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2D image-based crack monitoring: an affordable, sufficient and non-invasive technique for the democratization of preventive conservation of listed buildings

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Abstract

In order to democratize the preventive conservation of most listed buildings, we need to have an affordable tool that allows controlling their main vital signs. Complex and costly control installations, such as large digital data collection campaigns or 3D laser scanning, are not always possible. Methods for analogue data collection, such as comparators and callipers, are much more affordable and discreet but require the use of auxiliary lifting platforms for both installation and reading and control, hence resulting too invasive. In this paper we study techniques for digital indoor monitoring of cracks of listed masonry buildings. 2D image-based crack monitoring technique was found to be sufficient, affordable, traceable, and respectful with the use of the building. To verify its effectiveness, we performed laboratory tests and implement it in a real case study, a church in Zaragoza, Spain, currently undergoing a reparation process. The obtained results show that the proposed 2D image-based inspection technique provides measurements closer to the comparator, used as a reference, than the calliper, with a mean difference of 0.15 mm with respect to the reference, and a standard deviation of 0.17 mm, and its use can be up to 56% cheaper than the comparator. Therefore, the technique is easily generalizable to different heritage buildings.

Keywords: Preventive Pathology, Monitoring Structural health, Cracking, 2D image-based crack monitoring, Vault

Introduction

In preventive monitoring of historical buildings, in order to make a correct diagnosis of the cracks evolution, it is necessary to observe and analyse the system over time using periodically sampled response measurements to monitor changes to the material and geometric properties. This methodology is known as structural health monitoring (SHM) and it is one of the main challenges in architectural heritage conservation. The structures of heritage buildings constitute themselves invaluable evidence of cultural achievements and should be preserved for future generations. SHM of heritage buildings is essential to extend their service life, to predict locations of possible damages in unforeseen events, and to monitor factors that may cause future damages [1].

However, in countries like Spain, Portugal and Southwest France, there is a significant amount of heritage listed buildings (around 31,163 [2]), for whose preventive conservation there is no systematic policy. The available financial resources are scarce and mostly allocated to buildings of high social projection, and owners are often reluctant to invest in preventive conservation and maintenance programmes [2]. In order to preserve the buildings of lower social projection, it is necessary to define a low-cost SHM methodological strategy, so that the administration or owners can afford its preventive conservation.

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Nowadays, visual inspection is still the most common technique to detect damages in structures of heritage buildings or to evaluate their variation over time [3]. Nonetheless, the growth of digital technologies is leading to more efficient, less invasive, low-cost applications allowing the monitoring of areas of more difficult access.

Digital data collection is a technique that is performed through the use of real-time test data on structures obtained from various types of IoT sensors, which monitor several health parameters of structures, available on cloud-based data storage systems [4]. This technique is suitable for buildings that, due to their high social projection or due to the verification of risks that affect their stability, need great control over their security. As an example, sophisticated digital monitoring models are applied to Santa María de Florencia [5] or San Pedro de Roma [6]. This preventive monitoring provides high-quality data. However, it implies high costs, hence it cannot be generalized for the preventive monitoring of buildings with less social projection.

3D laser scanning is a technique to capture free-form shapes to generate highly accurate 3D point clouds. This technique is widely developed and is highly recommended to survey the geometry properties of buildings (e.g., [1, 7, 8]), but its use is restricted to buildings in which a pathological process is already confirmed because the associated costs for its installation are high and non-advantageous, especially when monitoring a single and localised set of cracks for preventive monitoring [9].

As pointed out by Casati and Gávez [10], a more sophisticated SHM method does not necessarily lead to a more accurate result. According to Coïsson and Ottoni [11], increasing the knowledge and understanding of the ancient monuments structural behaviour is the only method to decrease uncertainties and interventions, which should be as few as possible. SHM, with its different approaches, represents an important means of increasing this knowledge, investigating what happened to the structure in the past, understanding its present evolution, and controlling it in the future [11]. We can, therefore, consider that preventive monitoring must be neither excessive nor insufficient. To refer to this perfect quantity condition of monitoring we use the term 'sufficient' in this paper. On the other hand, the monitoring system must be able to manage data from the past, present, and future, that is, it must have adequate traceability to easily manage all the data obtained.

Three types of SHM approaches can be distinguished depending on the time goal:

- Historical monitoring corresponds to the analysis of historical data and its comparison with known models. It provides us with the first working hypotheses about the possible causes of a potential pathological process and allows us to plan adequate metrological monitoring.
- Metrological monitoring consists of collecting and managing the data of the evolution of the different parameters that may influence the trend of the process. Once analysed, the data allows us to confirm the first hypotheses, or to develop new ones in case of discrepancy. This type of monitoring is carried out as a preventive measure before a deterioration is triggered, or to check the success of an intervention carried out. In the event of new injuries, these data become part of the historical monitoring.
- Predictive monitoring is used to deduce the future behaviour of a structure, through its digital modelling (e.g. [12]), before variations in loads or other parameters actually occur. In order to properly calibrate the model, we must enter the actual data on the behaviour obtained from metrological monitoring.

In this paper, we focus on indoor metrological monitoring of masonry listed buildings of low social projection by means of the measurement of lesions (cracks) and symptoms (humidity and temperature), which are often the origin of future pathological processes.

The measurement of the real value of the width of a crack cannot be obtained. On the one hand, a crack in dynamic equilibrium is in constant movement of contraction and expansion due to the effect of temperature. This vital constant, known in the past by building contractors as "the breathing of the building", was not correctly interpreted until 1934 by Pier Luigi Nervi in the conclusions of the Commission for the study of injuries in Santa María del Fiore [13]. On the other hand, the lips of the crack present irregularities along its length, so its width varies according to the point of measurement. In the case of a masonry arch, the crack associated with the joint has an angular geometry with zero width at the joint and a variable value at the intrados. Therefore, in preventive pathology monitoring, we can state that the most important thing is to control the evolution of the width in the same meaningful spot every time, what represents a problem difficult to solve at present due to the fact that many of these buildings are in use. When the technique applied to measure the evolution of cracks requires an auxiliary lifting installation, it causes visual deterioration, an alarm among users, and it tends to take up space in detriment of the regular use of the building. This is what we call in this paper an invasive monitoring technique, which is not a feasible option because it involves bureaucracy and long waiting times to obtain space occupation permits.

The objective of this paper is to define an affordable, sufficient and non-invasive technique to measure indoor cracks width evolution of historical masonry buildings, so that together with the measurement of humidity and temperature, the method can be used for preventive monitoring. This method is aimed to contribute to the definition of a future systematic policy in the region of Aragón in Spain, so that preventive monitoring can be extended to all listed buildings.

Methods

In order to understand the cracks movements in historical masonry buildings and their causes, the most important parameter to monitor is the evolution of the width of cracks compared to the evolution of temperature and humidity because they give an idea of the loss of stiffness. Next, some low-cost techniques that could be applied to measure the evolution of cracks width are discussed.

Methods for analogue data collection, such as comparators and callipers, are common techniques to measure cracks evolution. Their main disadvantage is that to reach the most decisive injuries in arch and vault keys, it is necessary to use auxiliary lifting platforms for both installation and reading and control, hence they are quite invasive. These measurement techniques do not leave evidence of the validity of the measurement and therefore lack traceability. In case of doubt regarding a data, due to inconsistency with the series of measurements, it must be discarded. Additionally, the calliper is considered less precise than the comparator, because the device, which must be fixed to both sides of a crack, may give erroneous readings as it can be moved from its initial position by external agents (birds, rodents, ...). For these reasons, we explore, next, two low-cost digital techniques to measure cracks evolution: 3D photogrammetry and 2D image-based crack monitoring.

3D photogrammetry is another possible technique to measure cracks evolution. Close-range digital photogrammetry includes a large family of methods based on several acquisitions of a set of images used to produce a 3D point cloud of the scene [14]. Capturing data from the outside using photographic and photogrammetric management is currently having great success in 3D modelling of buildings and archaeological sites, monitoring broken specimens in the laboratory [15], and monitoring of cracks in outdoor infrastructures [16, 17]. Its attempts for indoor measurements (e.g., [12]) present a good quality/cost ratio but require particular attention during the shooting of images in survey campaign [18].

