Le Vie dei Mercanti
XIV International Forum
WORLD HERITAGE AND DEGRADATION
Smart Design, Planning and Technologies
Aversa | Naples 16 - Capri 17, 18 June 2016

# Static and numerical analysis of the ancient portal of the church of the “Riforma” in Bisignano (CS).

**Renato S. OLIVITO,[1] Rosamaria CODISPOTI[2] , Carmelo SURO[3] , Cinzia ANGOTTI[4]**
(1) Department of Civil Engineering, Full Professor UNICAL, Rende (CS), ITALY, renato.olivito@unical.it
(2) PhD, UNICAL, rosamaria.codispoti@unical.it
(3) PhD Student, UNICAL, carmelo.scuro@unical.it
(4) Engineering, certified technician of “NGT-test prove in sito diagnostica e monitoraggio”, Catanzaro, ngt.testcz@gmail.com

**Abstract**
The cultural heritage is of public interest and constitutes the wealth of a place and its people. In Italy often this public good is made from the remains of the glorious civilizations present in the past in our country, an example is Rome or the archaeological excavations of Pompeii, or isolated testimonies of masonry structures remained intact after an earthquake. These ruins are stacked in rigid blocks or mixed masonry in which the original state of the elements is often compromised by crack patterns and degradation of materials. Interventions aimed made in the past to pay full regard to the aesthetics which made these structures incompatible with the concept of security and the needs of fruition.
This work deals the study and the geometric survey of the portal of the first Franciscan complex of "Riforma", the only ruin remained intact after the earthquake that destroyed the original structure. The goal of this study will be to create a numerical model to be subjected to loads acting in the plane and out of plane, to identify weaknesses and the trend of stresses generated within the structure in order to locate possible deformations and critical areas on which to intervene.

**Keywords:** Masonry structure, Static analysis, Cultural Heritage, Numerical analysis

## 1. Church history

From the earliest times in every part of Calabria, the monasteries were the center of culture and art. St. Francis of Assisi in 1217 formed the nine provinces of the religious order, including Calabria. at that time many monasteries were built, among them was that of Bisigano, example of remarkable architecture, located outside the walls of the city on a hillside overlooking the valley of the river Crati.
It was built in the early part of the thirteenth century on existing ruins. In 1225 the monastery was headed by the guardian monk St. Nicholas from Corigliano and in it were housed A. Tancredi and Leone da Somma from Corigliano and Ugolino from Cerisano. They were unlucky and they died martyred in Ceuta in Morocco in 1227 with St. Daniel Fasanella. In 1380 the monastery was administered by the "Friars Minor Conventual", in 1445 it passed to the "Friars Minor Observant" and in 1559 to the "lesser brothers reformed", they derived the name "convent of Riforma” [1].
A group of Franciscans architects and builders, led by Blessed Peter Cathin of Sant'Andrea della Marca one of the first followers of St. Francis, they began construction on an unspecified date. In 1222 they finished the monastery and the church dedicated to the “stigmata of St. Francis”.[2]
Among the important people who lived in the convent we remember Humilis of Bisignano. It was a 17th-century Franciscan friar who was widely known in his day as a mystic and wonderworker. He has been declared a saint by the Catholic Church [3]. About the age of 18, Luca Antonio Pirozzo felt called to enter a religius order, but, for various reasons, did not do so until 1609. In that year, aged 27, he felt called to enter the Reformed Friars Minor, a branch of the Order following a more severe way of life, who had a community at the medieval Convento di Riforma (Friary of the Reform) in his city. He was admitted that same year as a lay brother into the novitate of those friars which was located

at Mesoraca in the Province of Crotone, at which time he received the religious habit and was given the name by which he is known. After overcoming various difficulties arising during that year of probation, he was allowed to profess religious vows as a full member of the Order on 4 September 1610.[4]

**1.2 Church and convent architecture**

The church and the convent of the "Riforma" are compact structures with strong symbolic particularity. The statues inside, the windows, the portal and the spaces follow a strict geometric sequence. Sideways develops the church with the bell tower, and the three remaining sides develop the cells and rooms of the convent. the convent has not undergone significant changes during the two centuries after the year 1830 to visit Andrea Pierbenedetto Bishop of Venosa. He wrote a report which says that "the church does not need to work" and that "there was a porch in front." This suggests that there was a porch that was heavily damaged in the earthquake 1638. The porch was walled, evidence of this is the design of Pacichelli where the church is represented with a facade composed of two staggered levels.

