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Investigations about the causes of structural damages of the St. Bernardino convent in Amantea (Cs)

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Abstract
The aim of this paper is to highlight the importance of correct design choices in architectural restoration of historical constructions to avoid damages able to produce loss of their structural integrity.
San Bernardino convent in Amantea (Cosenza province, southern Italy), a fifteenth-century architecture declared as national monument, has been seriously compromised by application of inappropriate techniques of restauration.
Wrong solutions have been proved through endoscopic tests, which allowed to visually inspect the inside of the masonry bodies affected by static instabilities, have highlighted the nature of the reinforcing elements which have been employed and their undergone transformations over time. Therefore, it has been possible to verify how these physical changes, suffered by the reinforcing elements, have damaged the masonry of the pillars of cloister, much more than the crushing phenomenon in progress on them.

Keywords: cultural heritage, crushing phenomenon, masonry pillars, endoscopic tests.

1. Introduction
It is known as the instabilities on the masonry buildings are always related to specific causes, which produce well-defined phenomena on the structure, connected to typical crack patterns. Therefore, observing the way a specific instability occurs on a masonry structure, the cause which produced the type of mechanism and the cause-effect link can be easily identified [1]. Inside the cloister of San Bernardino di Amantea (figs. 1a,b), a national monument located in the small Tyrrhenian town of the Cosenza province, during the detection of the arches some structural anomalies were recorded. In fact, it has been observed how the arches and pillars of the cloister, placed along the east, south and west front, are characterized by the typical crack patterns of a crushing instability due to overload problems [2]. Initially, the interpretation of the collapse in act and the identification of its causes, seemed simple and immediate. More guarantees about the correct interpretation were represented by the following elements:

- the evaluation of the internal stress to the exercise state (ES) and the ultimate limit state (ULS) characterizing the masonry of the pillars, performed by means of single and double flat jacks. The compression check, carried out according to the stress limits evaluated experimentally, was not respected on any pillar examined [3];
- the static analysis performed on the arcades. Known the loads acting on the arches of the cloister, the lines of pressure were built and the resultants of loads R_i on the single pillar were defined. Subsequently, known the resultants R_i and the compressive strength of the masonry f_{md} of the

arcades, the compression checks were carried out on each pillar and have had a negative outcome [4]. This has analytically demonstrated the crushing phenomenon in progress.

Fig. 1.a

Fig. 1.b

Figs. 1: The Franciscan complex of San Bernardino in Amantea: a) view from the parvis of the historical architecture; b) internal porch of the cloister.

The data reported so far proved irrefutably the overloading in act, explaining unequivocally most of the cracks and the signs of the instability detected on the arcades. However, through careful and detailed survey of the crack pattern characterizing the elements of the cloister, it has been possible to observe "unusual" cracks in correspondence of two pillars: in fact, these can be hardly ascribed to the crushing instability for the reasons explained below.

Usually, on the arcades of the cloister affected by the instability in act, a vertical "shortening" and a horizontal transversal expansion on the generic pillar are detected [5]. The lowering of the pillar entails the excess of the internal cohesion on the filling portion of masonry placed between two load-bearing semi-arches, supported by the slender element (fig. 2.a). This involves the formation of cracks with a parabolic trend on the filling masonry portions (fig. 2.b). The phenomenon described manifests in presence of overloaded arches affected by an advanced crushing instability. However a different trend of the cracks, on the filling masonry portions, has been detected in correspondence of two pillars located along the west front (this is the side of the cloister along which the overloading produces the heaviest effects). On these masonry portions the cracks have not more a parabolic trend, but they are approximately vertical (fig. 2.c).