2D image-based crack monitoring is a technique often used to measure cracks in aging civil engineering structures outdoor, e.g. [9, 16]. This technique is considered a solid alternative to other approaches for cracks width monitoring since it ensures the objectivity of measurements, possibility to achieve sub-mm accuracy and the convenience for quickly recorded and stored characteristics of the entire crack pattern, and possibility of permanent observations and off-line measurements performable at any time [9]. As far as the authors of this paper know, this method has never been applied to indoor crack monitoring of historical buildings. The starting hypothesis to select this technique is that to measure the shrinkage or increase of a crack in indoor conditions at a low cost, it is not necessary to deploy a large amount of media, but just to make a 2D measure using a single photo. Barazzetti & Scaioni [19] argue that usually, cracking expands in one plane, so that only one image is enough to reconstruct the 2D geometry. Only in the case of off-plane deformations or non-flat objects, the problem becomes 3D and it requires a stereo-pair of images in order to be solved [19]. In our case, the first movements of the buildings get manifested through cracks in the arches and vaults. These cracks occur in the plane, in 2D, and are the ones that we control in preventive monitoring. Other authors have also proposed the use of a single photo for crack monitoring to reduce costs [16]. They do it by means of indirect measurement systems, using reflective targets for outdoor cracks of infrastructures as reference measurements. However, in this paper, we propose a method for indoor cracks that does not require the use of targets because they would imply the use of lifting platforms, becoming an invasive method for buildings in use. Instead of targets, we look for surface accidents in the vicinity of the cracks, such as the width of the voussoirs, bricks or joints, which we use as references. Barazzetti & Scaioni [19] argue that the measurement of crack deformations between different epochs, as we do in this paper, require the use of permanent targets in order to have permanent references. In our proposal of 2D image-based crack monitoring technique applied indoor to masonry buildings, surface accidents act as permanent references.

In this paper, we first tested the low-cost analogue and digital techniques in a laboratory setting. We tested their accuracy comparing the results obtained with them, using the comparator as a reference. The reason for choosing the comparator as reference is that it is the most broadly used method because it is cheap and accurate. The in-lab study allowed us to identify the 2D image-based method as the most promising technique because it is accurate, low-cost, and does not present the disadvantages of the other techniques considered when applied to indoor cracks of historical buildings with low social projection. Afterwards we checked, in a real situation, its advantages and disadvantages in order to develop standardized protocols of inspection that allows to compare data between different buildings and injuries. As case study we used a church named Nuestra Señora de la Asunción in Cariñena (Zaragoza, Spain), which is currently undergoing a reparation process. In the in-lab test we made use of targets as measurement reference to validate the 2D image-based method, whereas in the in-situ test we used the surface accidents of the construction as reference to avoid the use of targets that would require a lifting platform. Additionally, we have conducted a cost comparison of the different techniques, applied to the case study, in order to show the economic advantage of the proposed technique.

In-lab research materials and methods

In the laboratory of the Mechanical Engineering Department of the School of Engineering and Architecture of the University of Zaragoza, which has controlled temperature and humidity, measurements were made by means of a comparator, a calliper, 3D close-range photogrammetry and 2D image-based crack monitoring, on an artificial crack in a mechanically cut and separated board, following the next indications:

- Analogue comparator: an IP64 Mitutoyo with 20 mm range and 0.01 mm precision was used, attached to both sides of the crack. Its anchoring system minimizes the possibility of movements unrelated to the model itself or errors for measuring in a different spot (Fig. 1). For this reason, it is considered the most accurate measurement technique, and is used as a reference.
- Calliper with digital reading: an IP54 Preciva with a range of 150 mm and an accuracy of 0.01 mm was used (Fig. 1). This device introduces a small uncertainty factor when repeating readings, since the width of a crack varies at each point in its length and it is highly unlikely to repeat the reading in exactly the same spot.
- 3D close-range photogrammetry: the camera used was a Canon 200d with 18-55 mm lens, 100 ISO sensitivity and locked Autofocus. A tripod was used to take the photos in order to increase the exposure time depending on the variability of the light conditions. The obtained photos were rendered three-dimensionally using the Agisoft application "PhotoScan Professional". This software tool allows to measure the distance between points of the model created by means of a specific module. The distance to the object was fixed at 12 m. This software has the advantage of including a series of targets (Fig. 1) that, located on the object to be measured, are detected with precision. In this way, once the targets are correctly located, the measurement can be carried out without having a great specialization in metrology. The problem with this technique, as in the case of the comparator, lies in the need to reach the cracks to place the targets. We made a first test of this technique in-lab and also in the Basilica del Pilar in Zaragoza in order to check the quality of the model in indoor conditions. Once done, we discarded the use of the 3D close-range photogrammetry because of its long processing times to create point clouds and meshing and the difficulty of achieving an acceptable model due to the lack of light in indoor spaces, besides the invasiveness that the placement of targets implies. The lack of indoor light could be overcome

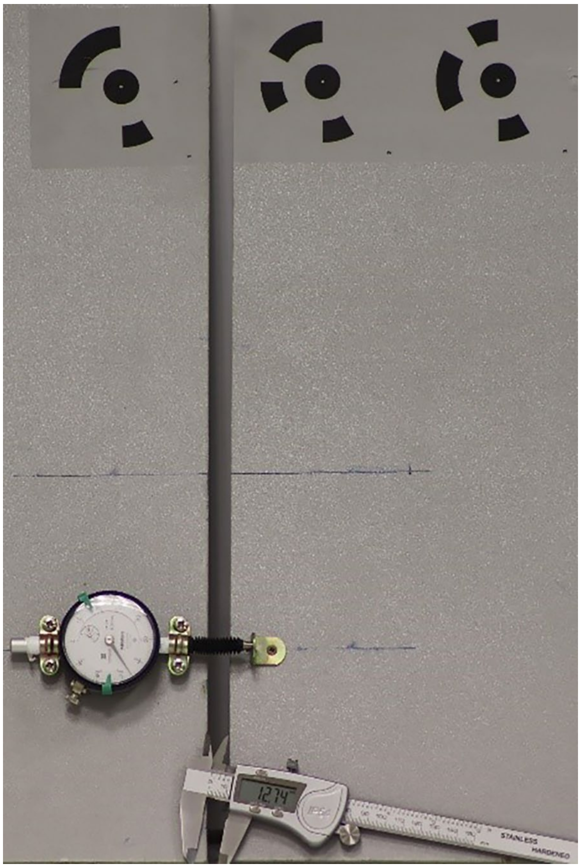

Fig. 1 Measurement stand (cracked wooden chipboard) and laboratory setup for the in-lab test. In the lowest position, the calliper; in the middle, the comparator; and above, the targets used for 3D photogrammetry and 2D image-based crack monitoring
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with reflectors. However, the reflectors installation for 3D photogrammetry is expensive and requires a permit to be placed in a building in use.

- 2D image-based method: the same camera was used at a fixed distance to the object of 12 m. The targets available in the Agisoft application "PhotoScan Professional" software were employed to define the references. With the aim to establish a proper 2D image-based crack monitoring procedure for masonry buildings, we considered the parameters of 3D photogrammetry [20–23] included in Appendix A to adapt them to our methodology. Then, the crack width was measured. In the literature, to measure the crack width some authors use an algorithm (e.g. [19]) and others use an image processing software (e.g. [16]). Since we had already observed that the image processing software tool for indoor conditions did not provide enough precision, we proposed the use of a drawing application to measure the crack width in indoor monitoring, and we studied the precision it provides. We preferred the use of this method to measure cracks width due to the ease of access and affordability of the tools it requires (camera and drawing application). To choose the most suitable drawing application for photo measurement, three different applications, known and accessible to anyone, were used on a same crack photo: AutoCAD, AutoCAD LT and DraftSight. Finally, AutoCAD LT was selected due to its user-friendliness, speed of loading and precision. The precision of AUTOCAD and AUTOCAD-LT is the same. However, due to its smaller number of modules, LT greatly accelerates its loading on the computer and the creation of new drawings for each crack. This software is available in most architecture and engineering firms. For a cheaper option, DraftSight should be considered. The method consists of comparing the width of the crack with a known fixed distance used as reference at different times to monitor its evolution over time. First, the photo is taken and inserted into a digital CAD file using the AUTO-CAD LT software tool. Then the image is scaled according to the measurement of the known reference distance. Finally, the width is obtained by means of the use of the linear dimension command of AUTO-CAD LT. The sequence of steps to measure cracks width with AUTOCAD LT is included in Appendix B. Since the support material used for the artificial crack is a wooden board, the reference distance practically does not undergo expansion. This 2D technique provides several advantages which make it an interesting method for crack evolution monitoring, such as no need for lifting platform and auxiliary materials to reach the furthest points, non-invasiveness with the use of the building, standard equipment for any technician, possibility of repeating the measurement in the same position and spot, and traceability. The latter is important, since it allows to reviewing the accuracy of the data obtained at any moment, and this is useful for future historical monitoring. However, this technique remains unexplored for this specific purpose, probably due to the increasing popularization of automatic monitoring.