*(a)* *(b)*

**Figure 1:** a) Church of the “Riforma” b) Facade of the church.

The fifteenth-century structure are preserved Gothic traces, identifiable in the vertical development of the façade. The plaster on the walls is yellow and mortar are visible the ancient stone walls. No trace remains of the fifteenth-century bell tower, it was joined in the Pacichelli design the facade of the church. On the occasion of the tercentenary of the death of S. Humilis the bell tower was rebuilt in brick and cement near the sacristy. The church façade is characterized by axial symmetry where stands the dating portal year 1380. It is in stone with decorations "rodiane" dating back to the fifteenth century, measuring 6 meters x 3.2 meters and has a form to ongee arch resting on capitals decorated with leaves. The church inside presents two types of flooring, the aisles have a type in marble while the presbytery has an example made of brick.

The church has a rectangular plan that widens at the presbytery. It measures 23,75 meters from the entrance to the central arch. The width is 13,18 meters occupied by the central aisle to 8,18 meters, while the aisle occupies 5,00 meters including the four columns in the Gothic style.

Adjacent to the church, from the west side you enter through a wooden door in the convent, typical example of Franciscan architecture. From the entrance you immediately reach the cloister which has typological and stylistic characteristics attributed to interventions fifteenth of Friars Minor Observant. Cloister in the years he was subjected to many changes and damages caused by the earthquake, the thirteenth-century structure remains only one side to witness the ancient splendor. It is Gothic with a square base composed of lancet arches, the sides are 12 meters and 24 arches resting on stone pillars, only eight pillars date back to the thirteenth century. In 1969 the friar Pio Spadafora started restoration by the arches and pilasters, entrusting the construction of the missing elements to famous stonemasons of the area. the central well and a cistern for collecting water have been closed and the whole area was paved with brick and stone. Around the four sides of the cloister various environments develop: on the west side the staircase leads upstairs where are the monks' cells and the big fireplace, in the north are located the library and archives, to the east there are the kitchen and the refectory, and finally to the south it is located the central hall [2].

(a) (b)

**Figure 2:** a) Cloister during restructuring b) Cloister today

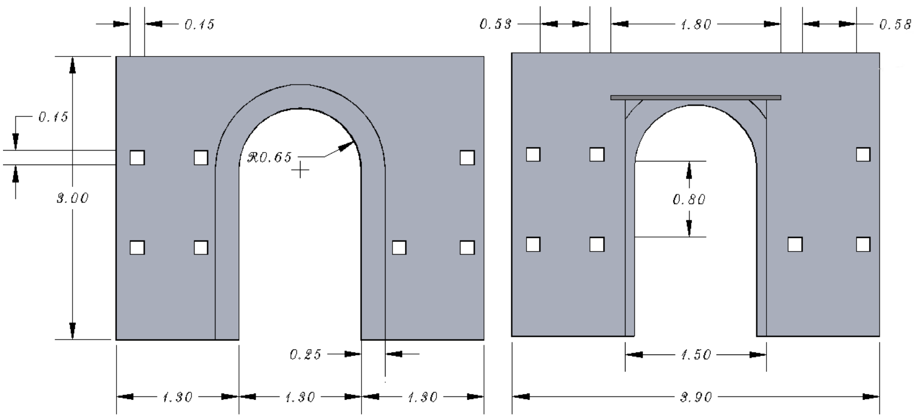
## 2. Case Study

The case study of this work is a portal isolated laterally placed in the parvis of the big Riforma's Square (fig. 3). That element, probably is a porch of ancient ruins destroyed by the earthquake of 1638. The earthquake was one of the strongest that hit the area, causing throughout the Calabria region more than 15000 deaths and destroying other 100 villages. The National Institute of Geophysics, has drawn up a document which attests that this earthquake has had a Mercalli intensity scale in the territory of Bisignano of 9, equivalent to a magnitude 8 [5].

(a) (b)

**Figure 3:** a) Frontal view b) View from behind

The structure is composed of two materials, clay bricks and mixed masonry; it is not symmetrical: a façade has a typical arched portal (fig. 4.a), while on the opposite side there is the presence of an architrave (fig. 4.b). The case study is characterized by the presence of seven holes, four placed on the left side and three on the right side, which extend for the entire depth of the wall and where once, the constructors located the scaffoldings.

