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Study of crack patters of historical masonry elements of the cloister of St. Bernardino and the church of St. Biagio in Amantea (Cs) by means of sonic tests

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INTRODUCTION

The execution of sonic tests on masonry structures represents an efficient techinque to obtain important qualitative information about the structural status of bearing elements of a construction (Vasanelli et al., 2015). Although an accurate characterization of the heterogeneous construction materials, such as masonry, cannot be carried out throught these tests, on the other hand they permit to establish the level of structural integrity of the investigated elements in a simple way, putting in evidence the possible presence of cavities, cracks or separations (Eissa & Kazi, 1988; Brotóns Torres et al., 2014). The qualitative evaluation about the diffusion of cracks inside the masonry bodies is possible measuring the propagation times of the instrumental vibrations that cross the masonry means. This method allows to identify different ranges of the propagation velocities of the sonic waves to which correspond variousdegrees of homogeneity of the masonry. The measurements experimentally obtained permit to draw a qualitative mapping of the tested volume as a function of its compactness, with which the internal spread of the instability in progress inside the thickness of mansory elements can be highlighted. This paper proposes the survey conducted on the thin bearing elements, affected by static instabilities, of two important architectures of the city of Amantea (Cs): the cloister of Saint Bernardino of Siena and the church of Saint Biagio.

MAIN OBJECTIVE
REALIZE A MAPPING ABOUT THE DIFFERENT DEGREES OF STRUCTURAL INTEGRITY OF THE ELEMENTS EXAMINED BY MEANS OF SONIC TESTS

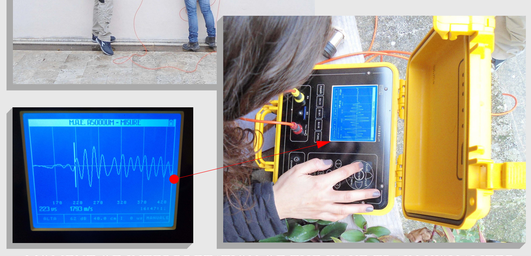
ARCHITECTURAL ELEMENTS EXAMINED
THREE COLUMNS OF THE CLOISTER OF SAINT BERNARDINO IN AMANTEA (CS) - XV CENTURY
ONE COLUMN OF THE CHOIR OF THE CHURCH OF SAINT BIAGIO IN AMANTEA (CS) - XVII CENTURY