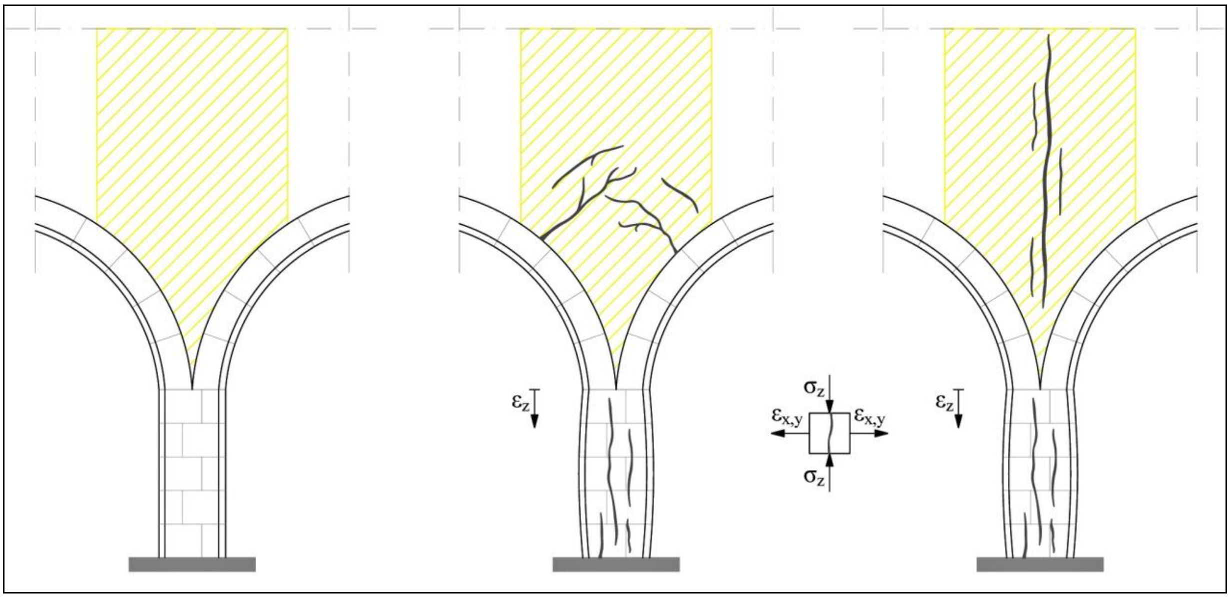


Fig. 2.a **Fig. 2.b** **Fig. 2.c**

Figs. 2: Investigated crack pattern: a) indication about the filling portion masonry on which the unusual lesions have been detected; b) classical crack pattern with a "parabolic" trend along the filling masonry; c) unusual crack pattern consisted from almost vertical lesions along the filling masonry.

This strange trend of the cracks on the filling portions has suggested to carry out further investigations in order to look for an intrinsic cause to the masonry that could explain a similar "anomaly." In fact, these vertical cracks cannot be attributed to the crushing phenomenon in virtue of ongoing collapse mechanism on the slender load-bearing elements (the pillars). For these reasons, it was decided to carry out endoscopic tests on the pillars of the cloister in order to investigate the masonry structure internally.

2. The cloister of St. Bernardino of Siena in Amantea. The origin of the structural issues

The religious complex of San Bernardino, located in Amantea, was built in the fifteenth century by the Minor Observants, arrived in the Calabrian town in 1436 [6], through different construction phases. The quadrangular cloister dates back definitely to the first construction phase, even if the porch suggests two different construction moments. In fact, the cloister is formed by pointed arches, supported by quadrangular cross-section pillars with rounded corners, arranged along the west, south and east sides (fig. 3.a), while along the northern side adjacent to the church there are Aragonese round arches, supported by columns [2] (fig. 3.b). The pointed arches date back to the first half of the fifteenth century, while the Aragonese arches, subsequent to the first ones surely, date back to the late fifteenth century - early sixteenth century. Originally, the sides with the pointed arches were equipped, on the first level, of a open gallery that allowed the access to the various rooms arranged along the three fronts of the convent built around the cloister [7] (fig. 4.a). Instead the north side, on the first level, was equipped by a terrace, protected by a covering wooden structure, delimited by the perimetral south wall of the church.

Fig. 3.a

Fig. 3.b

Figs. 3: St. Bernardino cloister: a) pointed arcades; b) Aragonese round arcades.

However, since 1812 the convent changed its appearance because, after the Murat edict and the suppression of religious orders in 1809, the structure became a property of the local baron Giulio Sacchi, who transformed the religious architecture in a "palaziata home" [8]. Among the works that he carried out there was the closure of the open gallery located at the first level of the cloister, in order to realize an internal gallery of service for the various rooms of his residence (fig. 4.b). The closure of the open gallery has been recently analyzed and highlighted through an important thermographic investigation [7], which demonstrated that the previous upper open gallery had been closed by the addition of portions of masonry in bricks. This closing operation represents, without any doubt, the origin of the structural problems which actually affect the arches of the cloister, as the load-bearing structures were subjected to greater overloading.
The closure of the upper open gallery was not the only cause of the overloading of the arches. Between the years 1948 and 1953, during the great post-war restoration directed by the Superintendent Gisberto Martelli, the original wooden floors were replaced with reinforced concrete floors, causing a new additional overload on the underlying load-bearing elements [9]. The situation, however, was further aggravated between the sixties and seventies of last century, when the first level of the convent was intended to several public uses (school, council archives, office of the C.I.M. and S.A.U.B.) [8]. These different uses of the conventual structure produced an increase of the loads in the exercise condition respect to those relative to the original use of the convent (residence of a religious family).