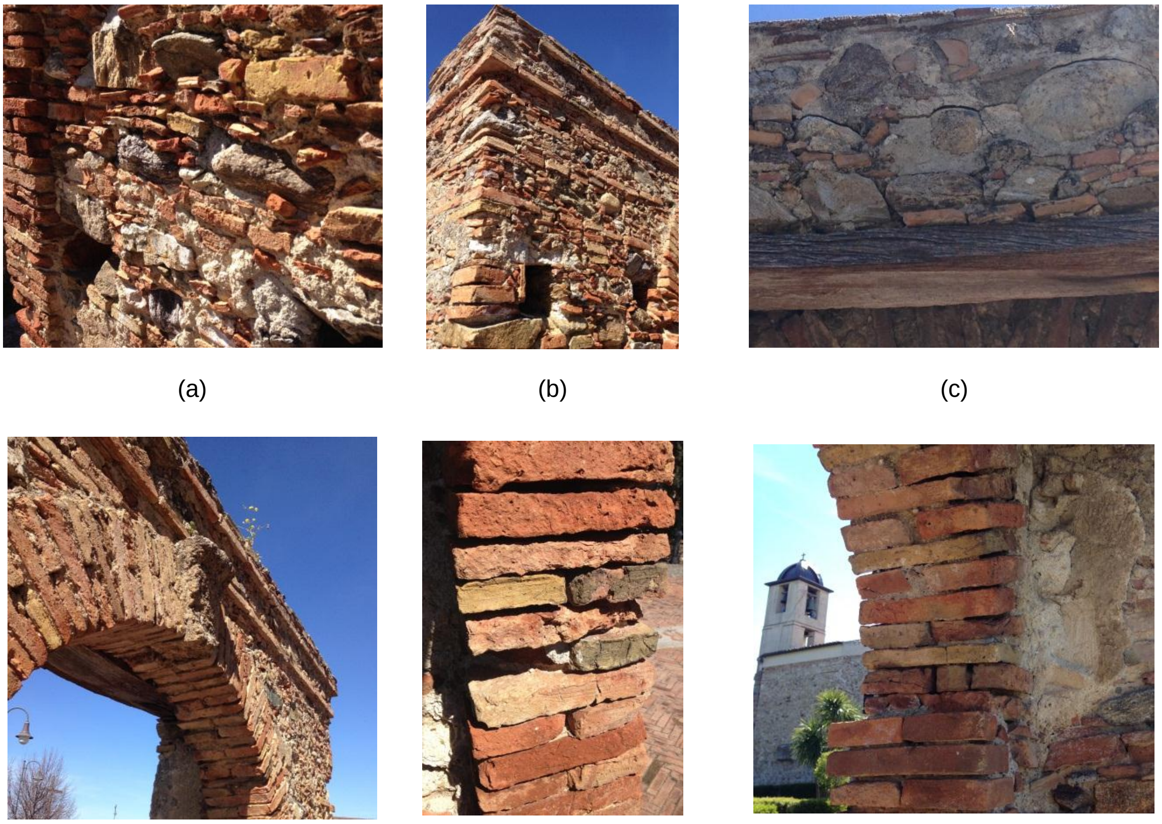



(a) (b)

**Figure 4:** Geometric survey in meters

## 3. Non-Destructive tests

Ultrasonic tests on the case study were carried out, in order to analyze the structural condition of the masonry portal. The ultrasonic tests are a non destructive tests, at the beginning of the fifties, the technician only knew radiography tests, as a method for detection of internal flaws in addition to the methods for nondestructive testing of material surfaces. After the Second World War the ultrasonic method was further developed so that very soon instruments were available for ultrasonic testing of materials. The ultrasonic principle is based on the fact that solid materials are good conductors of sound waves. Whereby the waves are not only reflected at the interfaces but also by internal flaws (material separations, inclusions etc.). The interaction effect of sound waves with the material is stronger if the wave length is smaller, this means the frequency of the wave is higher. The equation that regulate this type of test is based on wave length, that is equal to the ratio between sound velocity and frequency. [6].
This means that ultrasonic waves must be used in a frequency range between about 0.5 MHz and 25 MHz and that the resulting wave length is misured like a length (in mm). With lower frequencies, the interaction effect of the waves with internal flaws would be so small that detection becomes questionable. Both test methods, radiography and ultrasonic testing, are the most frequently used methods of testing different test pieces for internal flaws; This means that today many volume tests are possible with the more economical method, also because the element under investigated are conserved; on the other hand of particular test that many problems solve.
In this specific case, two types of materials that compose element were investigated. The first material is present in the majority of the portal because it composed largely of the structure. It is a mixed masonry composed of very irregular stones and bricks; the mortar used is made of sand and hydraulic lime (fig. 5.a.b.c). The second material studied, is a masonry built with clay bricks and mortar, they are present in the arch and the piers of the main façade (fig. 5.d.e.f).