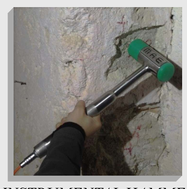
TESTS IN SITO CARRIED OUT
FLAT JACKS TESTS
SONIC TESTS

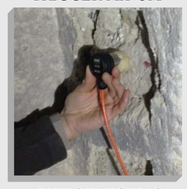
SONIC TESTS: PRINCIPLES OF THE INVESTIGATION METHOD AND THE EQUIPMENT USED

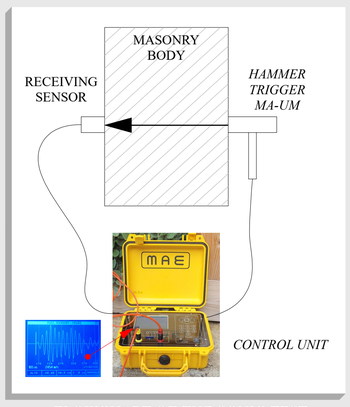
The sonic tests allow to determine the propagation speed of mechanical sound waves through the investigated masonry body. This is useful to obtain qualitative information about the compactness level of the masonry, the presence of cavities or cracks, and about the heterogeneity level of the materials crossed by instrumental waves. This non-destructive method of investigation is based on the generation of mechanical pulses with frequencies in the sound field (20-20000 Hz), by means to an appropriate instrument, which are received by a sensor (piezoelectric accelerometer) placed in a different point of the masonry structure. Both devices are connected to a control unit that converts analog signals into digital, but also displays the wave trains. Furthermore, the control unit returns automatically: the transit time of the waves through the masonry bodies; the crossing speed of the masonry (initially, it's known the space that divides the transmitter and the receiver). The sonic surveys applied to the architectures in masonry, especially historical ones, allow to obtain only qualitative results precisely because of the nature of the investigated material, which is highly heterogeneous and anisotropic. By virtue of this, the propagation speeds are very low if the crossed material is damaged and inhomogeneous, then if it is interested by the presence of significant empty spaces. Originally the execution of the sonic tests expected the identification of the "sonic grid", on the outer surfaces of the masonry elements to investigate, used like frame of reference to perform the instrumental measurements (Bufarini et al., 2010). Acquired the values of the propagation time and the propagation speed, it was possible to establish the degree of compactness of the masonry in relationship to different ranges of the propagation speed values v [m/s]. Then attributing to each range one color, it was possible to realize the color maps about the compactness levels of the masonry on the examined slender elements. The equipment used to perform sonic tests was composed of: a control unit MAE A5000UM S.N. M044771 to measure sonic impulses; an instrumental hammer Trigger MA-UM (transmitter) and a receiving sensor (piezoelectric accelerometer) SC55R with 55kHz frequency, both connected to the control unit through cable necessary to acquire data; connecting material (plasticine) in order to ensure the perfect adherence between the surface of the receiving sensor and the masonry support, allowing the passage of the sonic longitudinal waves in a continuous manner. The regulations in force relative to the execution of sonic tests are the UNI EN 12504-4. The surveys were conducted by the technicians of the NGT-TEST S.R.L. with legal headquarters in Catanzaro (Italy). The sonic tests were carried out in direct mode, known the thickness of the crossed masonry body (Cicchiello et al., 2010). This mode consist in the emission and the receiving of the instrumental waves in corresponding points, located on two opposite faces of the masonry element in exam.


MOMENT DURING THE MEASUREMENT OF THE PROPAGATION SPEED OF THE SONIC WAVES, CARRIED OUT ACCORDING TO THE SONIC GRID PREDETERMINATED


MOMENT OF INTERPRETATION OF THE WAVE TRAIN VISUALIZED INTO THE DISPLAY OF THE CONTROL UNIT


INSTRUMENTAL HAMMER TRIGGER MA-UM


PIEZOELECTRIC ACCELEROMETER SC55R



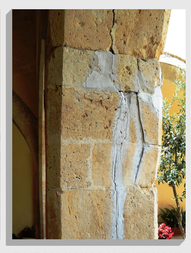
FLOWCHART OF THE SONIC TEST ACCORDING THE DIRECT MODE

THE CLOISTER OF SAINT BERNARDINO IN AMANTEA (XV CENTURY): MAPPING ABOUT THE DEGREES OF INTERNAL INTEGRITY OF THE MASONRY COLUMNS AFFECTED BY OVERLOADING

INSTABILITY FOR OVERLOADING IN ACTION ON THE ARCADES OF THE CLOISTER

The stability of the cloister elements has been compromised by possible effects of weathering and overloading. As a result, the load acting on some structural elements overcame locally their strength, with subsequent developments of cracks, leading towards a different equilibrium configuration. The crack pattern that occurred, was characterized by different features, depending on the cause that have generated it. The presence of cracks involves a decrease of the strength capacity of the masonry.The actual situation of the cloister shows a diffuse cracking pattern which requires an urgent strengthening intervention (Olivito et al., 2015).

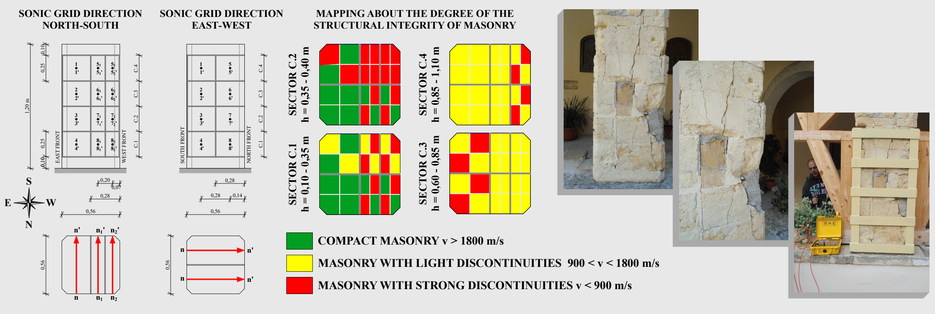

REDUCTION OF CROSS-SECTION (COLUMN 1 - EAST FRONT)