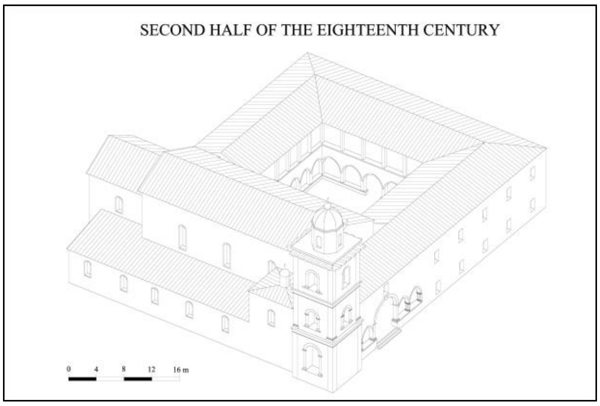


Fig. 4.a

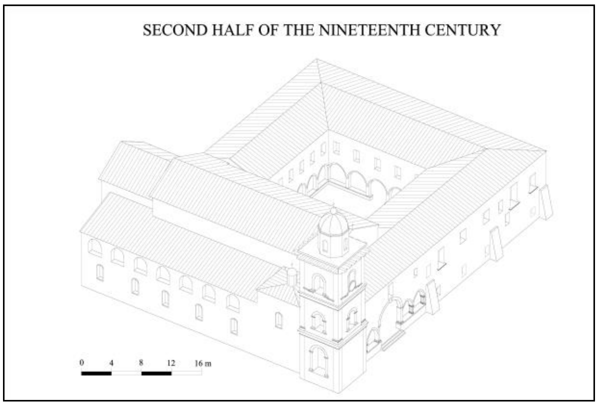


Fig. 4.b

Figs. 4: Isometric reconstructions of the St. Bernardino complex related to different historical periods: a) the complex during the second half of the XVIII century, characterized by the open gallery on the pointed arches of the cloister; b) the complex during the second half of the XIX century, characterized by the closure of the open gallery and the realization of an internal gallery located along the first level of the convent.

The effects of the overloading on the structural elements of the cloister were evident already in past, as shown by the numerous interventions of replacement of different deteriorated stone elements, performed on the arches over time, using calcarenite stone with a different color than the original one. At present, however, the advanced state of static instability in act has persuaded the municipal council to carry out appropriate interventions of temporary shoring, completed in 2014, to guarantee safety conditions inside the cloister [2], pending of a final definitive consolidation of the damaged structures. On some arches unusual cracks have been detected. Such damages cannot be explained with the overloading in act. Moreover, despite the pillars (belonging to a generic side of the cloister) are identical geometrically and subjected to the same resultant of loads approximately, it's possible to observe different crack patterns on consecutive load-bearing elements; this circumstance invites to search for an additional cause in addition to the overloading in progress. In order to respond to the underlined uncertainties, endoscopic tests were performed.

3. Endoscopic tests on the pillars of cloister

Endoscopic tests represent a non-destructive visual technique of inspection which allows to investigate the inside of the studied structures. Therefore, they are used: to get useful information about the type and the morphology of the masonry; to locate and to detect the presence of anomalies or problems of different nature, in zones difficult to reach and to inspect [10]. Initially, the endoscopic investigations, performed within the cloister of San Bernardino, involved the realization of 10 mm diameter holes by means of a low rotary speed drill, inside of which the video endoscope was inserted. An endoscope model SECURSCAN MW72 (figs. 5.a,b) was used, equipped with a probe 2 m long and having a diameter equal to 5,8 mm, able to capture pictures and videos with a resolution of 720x480 pixels, viewing angle 67° and having a lighting ensured by 6 micro leds. The investigations were carried out by the laboratory in situ testing, diagnostic and monitoring NGT-TEST S.R.L. based in Catanzaro (Italy).