Once the techniques to be compared were decided (comparator, calliper and 2D image-based crack monitoring), they were tested in two measurement ranges to evaluate their precision, in mm and hundredth of mm.

To compare the three techniques in the mm range, we used a cracked wooden chipboard (Fig. 1), which was subjected to a linear mechanical separation by steps of approximately 2 mm: from step 4 mm to step 20 mm, with separations at 2 mm interval. The first and last steps were eliminated for providing the most aberrant data. The two boards slide on a rail, allowing to maintain the parallelism of the crack. In the upper part targets were arranged to be able to measure the crack evolution using the 2D image-based technique. In the middle part, an analogue comparator was attached to both sides of the crack. In the lower part, a calliper was installed to measure the opening of the crack. Once the position was fixed, a picture of the whole was taken. To reduce the uncertainty of the calliper measurement, marks were drawn on the chipboard to perform each measurement at the same crack spot.

The usual cracks have a different width along their length and an angular shape. In our test, thanks to the equal separation throughout the entire crack and lack of the angular shape, we got a better comparison of the different measurement methods. We used the measurement offered by the analogue comparator as reference, and the calliper for validation as well as to be able to mechanically increase the crack by steps of approximately 2 mm. Measurements were taken in one day without humidity or temperature variation. In order to store the data, a model inspection sheet was prepared, and an example of its use can be seen in Fig. 2.

Afterwards, the comparator and the 2D image-based technique were compared in the tenth of a mm range. The crack was immobilized by fixing two steel plates above and below the measurement points at the back side. In this case the measurement stand is a wooden support, so there can be practically no expansions or

Step 4 mm

4.08 mm 3.00 mm 4.20 mm

Remark:

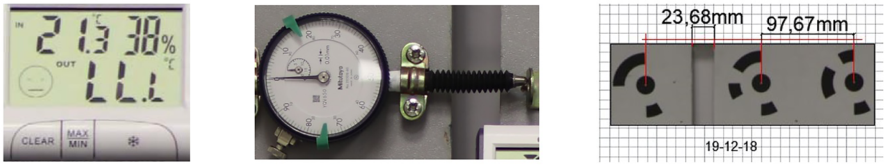
Comparator	4.08 mm (reference)
Calliper	3.00 mm (-1.50 mm)
2D image-based	4.20 mm (+ 0.12 mm)

Fig. 2 Example of use of the model inspection sheet for the in-lab mm test in the 4 mm step

retractions due to temperature, as compared to the high dilatation coefficient of the steel plates. Subsequently, the movement of the crack was measured due to the expansion of the steel plates with the variation of temperature, assuming negligible that of the wood. After a measurement of the crack in the initial position of 23.68 mm and calibrating the comparator in 0 mm, on 19th December 2018, the period without heating due to the Christmas holidays was used to allow contraction and subsequent expansion of the plates once the heating service resumed. To measure temperature and humidity, a commercial thermohygrometer (Oh!

Climatic data:

- Indoor Temperature: 21.3 ºC
- Indoor HR: 38%



Remarks:

Before Christmas measurement: Wednesday 2018-12-19.

Comparator shows a movement of 0 mm.

2D image-based crack monitoring shows an opening of 23.68 mm, using the same reference from other tests of 97.67 mm.

Action:

Repeat control on 2019-01-08.

Fig. 3 Example of use of the model inspection sheet for the in-lab tenth mm test for a given date haus & co brand) was used. In order to store the data, another model inspection sheet was prepared, and an example of its use can be found in Fig. 3. As can be observed, the 2D image-based technique shows the distance between the targets used as reference, whereas the comparator shows the crack width increase.

In-situ research materials and methods

The building used as case study was the Church of Santa María de la Asunción in Cariñena, facilitated by the archbishopric of Zaragoza. It presents injuries in the keystones of the arches on which the dome rests.

The first visit took place on June 14th, 2018. Permission was requested to introduce a lifting platform to place analogue comparators in the cracks against which to test the 2D image-based measurements. As it is a building in use, this permission was never obtained. This is how we realized that the methodology for crack monitoring should not involve the use of targets, since obtaining permissions to install lifting platforms in this type of buildings in use is a cumbersome and time-consuming task. In the Church of Santa María de la Asunción in Cariñena, we only applied the 2D image-based crack monitoring technique, after we had selected it and evaluated it in lab, in order to verify its efficiency in a real building.

The dome of the Church had suffered a lightning strike, on the 29th of June of 2016 which caused injuries to the lantern, dome and support arches. They had been repaired and hidden under the plaster and paint in March 2017. In addition, two tie rods were arranged in the arches 2 and 4 perpendicular to the naves (Fig. 4), which are the ones with the least horizontal offset in the supports. Subsequently, the visible cracks were grouted with elastic filler and the whole was painted. Therefore, our monitoring serves as validation control of the repair.

Four cracks were monitored in the keystones of four arches. To take the photos, the camera was placed under the arch opposite to each of the cracks, at a distance of 25 m between the camera and the crack. The positions of the camera can be seen in Fig. 4, where the photo taking points are indicated with a camera logo. Additionally, the direction towards which photos were made is indicated graphically and by means of an alphanumeric code (P#) whose number corresponds to the code given to each photographed keystone crack (Arch #). For example, P1 is the photo taking point, from which the keystone crack of Arch 1 was photographed. A pavement mark was used to place the camera in the same place all the visits. This distance of 25 m offers an angle close to 45° to better see the arch change in plane vertical-horizontal. Small variations in successive shots should not be considered because the proportion between the crack measurement and the reference measurement will always be the same regardless of the angle and distance to the object. Once the photo is scaled by means of the reference, we obtain