(a) (b) (c)

(d) (e) (f)

**Figure 5:** a) b) c) particulars of mixed masonry c) d) f) particulars of masonry bricks

After a first inspection, it was possible to notice, that the surfaces of both materials were irregular and the mortar crumbled after a not very powerful impact. The surfaces discontinuities of the portal, are characterized by cracks running vertically; the presence of vertical cracks frequently give many problems during the experimental tests. In this case, during the ultrasonic tests the wave have

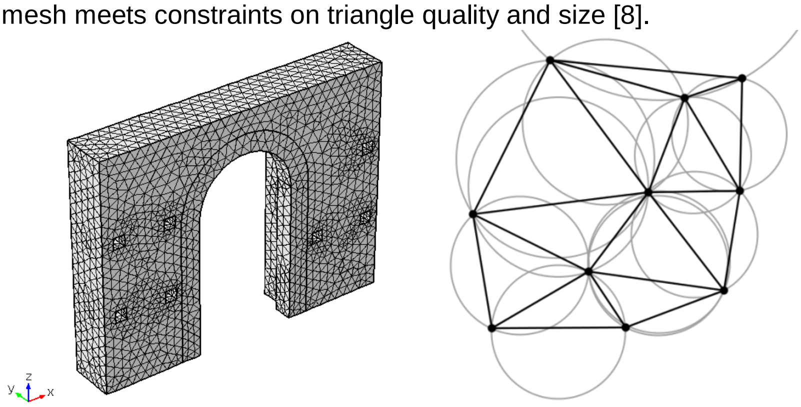
occurred in a overlapped way, due to the presence of interferences and cracks, consequently the sound wave reflection, on the side wall of the portal, seems as if the sound wave would bend with the respect to the corresponding side wall (fig. 6.a). In such cases, the probability of crack detection is very good if the angle reflection effect is used, Fig. 6b. At the 90° edge, between the crack and the surface of the test object, the sound waves are reflected back, this leads to double reflection. Use of the angle reflection effect is often useful when there are discontinuity due to the empty inside of the masonry. Often the tests carried out on thick-walled where there is the presence of vertical discontinuities, this condition cannot be fulfilled because the reflected sound waves on the discontinuity do not return to the probe. In this case, a second probe is used for receiving the reflected portions of sound, thus enabling detection of the discontinuity.
The results obtained are the following: the wall built with mixed masonry has a wave propagation speed equal to 1350 m/s while the propagation time is 481 microseconds. The masonry arch has values equal to 2500 m/s, for the velocity, and 100 μs for the time , Fig. 6c. These results highlight the state of the two materials. The propagation speed of ultrasonic waves in the mixed masonry is low, and this means that the masonry is characterized by lesions, the arch built with clay bricks masonry has a high speed so it is not damaged.


*(a)* *(b)* *(c)*

**Figure 6:** a)placement sensors b)test execution c)ultrasound specter

## 4. Numerical model

The creation of a numerical model requires identification of three important parameters: the mechanical strengths of the materials, the type of mesh and the yield criterion to be used in the analysis to predict cracks in the model.
The mesh used is triangular tetrahedral (fig. 7.a), it has many applications, including interpolation, rendering, and numerical methods such as the finite element method. Most such applications demand more than just a triangulation of the object or domain being rendered or simulated. To ensure accurate results, the triangles and tetrahedral must be “well shaped”, having small aspect ratios or bounds on their smallest and largest angles. Mesh generation algorithms based on Delaunay refinement, are effective both in theory and in practice. Delaunay refinement algorithms operate by maintaining a Delaunay or constrained Delaunay triangulation (fig. 7.b), which is refined by inserting carefully placed vertices until the mesh meets constraints on triangle quality and size [8].