Fig. 5.a

Fig. 5.b

Figs. 5.a,b: Video endoscope model SECURSCAN MW72, used during the investigations carried out.

Through the inserting and progressive advancement of the optical probe inside the holes, it was possible to document the internal aspect of the investigated masonry bodies. The endoscopic tests have been carried out on the pillars of the west side of the cloister (n. 5 pillars), having a cross-section of dimensions 40x40 cm, realizing holes along the geometrical axis of the same ones at the elevations of 1,15 m (share corresponding to half height of the pillar) and/or of 2,30 m (higher share than the one of the superior section of the pillar) respect to the level of the ground floor of the internal porch (fig. 6).

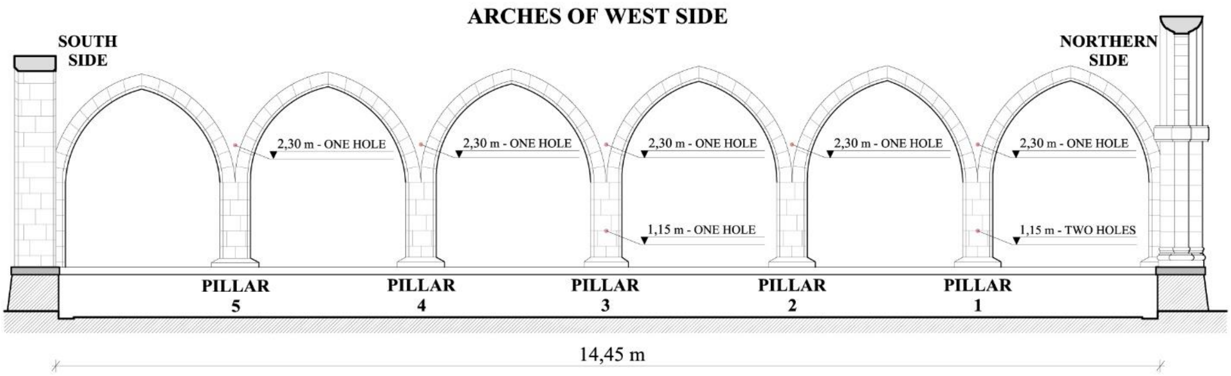
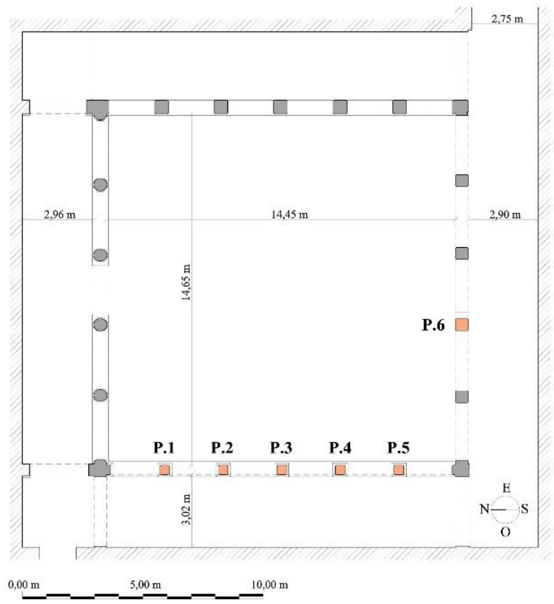


Fig. 6: Arches of the west side of the cloister, with the details about the shares and the number of the holes carried out to perform the endoscopic investigations



Moreover, a further endoscopic test was performed on a sixth pillar, located along the south side and having a cross-section of dimension 50x54 cm, on which a 54 mm diameter hole had already been practiced during the removal of a micro-carrot of masonry (fig. 7).

At the beginning, on the first pillar investigated (P.1) was performed an inspection at an altitude of 1,15 m along the axis of the west front. During the operation of drilling, therefore, the drill bit has succeeded to penetrate the masonry for only 16 cm (the side of the pillar measures 40 cm) before to stop. Inserting the optical probe into the hole and advancing gradually within it, the morphology of the masonry structure and the presence of potential anomalies were evaluated centimeter by centimeter.

Fig. 7: Plan of the cloister of St. Bernardino, with highlighted the pillars on which endoscopic tests were performed.