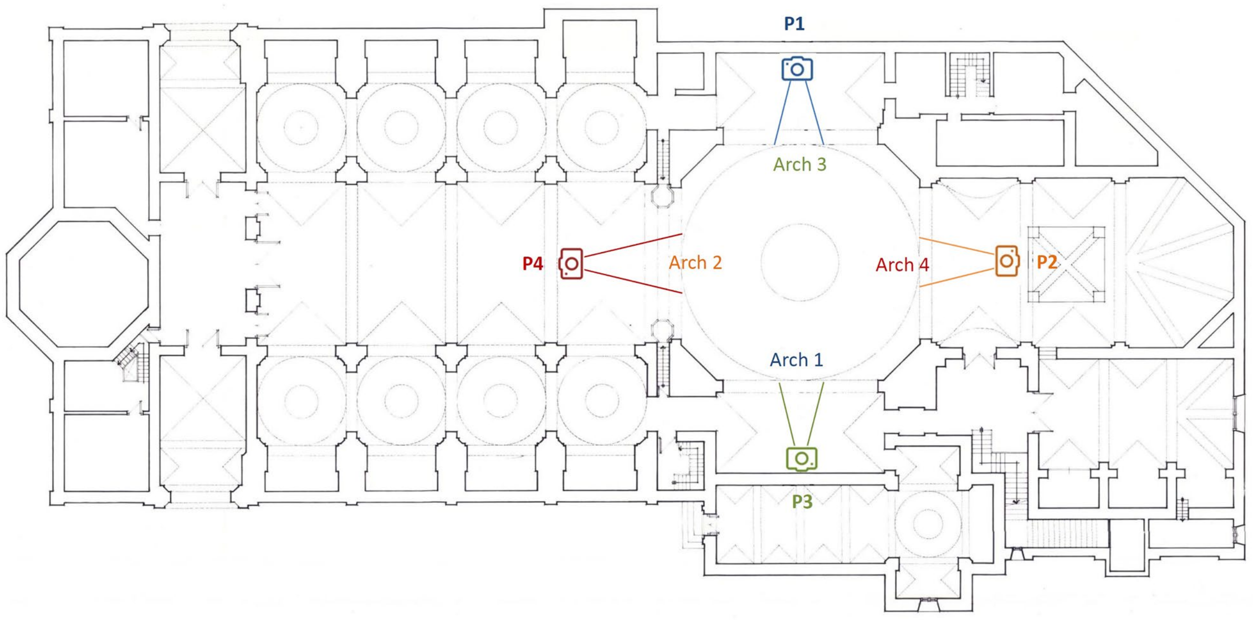
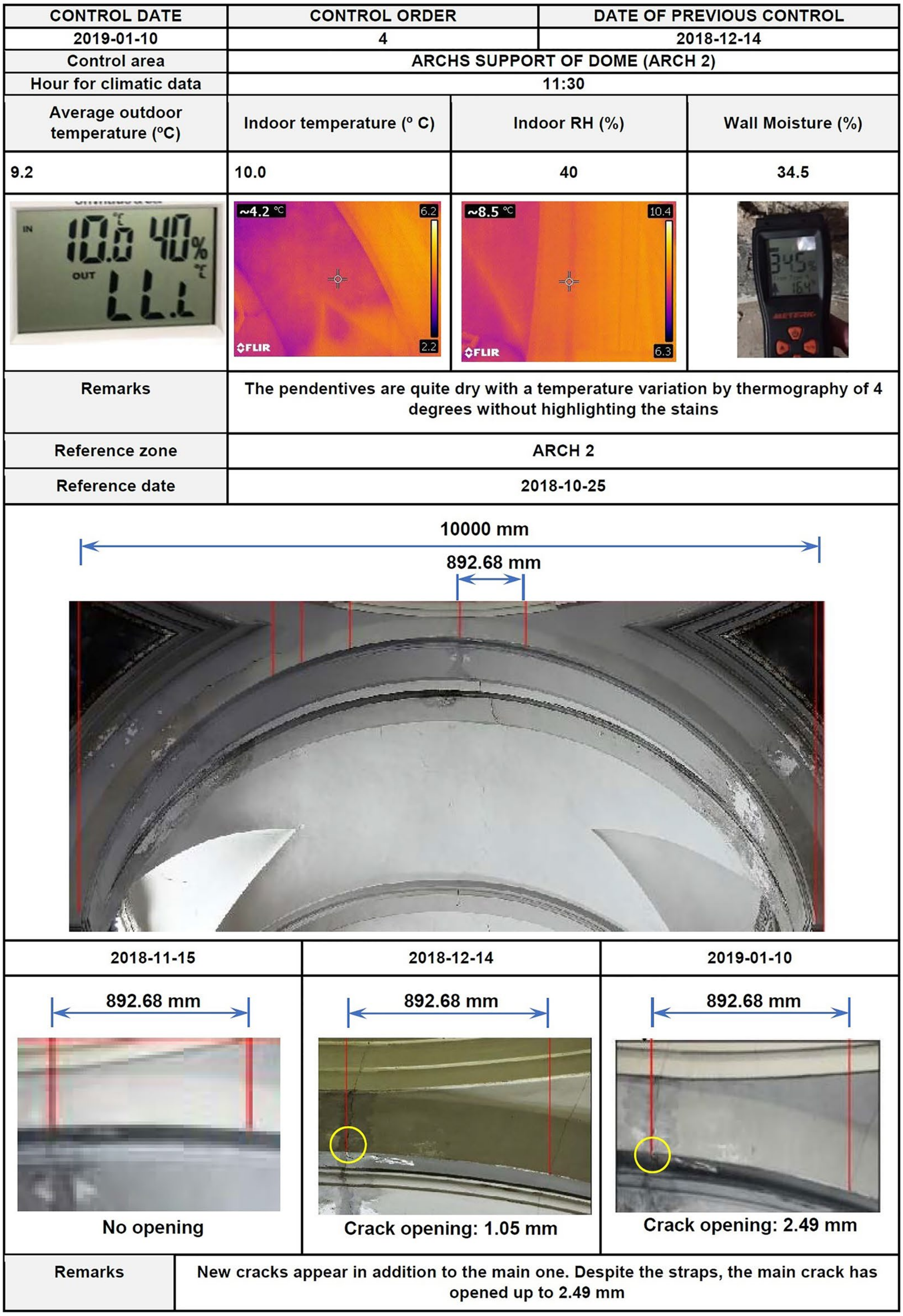


Fig. 4 Plan diagram of the location of the photo taking point for each photographed keystone crack in the Santa María de la Asunción Church in Cariñena



CONTROL DATE	CONTROL ORDER	DATE OF PREVIOUS CONTROL	
2019-01-10	4	2018-12-14	
Control area	ARCHS SUPPORT OF DOME (ARCH 2)		
Hour for climatic data	11:30		
Average outdoor temperature (ºC)	Indoor temperature (º C)	Indoor RH (%)	Wall Moisture (%)
9.2	10.0	40	34.5
Remarks	The pendentives are quite dry with a temperature variation by thermography of 4 degrees without highlighting the stains		
Reference zone	ARCH 2		
Reference date	2018-10-25		

10000 mm

892.68 mm

2018-11-15	2018-12-14	2019-01-10
892.68 mm	892.68 mm	892.68 mm
No opening	Crack opening: 1.05 mm	Crack opening: 2.49 mm

Remarks	New cracks appear in addition to the main one. Despite the straps, the main crack has opened up to 2.49 mm

Fig. 5 Model of data storage for the in-situ test

the measurement of the crack. To ensure that the width variation is measured at the same point, the change of plane between the vertical side and the intrados of the arch is chosen, due to its ease of observation and differentiation as can be seen (Fig. 5).

The camera used again was the Canon 200d with 75-300 mm zoom lens, 100 ISO sensitivity and locked Autofocus. A tripod 1.5 m high was used to take the photos to allow increase automatically the exposure time depending on the variability of the light.

The fact of having arches and vaults with painted mortar lining increases the difficulty of determining the measurements and location of the cracks, as they are masked by a continuous layer on the brick joints. If they were visible, the joints of the bricks could be used as reference distance, with which the precision of the result in the photographic measurement models is higher.

The ideal would be to have a reference of reduced size to facilitate the measurement of the crack and to minimize the expansion movement of the reference distance. In our case the reference distance was of 0.89268 m (Fig. 5). It is the distance to the closest crack. This high distance implies a higher uncertainty because it can suffer higher dilations due to temperature. To assess the uncertainty due to the high reference distance, we considered the dilation of the reference distance in relation to a dilation of the arch. If the arch has a width of 10m, the length of the perimeter is 39.27 m. If due to the retraction of the arch, the crack has a decrease of 3 tenths of a millimetre, i.e. 0.3 mm, it means that the dilation of the arch has a coefficient of 0.000007. For the reference distance considered, 0.8926 m, it would involve an increase in the size of 0.00000625 m, i.e. 0.000625 mm. This is a low uncertainty since it is outside the range of 0.1 mm, considering a crack is severe when its width is over 2 mm [24, 25]. For this reason, we validated the reference distance.

It is considered that if a measurement is carried out annually and the building does not have problems, in the same month the next year the width of the crack and the size of the reference distance will be substantially the same for the same temperature of the arch. If the building has no heating system, as is the case, this temperature depends on the average outside temperature of the previous month due to the thermal inertia of the arch. For this reason, it is important to determine the average outside temperature of the previous month. This allowed us to verify at the end of the monitoring process, that it is substantially the same than the previous year.