*(a)* *(b)*

**Figure 7:** a) Numerical model with mesh; b) Delaunay triangulation

The yield criterion used is that Willam-Warnke, it is used to predict failure in concrete and other cohesive-frictional materials such as rock, soil and ceramic. Just as the Bresler-Pister criterion, it depends only on three parameter. It was developed to describe initial concrete failure under triaxial condition. The failure surface is convex, continuously differentiable, and is fitted to test data in the low compression range. The material is considered perfect elastoplastic (no hardening). The original Three Parameter Willan-Warnke failure criterion was defined as:

$$F_y = \sqrt{\frac{3}{5}} \cdot \frac{\tau_{oct}}{f_c} + r(\theta)\left(\left(\frac{1}{f_t} - \frac{1}{f_b}\right)\sigma_{oct} - 1\right) = 0$$

Where $f_c$ is the uniaxial compressive strength, $f_t$ is uniaxial tensile strength and $f_b$ is obtained from the biaxial compressive test. All parameters are positive. The octahedral normal and shear stresses are defined as usual:

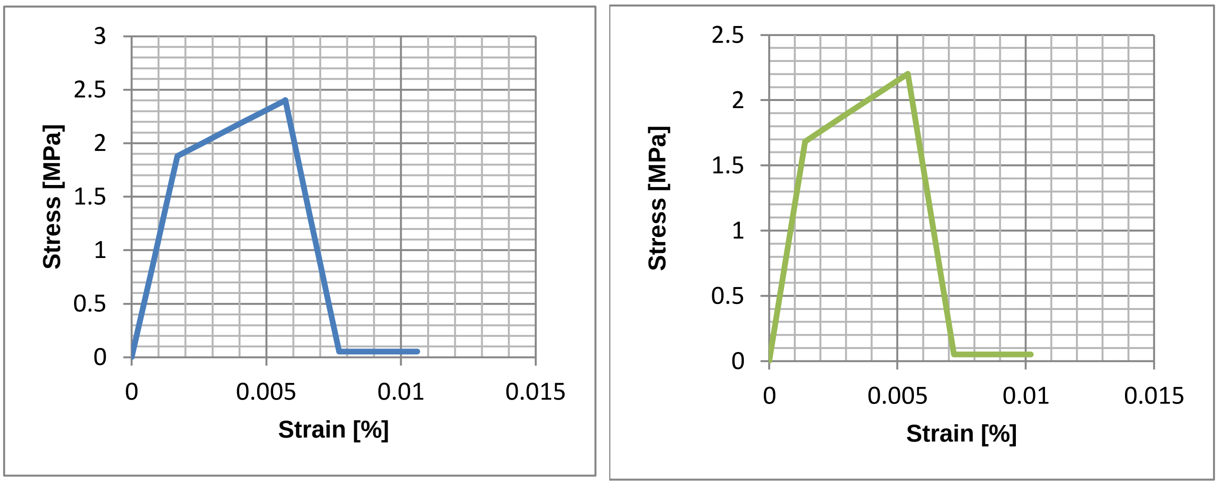
$$\sigma_{oct} = \frac{I_1}{3} \qquad \tau_{oct} = \sqrt{\frac{2 \cdot J_2}{3}}$$

Where $I_1$ is the first invariant of the Cauchy stress tensor, and $J_2$ $J_3$ are the second and third invariants of the deviatoric part of the Cauchy stress tensor. [9]
The last step to the creation of the model is the identification of a law Strain stress of materials. The structure is composed of two different types of masonry: mixed masonry and bricks masonry. Through experimental tests in the literature the constitute laws (fig. 8.a.b) were considered [10] and implemented in the calculation program. The mechanical properties of the materials used are listed in the following table 1.

| | E [MPa] | v | ρ [Kg/m$^3$] | $f_c$ [MPa] | $f_t$ [MPa] | $f_b$ [MPa] |
|---|---|---|---|---|---|---|
| Mixed masonry | 2200 | 0.15 | 1800 | 2.20 | 0.36 | 3.30 |
| Brick masonry | 2400 | 0.15 | 1800 | 2.40 | 0.40 | 3.60 |
| Wood | 800 | 0.40 | 500 | | | |

**Tab. 1:** Characteristic values of the materials [11][12]

The analysis was carried out taking into consideration in addition to the materials listed above also the wooden lintel present in the back part of the structure. The wood, a material with more elastic behavior than the masonry was analyzed without imposing strengths characteristics, in order to lighten the analysis because the fractures will occur of a rigid material such as masonry.