In detail, at different depths of the hole x [cm] has been verified:
- for 0 ≤ x <10 cm, the calcarenite stone is devoid of anomalies (fig. 8.a);
- for 10 ≤ x <15 cm, the calcarenite stone shows a longitudinal crack (fig. 8.b);
- for 15 ≤ x <16 cm, there is an empty space produced by the separation between the masonry and an internal metal element (fig. 8.c);
- for x = 16 cm the presence of a metallic oxidized element can be observed (fig. 8.d).

At the end of the inspection through the first hole, it was decided to carry out a second hole in the opposite position respect to the first one, at the share of 1,15 m along the axis of the east front of the same pillar. This time, the drill bit stopped at a depth of x = 14 cm and the optical probe has showed:
- for 0 ≤ x <13 cm, the calcarenite stone is devoid of anomalies (fig. 9.a);
- for 13 ≤ x <14 cm, there is an empty space produced by the separation between the masonry and the internal metal element;
- for x = 14 cm the presence of the metallic oxidized element, previously discovered, can be observed (fig. 9.b).

Thanks to the two specular holes, performed on the first pillar, it was possible to discover the internal presence, ignored entirely up to this moment also from the specialists of the Superintendence, of a metal element, of box-shaped type probably, with a quadrangular cross-section having a side of dimension 10 cm (or a circular cross-section, if the drilled holes correnpond perfectly with the extremes of a diameter equal to Φ = 10 cm) (fig. 10). Moreover, thanks to the endoscopic images taken, the oxidation of the metal element has been observed, which has produced the detachment between the internal element of reinforcement and the surrounding masonry due to the resulting increase of the metal volume. Therefore, the oxidation of the metal element has generated, from inside the pillar, a horizontal thrust on the surrounding masonry. This is explained by the presence of empty spaces between the reinforced metal element and the masonry, as well as by the damages that from the inside the pillar are developed up to the outer surfaces. The so produced instabilities are amplified by major internal stresses to the masonry due to the vertical loads of the superstructure. The complicated situation described is shown by the common cracks pattern (fig. 11.a), the expulsion of stone elements from the masonry bodies (fig. 11.b) and the reduction of the resistant cross-sections (fig. 11.c).

Fig. 8.a **Fig. 8.b** **Fig. 8.c** **Fig. 8.d**

Figs. 8: Endoscopic investigations throught the first hole realized on the pillar P.1: a) 0 ≤ x < 10 cm; b) 10 ≤ x < 15 cm; c) 15 ≤ x < 16 cm; d) x = 16 cm.

Fig. 9.a

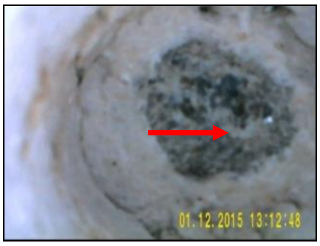


Fig. 9.b

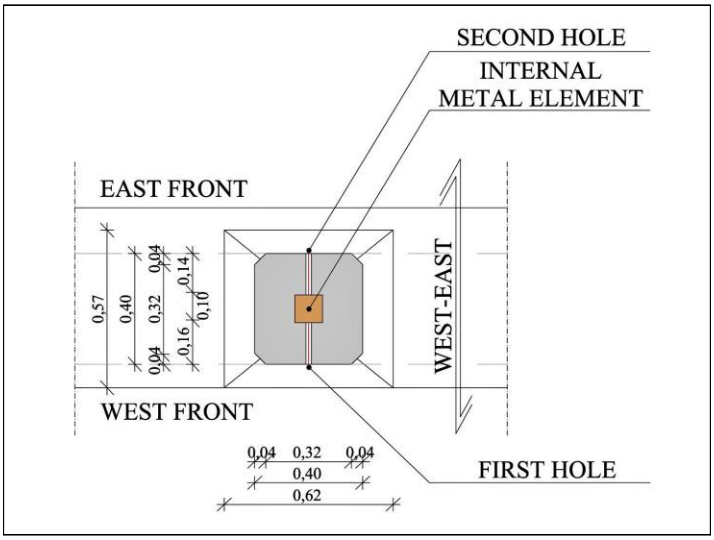


Fig. 10

Figs. 9: Endoscopic investigation through the second hole on the pillar P.1: a) 0 ≤ x < 13 cm; b) x = 14 cm.
Fig. 10: Generic cross-section of the pillar P.1, with indications about the holes performed.