The pendentives had moisture spots due to lack of waterproofing, appearing to be the origin of the deformation of the arches. To control the humidity of the pendentives, a thermographic control was carried out that would make it possible to locate variations in the accumulation of water by comparison with an accessible area of a wall moistened by capillarity. Thermography allows to detect a temperature scale from which the existence of thermal bridges caused by moisture becomes visible. A termography camera (Flir brand) was used to take temperature photos of the arches. To measure the moisture of the base wall, a moisture meter (Meterk brand) was used with a range of 2% to 70%. These measurements were made systematically in dry and rainy periods monthly throughout the crack measurement period.

To manage the cracks data collection of each arch, a model sheet was created (Fig. 5). The collected data included the average exterior temperature of the previous month, the interior temperature at the time of the measurement, the interior relative humidity, and the surface humidity on a wall due to capillarity. In this way, it could be discerned if the movement of each crack was due to the variation in temperature or to the cession of the supports because of humidity.

Table 1 In-lab measurements of cracks in the mm range with calliper, comparator and 2D image-based crack monitoring technique

	Comparator (reference) [mm]	**Calliper**		**2D image-based**	
		Measurement [mm]	**Difference [mm]**	**Measurement [mm]**	**Difference [mm]**
Step 6 mm	7.50	6.81	− 0.69	7.27	− 0.23
Step 8 mm	8.88	8.22	− 0.66	8.8	− 0.08
Step 10 mm	10.55	10.11	− 0.44	10.45	− 0.10
Step 12 mm	13.33	12.74	− 0.59	13.23	− 0.10
Step 14 mm	15.15	14.45	− 0.70	14.99	− 0.16
Step 16 mm	17.16	16.52	− 0.64	17.07	− 0.09
Step 18 mm	19.82	18.59	− 1.23	19.36	− 0.46
Mean value	–	–	− 0.71	–	− 0.15
Statistical variance	–	–	0.06	–	0.03
Standard Deviation	–	–	0.25	–	0.17

Results

The results obtained in the laboratory and in-situ are shown below.

Results from in-lab measurements

The results of the in-lab measurements in the mm range with the different techniques can be seen in Table 1 for the different steps. The calliper has a mean difference of 0.71 mm with respect to the comparator and a standard deviation of 0.25 mm, which we considered an acceptable difference that may be caused by an irregularity in the measurement spot, as it would be in reality.

For all steps, the 2D image-based measurements were closer to the comparator than the ones taken with the calliper. They had a mean difference of 0.15 mm with respect to the reference, and a standard deviation of 0.17 mm, which is enough for pathology monitoring, considering that cracks are severe when they are wider than 2 mm [24, 25].

Regarding in-lab measurements of cracks in the tenth of a mm, measurements were taken at the beginning of the Christmas holidays (Fig. 3), two days later in the absence of heating, a third day with the heating running after the holidays and a fourth and a fifth time with a separation of three days each (Table 2). Small temperature variations were registered, which caused the dilation and contraction of the steel plates and subsequent increase and shrinkage of the crack. Relative humidity is practically the same in all measurements and cannot affect the expansion of the specimens. It can be seen (Table 2) how the 2D image-based technique is able to detect the first dilation when heating resumed and the retraction when the temperature drops on the 14th January 2019, whereas the comparator hardly detects movement. Probably the stem of the comparator also suffered the effect of expansion with heat as the plate attached to the board, although with a different speed.

In-situ results

The small variations in the range of temperatures between pendentives and the visual continuity in the colour gradient in each pendentive (Fig. 5) shows that there is no humidity that could cause a possible local redistribution of stresses in the supports due to the rainy periods.

Table 3 shows the data regarding the movement of cracks due to the dilation of each arch and its relationship with

Table 2 In-lab measurements of cracks in the tenth of a mm range with comparator and 2D image-based technique due to the effect of temperature

Date	Indoor Temperature	Indoor RH %	Crack width increase measured with the comparator (reference) [mm]	2D image-based [mm]	
				Distance between targets	Crack width increase
17 December 2018	–	–	0.00	23.68	0.00
19 December 2018	21.3º C	38%	0.00	23.68	0.00
8 January 2019	19.4º C	34%	0.10	23.82	0.14
11 January 2019	21.3º C	38%	0.20	24.14	0.46
14 January 2019	19.8º C	38%	0.20	23.81	0.13

Table 3 Summary table of humidity and movements cracks

Date	Average outdoor temperature [ºC]	Indoor temperature [ºC]	Indoor RH [%]	Wall Moisture [%]	Crack 1 [mm]	Crack 2 [mm]	Crack 3 [mm]	Crack 4 [mm]
11 June 2018	17.1	–	–	–	–	–	2.12	-
15 October 2018	21.9	20.2	46	47	–	–	–	–
15 November 2018	15.2	18.5	60	54	–	–	3.06	7.54
14 December 2018	11.6	13.1	49	56	–	1.05	3.03	9.05
10 January 2019	9.2	10	40	34.5	1.27	2.49	3.45	9.94
7 February 2019	7.1	11.2	46	56	2.07	2.34	2.99	10.35
5 March 2019	7.1	14.6	40	26	2.41	1.67	2.65	9.16
30 August 2019	24.6	25.7	51	44.5	–	–	0.82	–

the moisture of wall and indoor relative humidity (RH). The first column shows the date of the performed control. In the second column the average outdoor temperature of the previous month is shown, to compensate the thermal inertia. In the third column the indoor temperature is indicated in ºC at the time of inspection. In the fourth column the indoor relative humidity is indicated in % at the time of inspection. This is included since if there was a general high relative humidity it could affect the resistance of the supports. In the fifth column, the humidity of the support wall is controlled in % at the time of inspection. This parameter was considered because if the increases in the size of the cracks were produced due to the increase in the humidity of the wall, there would be a problem of transfer of supports. The following columns show the evolution of the opening of the main cracks in the key of each arch according to a sinusoidal pattern. Having all of them correlated, it is very easy to detect the seasonal pattern of their opening, or conversely to detect other problems.

As can be seen from the results in Table 3, the expansion of the cracks in the four arches increased until the control visit in March, when they began to retract with the increase of the indoor temperature. In the interior temperature column, there is a smooth continuity damping the averages of outdoor temperatures. The relative humidity is often around 50% in Cariñena, according to the climatological data in Aragon Institute of Statistics, [26]. On the other hand, the moisture of the wall in the studied area presents alterations, probably due to the variation of the phreatic level. However, these variations do not affect the size of the cracks.

After August, the control visits were suspended due to the coincidence with the theoretical seasonal pattern, considering the already taken measures sufficiently representative of the summer period. The August measurement is considered the theoretical moment of minimum amplitude demonstrating the closure of all the cracks. From this moment on, an annual control in winter is considered enough to control the maximum values of opening of the cracks.

Comparison of costs of the different techniques

Table 4 shows a cost comparison of different techniques to measure cracks width, applied to the case study of Santa María de Cariñena church. For the cost analysis, we considered a monthly control visit of a technician during one year, as well as the costs of installation, equipment and data processing to control the evolution of the keystone cracks in the four arches of Fig. 4.

As can be observed in Table 4, the 2D image-based approach is the cheapest technique of all those considered here. Its cost is 56% cheaper than the analogue technique used in this paper as a reference, the comparator, and 76% cheaper than the most expensive digital one, the 3D laser scanner.