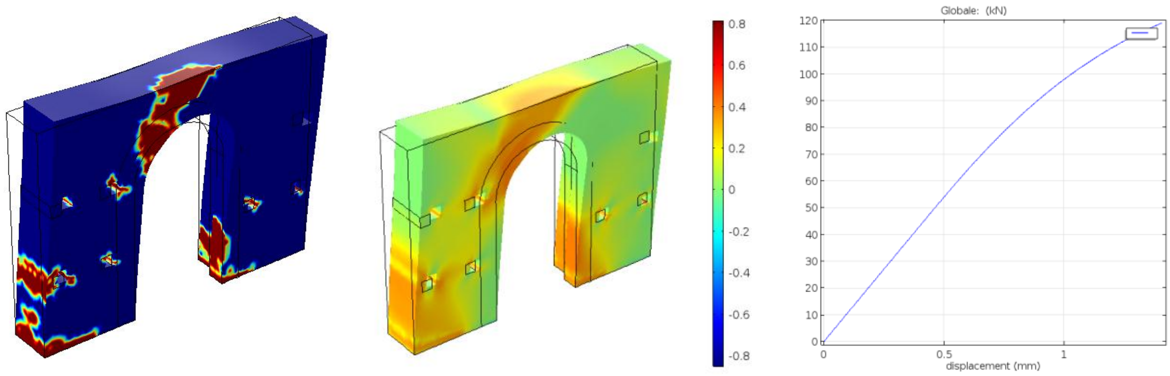



*(a)* *(b)*

**Figure 8:** a) Compressions strength bricks masonry b) Compressions strength mixed masonry

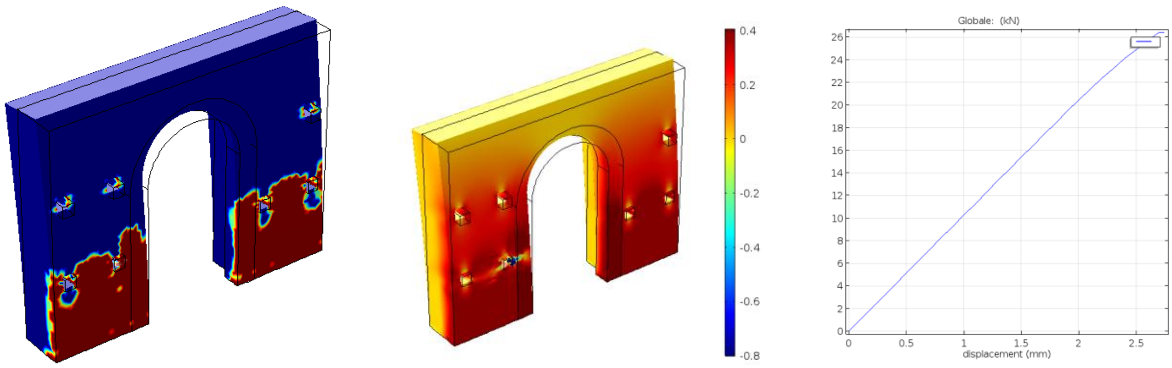
## 5. Results and conclusions

The results obtained from the numerical analysis, different behavior have been observed by imposing a displacement control about the principal directions. Two different models have been created: the first that completely real to the state of art , the second equal to the first but without the holes intended for scaffolding; for both the models have been carried out the same analysis in order to study the influence of the holes under out-plane force and to identify weaknesses and the trend of stresses generated within the structure in order to locate possible deformations and critical areas on which to intervene. In the following figures are reported for each model the maximum displacement in both direction (x-y positive and negative) and the force-displacement diagrams.



