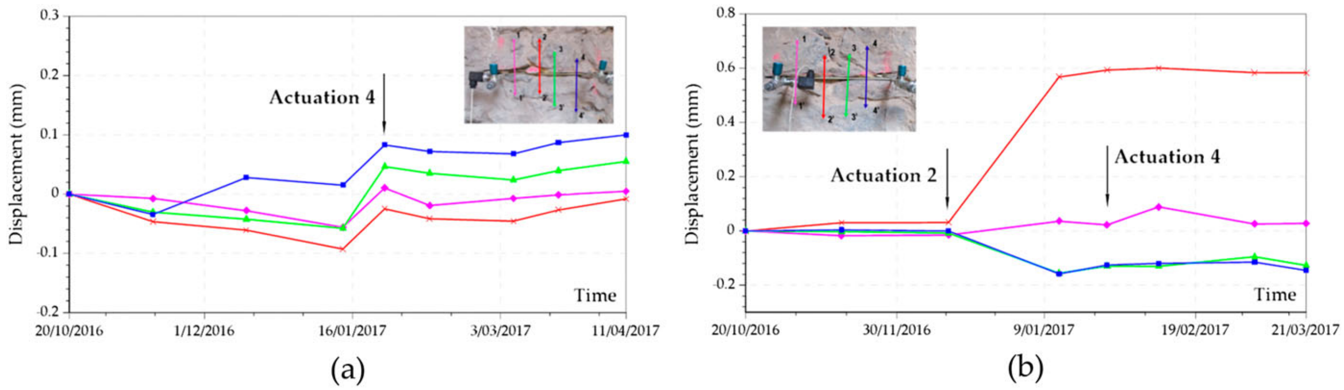


FIGURE 18 Evolution of the displacements in the manual monitoring points: (a) D-Buttr02W and (b) D-Buttr03W located on the west buttresses of the building ("+": increase in monitoring distance)

Of these, it is important to note the correlation between the abrupt fall of the SS-Buttr03W stress sensor (as a consequence of Actuation 2, Figure 11) and the evolution of the displacements in some of the points in the D-Buttr03W monitoring area (Figure 18b). As mentioned above, this occurred as a result of the cutting of the wall in the vicinity of the sensor. The effect on one of the masonry pieces in the monitoring area generated a crack that brought about a modification of the associated displacement registers. Control Point 2-2′ was more affected as it was closer to the crack, which registered a significant increase (Figure 19). The opening of the crack 0.54 mm brought about an abrupt lowering of the stresses of 0.56 MPa.

Additionally, the repressurization (Actuation 4) carried out on the two sensors on January 26, 2017 is reflected in the readings of both control points.

FIGURE 19 Aperture of the crack near control Point 2 of the stress sensor installed on Buttress 03

6 | CONCLUSIONS

This research developed a new SHM system that was applied to a historical masonry building under rehabilitation. The novel methodology implemented in several buttresses of the church for continuously monitoring the stress variation was very useful, as it enabled the interventions carried out on the building to be monitored without the occurrence of any significant irregular incidence. The serviceability stresses were at all times maintained below the characteristic strength of the masonry.

Analysis of the long-term (19-month) measurement results demonstrates the proposed device is capable of automatic and real-time monitoring and can be applied and utilized for safety evaluation of ancient buildings. In relation to the evolution of the stress sensors, their good response during the work actuations should be highlighted, being shown in the registers of the incidences occurring. Thus, the measured values obtained through this device can be utilized when analysing and evaluating the response of a structure the building's service period.

In order to guarantee the proper functioning of the sensor, it is necessary to install it at a minimum distance of 1½ pressure pad lengths in relation to openings or ends of the walls. Likewise, this minimum distance must be taken into account in the event of any action being taken around the sensor (cuts, perforations, etc.).

Regarding the behaviour of the displacement and stress sensors, it should be indicated that their registers are generally influenced by the thermal changes in the building. In addition, they are affected to a greater extent if they are placed in outdoor spaces exposed to the incidence of the sun's rays. Therefore, it is necessary to carry out, at the same time, monitoring of the ambient temperature around the sensor, in order to quantify its influence on the results. In this sense, it is recommended to further study the influence of thermal variations on the behaviour of the fluid contained within the device.

It was verified that the displacements registered by manual and continuous electronic monitoring showed good fit. Hence, it is recommended to combine both types of control, not only to increase the number of monitoring points at a reduced cost but to provide contrast measurements.

A good correlation was also obtained between the variations of the stresses and the displacements. Consequently, the latter make it possible to provide an additional control element for continuous monitoring of the stresses.

With regard to the data acquisition and management system used, the performance of the system that made it possible to keep the agents involved informed about any incidences that arose through the automatic alarm system should be highlighted.

From all of the above, it can be concluded that the use of monitoring systems before, during, and after an intervention contributes to an increase in the safety of the construction, and the personnel involved in the intervention, by providing warnings of possible danger due to damage and/or degradation of the elements being monitored. This is a tool of great interest for its application during interventions in historic buildings.

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ORCID

Haydee Blanco http://orcid.org/0000-0003-0812-5476
Yosbel Boffill http://orcid.org/0000-0003-2448-5885

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