Discussion

The measurement of cracks evolution against the measurement of humidity and temperature throughout the year is a suitable method for preventive conservation of listed buildings. The most important thing is not the actual measurement of the cracks but the accuracy in the measurement of their evolution throughout the control period of one year. As discussed along the paper, there are different techniques to measure the evolution of width of indoor cracks in historic masonry buildings. Different techniques are appropriate for different cases. The most sophisticated methods, such as digital data collection method or 3D laser scanning, provide high-quality data and are being used for listed buildings of high social projection. However, there is a large number of listed buildings with less social projection in countries such as Spain, Portugal and France, for which there is currently no systematic preventive conservation policy and for which funding is scarce. There are low-cost analogue techniques, such as the comparator and calliper, and digital techniques, such as 3D photogrammetry and 2D image-based crack monitoring. We discarded the analogue techniques because they are invasive and

Table 4 Comparison of costs of the different techniques for crack monitoring applied to the case study during one year

Technique	Lifting platform	Equipment, installation and data processing	Technician	Annual cost
Digital data collection	1350 €	6.529 €	250€ · 12 control visits	10,879 €
3D laser scanner	540 €	750 € · 12 control visits	250€ · 12 control visits	12,540 €
Comparator	270 € · 12 days	144 € · 4 comparators	250€ · 12 control visits	6816 €
Calliper	270 € · 12 days	0	250€ · 12 control visits	6240 €
3D photogrammetry	540 €	0	250€ · 12 control visits	3540 €
2D image-based	0	0	250€ · 12 control visits	3000 €

non-traceable. The following two low-cost digital techniques were further considered:

- 3D photogrammetry was found to present three main drawbacks. In the first place, the bad indoor light conditions cannot be easily overcome. There are positive experiences in 3D photogrammetry for crack monitoring in exterior infrastructures (e.g. [8, 16]). However, in this paper we focus on techniques to be used inside historic buildings, where the natural light conditions are inadequate and images do not have sufficient photographic resolution to build the points cloud. The installation of reflectors to solve the light conditions is invasive and requires permits, and therefore it is not an option for this type of buildings. Secondly, point cloud creation applications are expensive, but above all they need to have a large number of photos to be processed, with long waiting times, to provide 3D information. This implies important resources that are non-available for listed buildings of less social projection and with a high number of cracks. In the third place, the technique includes the use of targets, whose use is also invasive because their installation requires the use of lifting platforms.
- The 2D image-based inspection technique is a technique commonly used to measure cracks in aging civil engineering structures outdoor. We have adapted this technique to be used indoor in historic buildings. It is an indirect measurement system, which we have found to be an affordable, easy, fast, and non-invasive control system, designed to respond to the needs of preventive monitoring of historic buildings of less social projection in use. The innovation of the method proposed is that it is useful for indoor cracks monitoring, it requires a single photo (and therefore, it is easy, fast and affordable), and it does not need the use of targets to avoid lifting platforms (and therefore, it is non-invasive).

The use of the 2D image-based crack monitoring technique against the measurement of humidity and temperature along a control period of one year can be used for preventive conservation at a low cost and in a non-invasive way of listed buildings of low social projection. This methodology, which analyses the cracks in 2D, can be used before these buildings develop serious pathologies or to verify the adequacy of a recent intervention. When the cracks in the 2D plane increase their maximums and minimums, it is the announcement that we must use other techniques. Therefore, the technique presented here allows for timely detection of anomalies, optimized long-term allocation of the resources and prioritisation of the required measures. Once active pathological processes are detected, or deformations, collapses and twists are observed, which get manifested through three-dimensional cracks, other more sophisticated monitoring systems are advisable, such as 3D laser scanning to check deformations and geometry stability of the whole building (e.g. [8, 27]), exterior 3D photogrammetry captured by drones, or the installation of an automatic digital data collection system using digital sensors connected to a data storage station, taking advantage of advances in IoT through wireless sensors. In short, the metrological monitoring techniques discussed in this paper have all their advantages and disadvantages, which make them more appropriate for the monitoring of each phase of the evolution of the pathological process. The technique proposed in this paper is useful for preventive conservation, for its low cost and comfort, since it allows anticipating the evolution of the symptoms and injuries of this type of buildings.

In relation to the 2D image-based approach that we propose here, the following issues were observed to be important when applied in-situ:

- In arches, vaults and domes, strain cracks occur in the same positions and with similar shapes in all masonry buildings [28]. The technique proposed is useful just to assess the increase or decrease of this type of crack over a year. As such, the system does not claim to know the absolute value of the width of a crack but its seasonal variation by comparison between two different moments in the range of 0.1 mm. Normally in pathology work, we need to know the evolution of cracks bigger than 2 mm in a range of 0.1 mm [24, 25].
- It is necessary to check that the width of the crack returns to be the same at the end of the period regardless of its value. In this sense, the 2D image-based technique allows the traceability of all the measurements of each visit. Thus, in case of obtaining aberrant measures, it is possible to assess which is the wrong one.
- There are two main uncertainties in the use of this technique when applied in-situ. One of them is that if the masonry is coated, then the real size of cracks is never known. It is only possible to measure the symptoms (visible cracks in the mortar). This type of uncertainty is common to all methods discussed in this paper. The other uncertainty is due to the dilation and contraction of the reference with temperature.

Since the expansion affects the entire arch, the larger the references size the higher the uncertainty due to the dilations caused by temperature. For this reason, the recommended distance is the smallest possible, so that the effect of dilation can be neglected. In the case of plastered surfaces and in the absence of nearby reference points, the creation of artificial references, such as marks with a sharp object, could facilitate the work.

- One of the main problems detected during the inspections were the dependence on an adequate light source to achieve the desired precision in the photos. Bad light conditions can be solved with a reflector. Increasing the lighting on the crack improves the resolution of the images, although it can be cumbersome to move all the equipment for a single photo. We found that increasing the exposure time thanks to the use of the tripod is a more convenient approach.

Conclusions

The research question that is explored in this paper is whether or not we can find a technique that is affordable, non-invasive and sufficient to measure the width of cracks in listed masonry buildings of low social projection. We explored and tested several possible techniques in in-lab settings and found a novel promising technique. Afterwards, we tested it as well in a real case, a church in Zaragoza (Spain).

This technique, 2D image-based crack monitoring, is often used to measure cracks in aging civil engineering structures outdoor. The novelty is that we adapted it for use inside historic masonry buildings of low social projection. This technique requires a single photo to be taken, and, therefore, it is easy and fast to apply. In outdoor civil engineering structures, it is often applied with the use of targets to obtain a known reference distance against which to scale up the photo and measure the crack width. However, in our case, the use of targets is not advisable because it would entail various inconveniences, such as higher costs to install lifting platforms, administrative bureaucracy to obtain permits or longer waiting times.

In order to avoid the use of targets, we proposed the use of surface accidents to obtain the reference distance. Cracks in masonry buildings expand and contract in a seasonal pattern which was found to be easily detectable by the 2D image-based crack monitoring technique developed here. Since cracks are in constant movement of contraction and expansion, and the width is irregular along their length, what is interesting for preventive monitoring is not the exact value of the width of the crack, but to check how much the width of the crack expands and contracts at a same spot, as well as whether it returns to the same magnitude when completing the pattern or not. The method proposed is useful for this purpose, and at the same time it is affordable, easy, fast to use, and non-invasive and, therefore, it can contribute to the democratization of cracks metrological monitoring of listed buildings with low social projection. The proposed technique was found to be 56% cheaper than using a comparator and 76% cheaper than using a 3D laser scanner.

In laboratory tests when analysing the mm measurement range, it was found that the 2D image-based technique provides greater precision than the calliper in all the steps. In the most precise range of a tenth of a millimetre due to the expansion of the steel, the 2D image-based method is proven to be more sensitive than the comparator, recognizing temperature variations. In the in-situ measurements of the cracks, after learning during the first visits to stabilize the photos in low light, it was possible to make a normal follow-up of the process of opening and closing of cracks, responding the obtained results to the expected behaviour of sinusoidal and seasonal movement.

This technique is recommended to be used together with the use of thermography and moisture meter to compare the interior relative humidity and the humidity of the wall. This allows to check that the moisture does not have an effect on the crack width, and in the case it has, to predict the next evolution of the building geometric stability.

The proposed method is, therefore, proven to be effective, reliable, cheap, traceable, non-invasive and easily generalizable to almost all listed heritage buildings of any institution.

Future work should include the automation of the measurement process of cracks with the drawing application. For example, the creation of an improved module with cursor attractors to locate the crack lips in AUTOCAD LT would be of great interest. Another line of future work is to get the method proposed here implemented in buildings that already have monitoring preventive based on digital data collection, 3D photogrammetry, laser scanner, or any other method, in order to be able to compare the results and to mutually validate them. Finally, another future line of work is the development of a systematic conservation policy for listed buildings together with the public administration.