EXPULSION OF STONE ELEMENTS (COLUMN 5 - WEST FRONT)

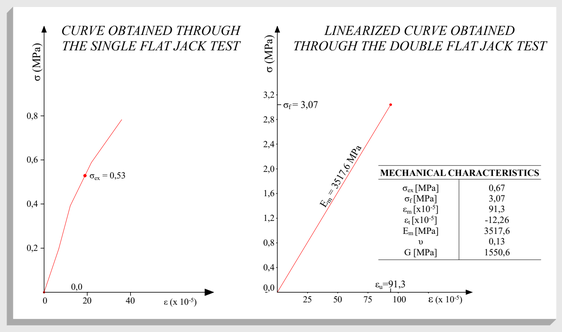

ELEMENTS OF DIFFERENT NATURE (COLUMN 4 - WEST FRONT)

SONIC TEST CARRIED OUT ON THE COLUMN 1 - EAST FRONT

COLUMN 1 - EAST FRONT		
MEASUREMENT DIRECTION NORTH-SOUTH		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	320	1750
2-2'	740	756
3-3'	270	2074
4-4'	220	2545
5$_1$-5$_1$'	420	1383
5$_2$-5$_2$'	---	---
6$_1$-6$_1$'	500	1120
6$_2$-6$_2$'	394	1420
7$_1$-7$_1$'	720	777
7$_2$-7$_2$'	---	---
8$_1$-8$_1$'	900	565
8$_2$-8$_2$'	880	636
MEASUREMENT DIRECTION EAST-WEST		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	370	1513
2-2'	470	1190
3-3'	1076	520
4-4'	554	1010
5-5'	360	1555
6-6'	470	1191
7-7'	200	2800
8-8'	280	2000



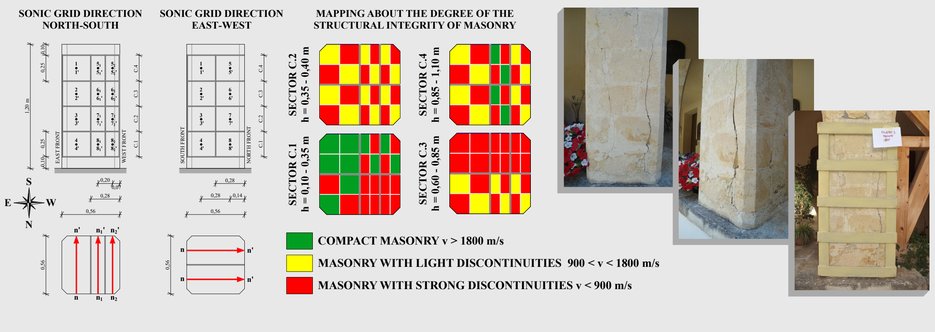
MECHANICAL CHARACTERIZATION OF THE MASONRY OF THE COLUMNS



The masonry of the arches was realized by means of calcarenitic stone characterized by an high porosity and alteration. Single and double flat jacks tests were carried out on a column of the east side of cloister. At first, the measurement of the exercise stress σ_{ex} was performed through the single flat jack test. Subsequently, on the same column the test with double flat jack was performed in order to evaluate the mechanical characteristics of the masonry: first crack tension σ_f, identified as the characteristic value of the compressive strength of masonry f_k; longitudinal and transverse strains ε_m and ε_t; longitudinal elastic modulus E_m; Poisson modulus υ; shear modulus G.