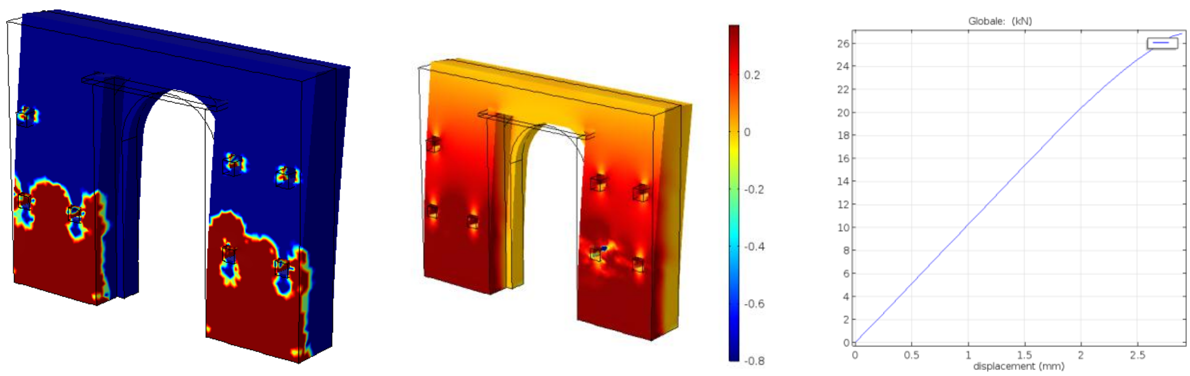

*(a)* *(b)* *(c)*

**Figure 9:** Model with holes displacement along x: a)after elastic zone; b)stress maps; c) force displacement diagram



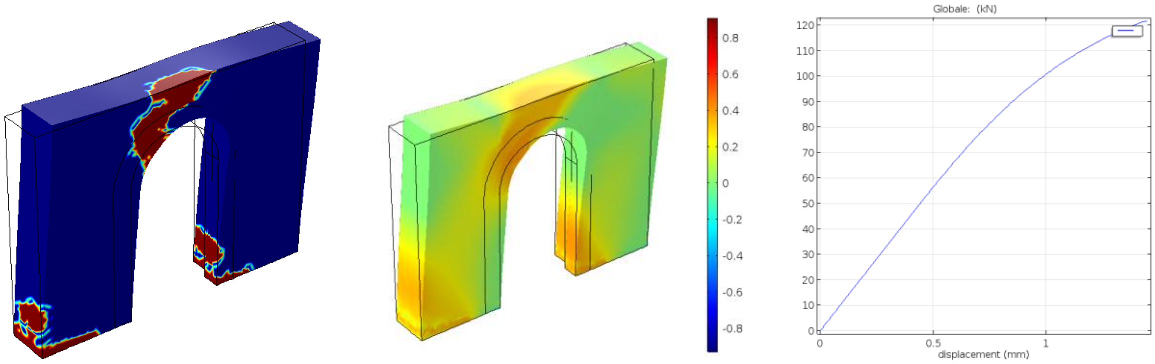

*(a)* *(b)* *(c)*

**Figure 10:** Model with holes displacement along y: a)after elastic zone; b)stress maps; c) force displacement diagram



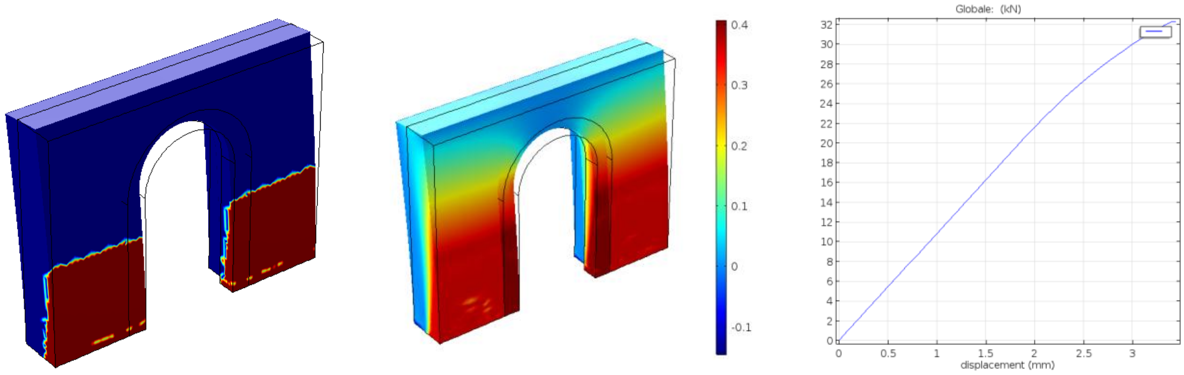

*(a)* *(b)* *(c)*

**Figure 11:** Model with holes displacement along -y: a)after elastic zone; b)stress maps; c) force displacement diagram