Appendix A

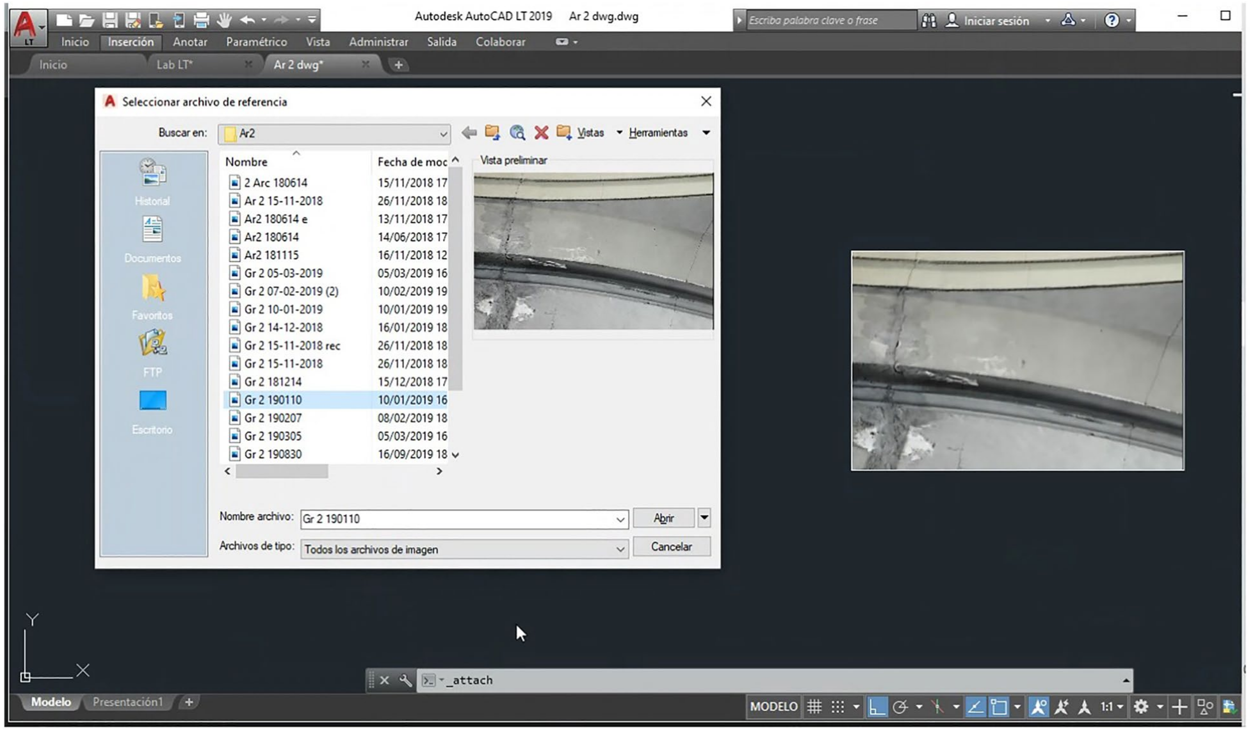
Parameters of 3D photogrammetry [19–22] applicable to our 2D image-based inspection method.

Parameter	Definition	Consideration made for 2D image-based technique in this paper
Distance to the object	Distance between the camera sensor and the object to be photographed	In order to have as similar conditions as possible regarding light and shadow, marks were made on the pavement to place the camera on a same chosen point
Focal length	Distance between the projection centre or optical centre and the sensor or focal plane	The variation of this distance gives us the scale of a photograph, as well as the image field to be photographed. The shorter the focal length, the higher the scale. In our case, the focal length is not important because the photo is taken using a telephoto lens, looking for the size with better lighting. The scale is given later for comparison
Sensor format	Physical dimensions of the camera sensor in horizontal and vertical	It is an interesting piece of information to discern the overlap of the different photos, but it does not apply here because we just need one photo per visit
Coverage distance	Distance of terrain covered by each photograph	It is not applicable to a single photo either
Overlap or traslape	Portion of the photograph that is covered by another of the same scene, with a lateral and transverse displacement	It is not applicable to a single photo either
Base	Distance of terrain that exists between two consecutive shots of photographs to have the desired overlap percentage	In 2D there are no consecutive photos
Scale of the photograph	Relationship between the dimensions of the photograph with respect to the dimension of the photographed terrain	In this work, the scale is obtained using a known reference measurement
Resolution	It is the number of pixels in an image in each of its axes (horizontal and vertical) forming a grid, establishing the level of detail of the image	In our case, the best resolution is achieved with the maximum telephoto lens
Ground Sample Distance (GSD)	The coverage that the pixel has in real scale of the ground	When adjusting the telephoto lens for the best lighting, each photo has a different GSD that is later corrected by scaling
Parallax	The apparent displacement of the position of a fixed object due to the change in the position of the camera	Since we just take one photo per visit there is not a relative displacement between photos
Optical aberration	The image is deformed due to the shape of the lens	In 3D there is an application to compensate for the deformation caused by the lens and to be able to combine the images properly. In 2D it is enough that the measured object and the reference are in the centre of the image. There is no need to combine images. A wide angle deforms the image sides. A telephoto lens like the one used, takes a photo without deformation. The photos in the different visits are taken from the same place for each crack, so the small deformation that may exist is always very similar

Appendix B

Sequence of steps to measure cracks width with AUTOCAD LT.

1. The image of the crack is inserted in AUTOCAD LIT (Figure B1)



Buscar en: Ar2

Nombre	Fecha de moc
2 Arc 180614	15/11/2018 17
Ar 2 15-11-2018	26/11/2018 18
Ar2 180614 e	13/11/2018 17
Ar2 180614	14/06/2018 17
Ar2 181115	16/11/2018 12
Gr 2 05-03-2019	05/03/2019 16
Gr 2 07-02-2019 (2)	10/02/2019 19
Gr 2 10-01-2019	10/01/2019 19
Gr 2 14-12-2018	16/01/2019 18
Gr 2 15-11-2018 rec	26/11/2018 18
Gr 2 15-11-2018	26/11/2018 18
Gr 2 181214	15/12/2018 17
Gr 2 190110	10/01/2019 16
Gr 2 190207	08/02/2019 18
Gr 2 190305	05/03/2019 16
Gr 2 190830	16/09/2019 18

Nombre archivo: Gr 2 190110

Archivos de tipo: Todos los archivos de imagen

Figure B1. Step 1: image insertion

2. The following lines are drawn:
The tangent lines to the lips of the crack to be analysed. Tangency is drawn at a change of plane (lines 1 and 2 in Figure B2)
The tangent line to a reference point with known crack distance. It is also drawn at the change of plane (line 3 in Figure B2)
A horizontal line is drawn perpendicular to the previous ones (line 4 in Figure B2) to facilitate the annotation and scaling in the following steps