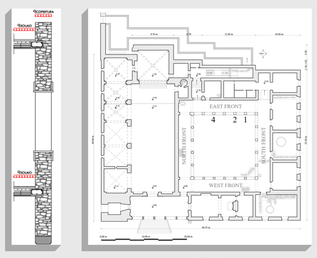
SONIC TEST CARRIED OUT ON THE COLUMN 2 - EAST FRONT

COLUMN 2 - EAST FRONT		
MEASUREMENT DIRECTION NORTH-SOUTH		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	440	1272
2-2'	640	875
3-3'	622	900
4-4'	270	2074
5$_1$-5$_1$'	240	2333
5$_2$-5$_2$'	520	1076
6$_1$-6$_1$'	770	727
6$_2$-6$_2$'	830	674
7$_1$-7$_1$'	---	---
7$_2$-7$_2$'	---	---
8$_1$-8$_1$'	700	800
8$_2$-8$_2$'	---	---
MEASUREMENT DIRECTION EAST-WEST		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	1080	518
2-2'	640	875
3-3'	520	1076
4-4'	230	2434
5-5'	800	700
6-6'	350	1600
7-7'	420	1333
8-8'	840	666

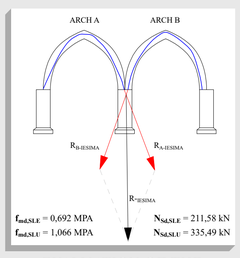


COMPRESSION CHECK CARRIED OUT ON THE COLUMNS

On the arches of the cloister affected by overloading were performed in-depth static analysis. At first the lines of pressure on the Gothic arches of the cloister have been built and the safety checks have been carried out in according to the Safe Theorem of Heyman. Subsequently, the resultants of the loads acting have been evaluated and the compression tests have been executed on the resistant sections of the masonry elements. The results of these checks have been analytically shown the instability for overloading in act, already observed. At the end, sonic tests have been performed in order to study the internal diffusion of the instability. The aim of these tests has been to realize a mapping about the structural integrity of the masonry bodies investigated. Three pillars of the east front of the cloister have been tested by means of sonic tests.



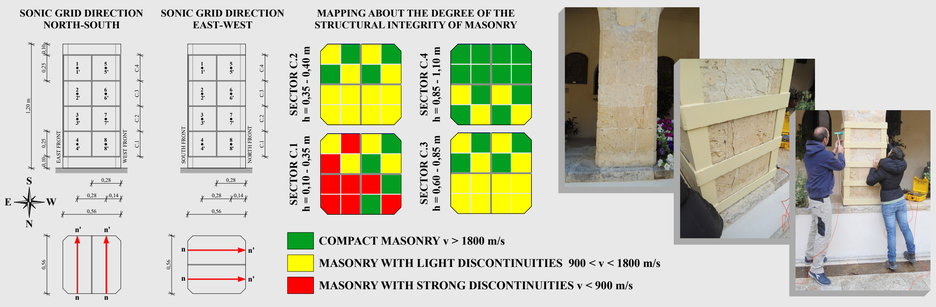
SUPERSTRUCTURE OF ARCHES; GROUND FLOOR OF THE COMPLEX



EVALUATION OF THE RESULTANT OF LOADS

SONIC TEST CARRIED OUT ON THE COLUMN 3 - EAST FRONT

COLUMN 3 - EAST FRONT		
MEASUREMENT DIRECTION NORTH-SOUTH		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	265	2113
2-2'	610	918
3-3'	519	1077
4-4'	1170	478
5-5'	280	2000
6-6'	535	1046
7-7'	354	1580
8-8'	253	2213
MEASUREMENT DIRECTION EAST-WEST		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	200	2800
2-2'	230	2434
3-3'	210	2666
4-4'	560	1000
5-5'	320	1750
6-6'	330	1696
7-7'	570	982
8-8'	660	848



THE CHOIR OF THE CHURCH OF SAINT BIAGIO IN AMANTEA (XVII CENTURY): DIFFERENT LENGTH OF THE CRACKS BETWEEN EXTERNAL SURFACE AND THE INSIDE OF THE MASONRY BODY

The church of San Biagio in Amantea was built during the seventeenth century and currently it doesn't show a good degree of conservation. The architecture is characterized by a series of damages, diffuse and extensive, which suggest structural mechanisms in act. The instabilty condition of the entire masonry structure totally compromises the functionality of the choir of church which along the south front is structurally connected to the principal facade, while on the northern front it rests on two columns in turn supported by two bases of parallelepiped shape. One of the two support columns and its base are interested by a crossing wide crack that develops starting from the base and goes back along the cylindrical body of the bearing masonry element. This dangerous crack has compromised the structural functionality of the system base-column, inviting the execution of appropriate interventions of temporary shoring for the choir. By means of sonic tests it was verified how the length of the external crack, measurable on the surface of the masonry element, is lower than the length characterizing the masonry of the column internally (there is not an exact correspondence between the two lengths, external and internal ones). This difference was verified through the sonic test carried out on the system base-column and defining a "sonic strip" with which to highlight the degree of integrity of the masonry.