Fig. 11.a

Fig. 11.b

Fig. 11.c

Figg 11: Typical forms of instability on the pillars of the cloister of San Bernardino: a) diffused longitudinal cracks; b) expulsion of corner elements from the masonry body; c) reduction of the resistant cross-sections.

In order to evaluate the length of the metal element of reinforcement, then to understand if this element develops only for the height of the pillar or it has a greater length, it was decided to perform a third inspection at about 20 cm above the superior section of the pillar P.1 (to the share of 2,30 m respect to the one of the ground floor of the internal porch) on its surface of the west front (fig. 6). In this case, the drill bit stopped its running at a depth of the hole x = 14 cm. About the morphology and the anomalies of the masonry, at different depths of the hole x [cm] has been verified:
- for 0 ≤ x <12 cm, the calcarenite stone / the c is devoid of anomalies (fig. 12.a);
- for 12 ≤ x <14 cm, the calcarenite stone / the mortar shows a longitudinal crack (fig. 12.b);
- for x = 14 cm the presence of a metallic oxidized element can be observed (fig. 12.c).

Fig. 12.a **Fig. 12.b** **Fig. 12.c**

Figs. 12: Endoscopic investigation performed through the third hole carried out on the pillar P.1: a) 0 ≤ x < 12 cm; b) 12 ≤ x < 14 cm; c) x = 14 cm.

The images taken during this third inspection have shown how the metal tube has a length greater than that of the pillar. Even if additional holes have not been performed, it's possible to affirm almost certainly that the metal element has a length equal to the share of the floor of the first level. The metal tube was used as an element of reinforcement for the masonry; in fact, it is able to collaborate to the load-bearing function of the masonry body within which it has been inserted. Furthermore, the development in height of the metal tube, its oxidation and the consequent volumetric expansion explain the appearance of the vertical unusual cracks on the filling portions of masonry placed between two load-bearing semi-arches, as those supported by the pillar investigated P.1. (fig. 2.c).
Further 10mm diameter drillings were performed on the remaining n. 4 pillars of the west side and on the second pillar of the south side (P.6), in order to proceed with the endoscopic inspection. In the tab. 1 are summarized the results obtained inspectioning these other pillars, by performing a minimum number of holes.

NAME OF PILLAR	FRONT OF PILLAR, DIRECTION OF HOLE, HEIGHT OF HOLE	DEPTH OF HOLE [CM]	MORPHOLOGY	ANOMALIES
PILLAR P.2 (WEST SIDE)	WEST; WEST-EAST; 2,30 m	0 ≤ x < 14 x = 14 cm	CALCARENITE STONE METAL TUBE	NOTHING OXIDISED METAL
PILLAR P.3 (WEST SIDE)	WEST; WEST-EAST;1,15 m	0 ≤ x < 14 x = 14	CALCARENITE STONE METAL TUBE	NOTHING OXIDISED METAL
	WEST; WEST-EAST; 2,30 m	0 ≤ x < 14 x = 14	CALCARENITE STONE METAL TUBE	NOTHING OXIDISED METAL
PILLAR P.4 (WEST SIDE)	WEST; WEST-EAST; 2,30 m	0 ≤ x ≤ 35 cm	CALCARENITE STONE	NOTHING
PILLAR P.5 (WEST SIDE)	WEST; WEST-EAST; 2,30 m	0 ≤ x ≤ 35 cm	CALCARENITE STONE	NOTHING
PILLAR P.6 (SOUTH SIDE)	SOUTH; SOUTH-NORTHERN;1,30 m	0 ≤ x < 16 cm x = 16 cm	CALCARENITE STONE METAL TUBE	NOTHING OXIDISED METAL

Tab. 1: Results obtained on the pillars P.2, P.3, P.4, P.5 e P.6 by means of the endoscopic tests.

The results have shown how the pillars P.2 and P.3 are affected by the same problem detected on the pillar P.1, due to the presence of internal metal tubes, probably having the same characteristics as the one characterizing the pillar P.1. Furthermore, these metal elements are oxidized and, because of the oxidation process, the masonry of P.2 and P.3 is greatly compromised in its structural integrity, presenting crack patterns and damages as those observed on the pillar P.1.
Inside pillars P.4 and P.5 the presence of reinforcement metal elements along their axis has not been detected; in fact, the drill bit is penetrated horizontally inside the masonry bodies, perpendicularlyb to the geometrical axis, for all its length equal to 35 cm (the length of the side of the pillar is equal to 40 cm). Therefore, it's possible to think two different hypotheses: a) inside the two pillars there are metal tubes in a decentralized position, distant from the position of the geometrical axis; b) inside the two pillars were not inserted metal reinforcements.