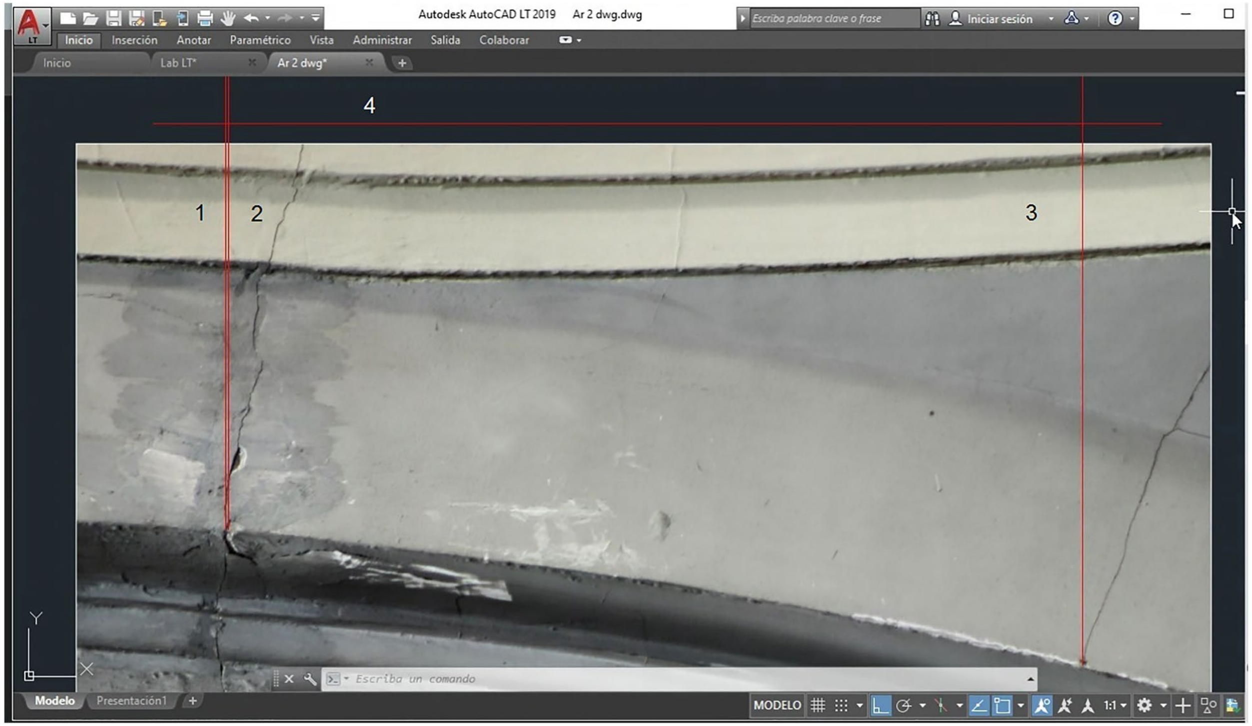
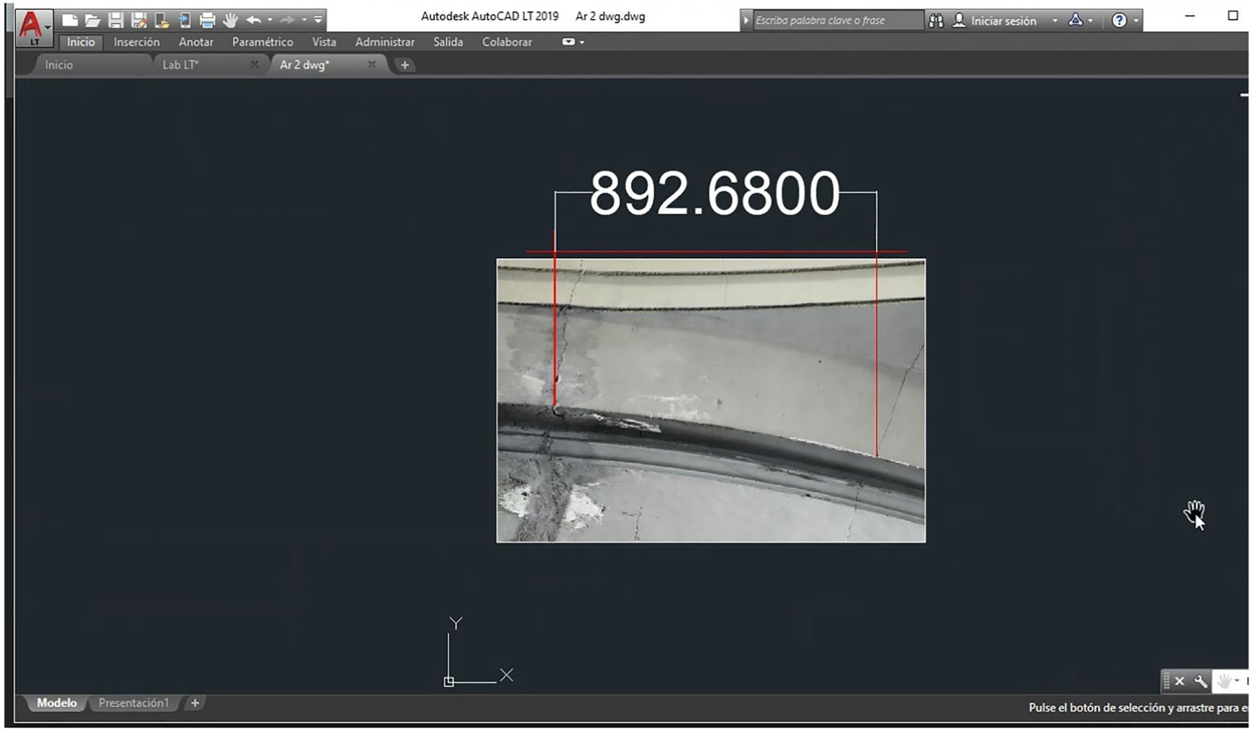


Figure B2. Step 2: auxiliary lines

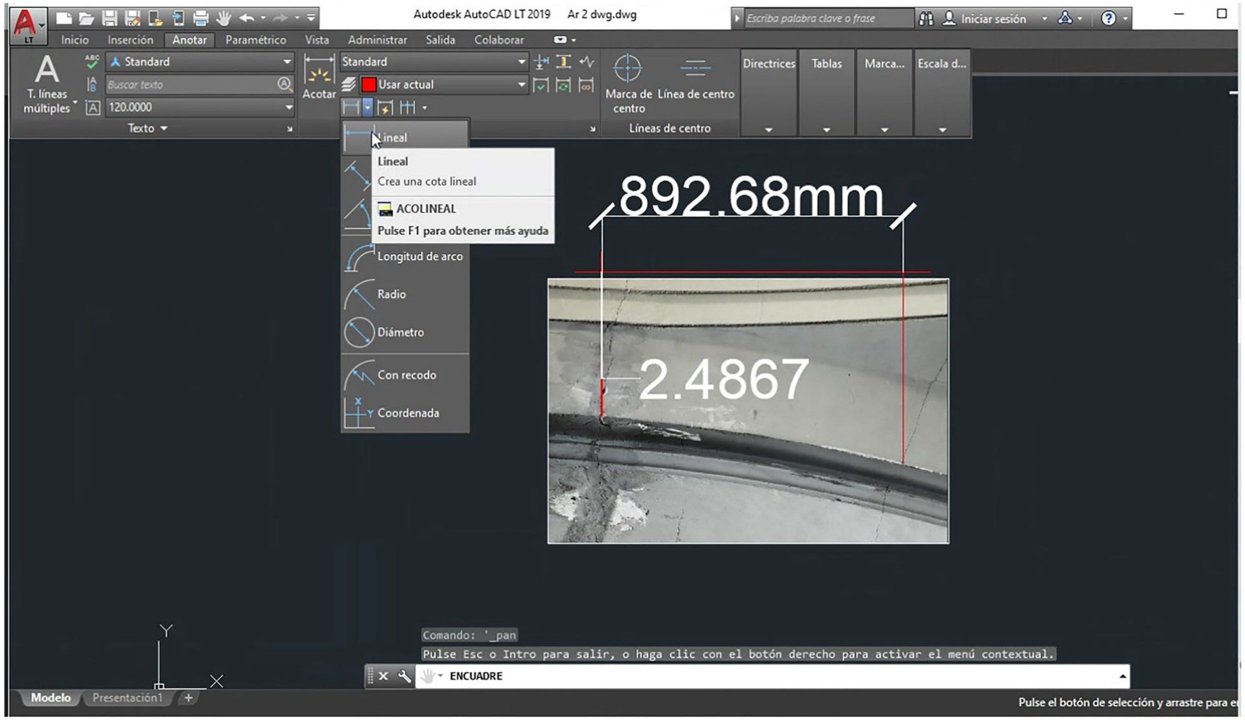
3. The image is scaled by reference using the known distance



Pulse el botón de selección y arrastre para e

Figure B3. Step 3: scaling by reference

4. The crack is dimensioned using the command linear dimension



```
Comando: '_pan
Pulse Esc o Intro para salir, o haga clic con el botón derecho para activar el menú contextual.
```

Figure B4. Step 4: Crack width dimensioning

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Author contributions
Conceptualization, JO-E, LG-V and BL-M; methodology, JO-E, LG-V and BL-M; software, JO-E; validation, LG-V and BL-M; formal analysis, JO-E; investigation, JO-E; resources, LG-V and BL-M; data curation, JO-E; writing—original draft preparation, JO-E; writing—review and editing, LG-V and BL-M; visualization, JO-E; supervision, LG-V and BL-M; project administration, LG-V and BL-M.; funding acquisition, LG-V and BL-M All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no competing interests.

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