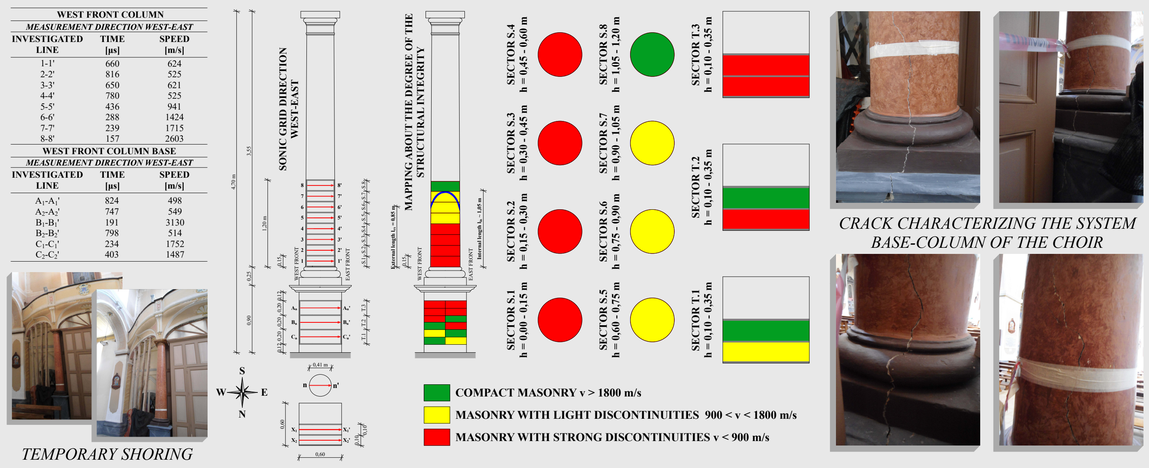

CHURCH OF S. BIAGIO


DAMAGED SYSTEM BASE-COLUMN


CHOIR OF THE CHURCH


SHORING OF THE CENTRAL PART

WEST FRONT COLUMN		
MEASUREMENT DIRECTION WEST-EAST		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
1-1'	660	624
2-2'	816	525
3-3'	650	621
4-4'	780	525
5-5'	436	941
6-6'	288	1424
7-7'	239	1715
8-8'	157	2603
WEST FRONT COLUMN BASE		
MEASUREMENT DIRECTION WEST-EAST		
INVESTIGATED LINE	TIME [µs]	SPEED [m/s]
A$_1$-A$_1$'	824	498
A$_2$-A$_2$'	747	549
B$_1$-B$_1$'	191	3130
B$_2$-B$_2$'	798	514
C$_1$-C$_1$'	234	1752
C$_2$-C$_2$'	403	1487



CRACK CHARACTERIZING THE SYSTEM BASE-COLUMN OF THE CHOIR

TEMPORARY SHORING

CONCLUSION

As it was demonstrated through the sonic tests carried out, the results obtained about the characteristics of the masonry aren't exact, but through this type of test it's possible to determinate qualitative information which, if correctly interpreted, suggest the conservation state of the masonry with some precision. It has been demonstrated how, doing instrumental measurements in relationship to an appropriate sonic grid, or line, identified on the outer surfaces (by performing a careful prediagnosis phase), it's possible to build realistic mappings about the degrees of structural integrity about the masonry elements investigated. The resulting mappings will be more accurate if the discretization of the masonry volume will be more dense, therefore how much more small will be the elementary meshes that make up the sonic grid, or line, adopted.
The information so obtained about the conservation state of the mansory could be used to define, in a optimal manner, intervations of structural consolidation, necessary to allow an improvement of the static functionality of the architecture.

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