Visual observation of the two pillars suggests that the second hypothesis seems to be the correct one. In fact, the masonry bodies P.4 and P.5, unlike the pillars P.1, P.2 and P.3, although subjected to equal loads show only few little cracks due to the overloading phenomenon in act.
Therefore, the presence inside of pillars P.1, P.2 and P.3 of the west side of the cloister of metal reinforcement elements causes damages to their masonry due to oxidation phenomena (fig. 13); pillars P.4 and P.5, which have not been reinforced by means of metal elements are just little (the pillar P.4) or in no way (the pillar P.5) damaged (figs. 14.a,b), ensuring their full load-bearing function.


Fig. 13


Fig. 14.a


Fig. 14.b

Fig. 13: Pillar P.3 greatly damaged, in virtue of the crushing in act and the internal presence of a oxidized metal tube.
Figs. 14: Examples of pillars placed along the west side: a) pilllar P.4; b) pillar P.5.

The presence of reinforcement metal tubes inside of the pillars of the south and east sides of the cloister has been investigated. These pillars have cross-sections greater than those of the pillars of the west side; therefore, on the pillars of the south and east fronts have been detected lower internal stresses that attenuate the problems relative to crushing from overloading. Nevertheless, performing endoscopic tests on the pillar P.6 of the south side, a further metal tube placed in a off-center position respect to the geometrical axis of the masonry body has been detected (figs. 15.a,b). Its decentralized position has not allowed the corer to meet the internal tube (fig. 16), during the operation of core drilling previously carried out on this pillar.

Fig. 15.a

Fig. 15.b

Figs. 15: Endoscopic investigation through the pre existing hole on the pillar P.6: a) x ≈ 10 cm; b) x ≈ 16 cm.

Further holes were performed on the remaining pillars of the south side and on the ones constituting the eastern front of the cloister, but the drill bit did not stop advancing inside the masonry bodies. This has proved the absence, within these pillars, of metallic elements of reinforcement. Moreover, this absence suggests that the structural damage, detectable on these further pillars, can be attributed only to the mechanism caused by the crushing phenomenon in act on the arches of the cloister.

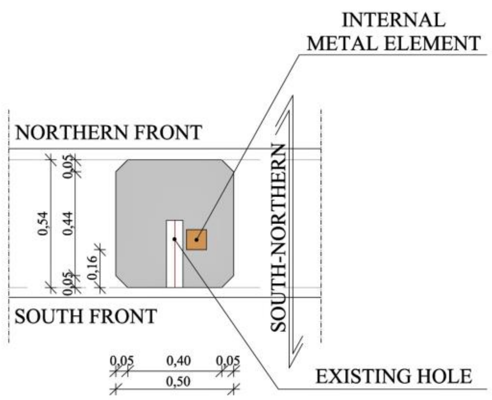


Fig. 16: Generic cross-section of the pillar P.6.

4. Conclusions

Tests results, carried out on the arches of the San Bernardino cloister in Amantea, have shown the importance of correct solutions in restoration and the structural consolidation of historical buildings in order to avoid significant damages. Volumetric additions and changes in the monuments functions have produced a significant increase of “permanent” and “operating” loads on structural elements which need to be adequately strengthened. Furthermore, is to be highlighted the importance of compatibility between building material and the reinforcement materials for interventions of structural consolidation as another factor in the conservation of the historical architecture. Reinforcement interventions of some of the pilasters were performed by means of metal elements inside the walls, without protective solutions. Due to the oxydation processes, if the surface of the metals elements is not preventively treated, volumetric expansion manifests, also inducing stress on the surrounding masonry, irreparably damaging it. Tests results suggested that such structural damage could have been avoided, adopting these precautions:

- performing a different intervention of consolidation of the pilasters in order to obtain the same structural results but using different reinforcing materials, not susceptible to oxidation;
- carrying out the chemical and the morphological characterization of the building materials of the masonry, in order to evaluate the compatibility between original materials and the reinforcing ones.

Finally, the structural problems detected on the arches of the San Bernardino cloister are the result of design choices and wrong interventions performed in the past, as evidenced by the visible damages.

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