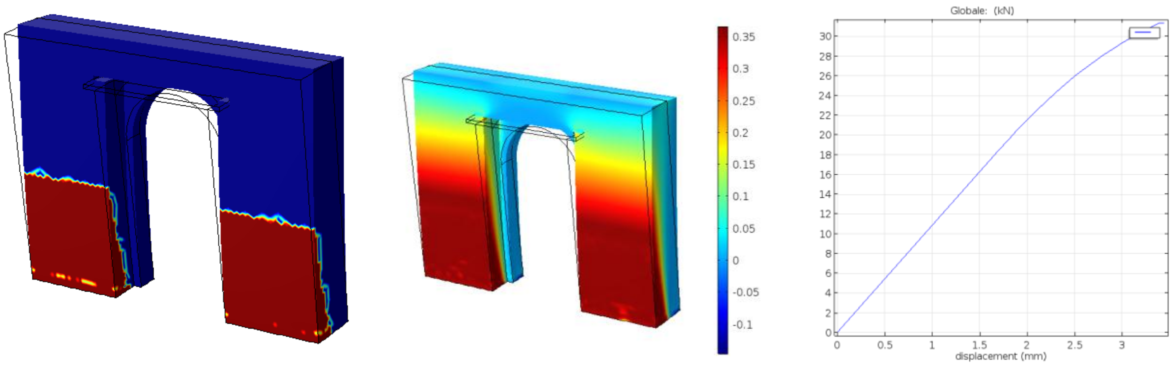

(a) (b) (c)

**Figure 12:** Model without holes displacement along x: a)after elastic zone; b)stress maps; c) force displacement diagram




(a) (b) (c)

**Figure 13:** Model without holes displacement along y: a)after elastic zone; b)stress maps; c) force displacement diagram




(a) (b) (c)

**Figure 14:** Model without holes displacement along -y: a)after elastic zone; b)stress maps; c) force displacement diagram

Taking into account the technical standards [13] regarding the failure mechanisms out of the plane of masonry structures [14], it was possible to see that the results obtained on the portal without the holes due to the scaffolding, guarantee minor displacements corresponding to lower forces out the plane, rather than portal as a state of fact that instead reaches greater displacement values with corresponding maximum forces. Moreover in the case of the presence of the holes the cracks are concentrated precisely in proximity of the same holes, while in the case of the portal without holes the cracks grow from the bottom part of the portal until the plasticization of the entire section.

## Bibliographical References


[1] D'ALESSANDRO, Rosario. *L'epoca del Beato Umile da Bisignano (1582-1637).*Pellegrini, Cosenza 1988. nota 1,p. 18.

[2] GUIDO, Angela, *Misure e credenza religiosa,* Città Calabria Edizioni, Soveria Mannelli 2006.

[3] *Omelia di Giovanni Paolo II, Cappella papale per la canonizzazione di 5 beati.* Solennità di Pentecoste, Domenica 19 Maggio 2002. Libreria Editrice Vaticana.

[4]Web:http://www.vatican.va/news_services/liturgy/2002/documents/ns_lit_doc_20020519_umile_en.html

[5] BOSCHI, Enzo et al. *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990.* Roma: Istituto nazionale di Geofisica e Bologna SGA, 1997, ISBN 88-85213-08-1

[6] http://www.ndt.net

[7] 01/01/2005 In vigore CLASSIFICAZIONE ICS UNI EN 12504-4:2005 NRIF AA021497 91.100.30, UNICEMENTO

[8] SHEWCHUK, Richard, Tetrahedral Mesh Generation by Delaunay Refinement, Jonathan School of Computer Science Carnegie Mellon University Pittsburgh, Pennsylvania 15213.

[9] WILLAM, K. J.,WARNKE, E.P.,1974 ,Constitutive Model for the Triaxial Behavior of Concrete, ABSE Reports of the Working Commissions, Colloquium (Bergamo): Concrete Structures Subjected to Triaxial Stresses, vol. 19.

[10]MINGHINI, Fabio, BERTOLESI, Elisa, DEL GROSSO, Antonio, MILANI, Gabriele, TRALLI Antonio, Modal pushover and response history analyses of a masonry chimney before and after shortening, Elsevier, Available online 29 December 2015.

[11] CNR-DT 206-2007, Istruzioni per la Progettazione, l'Esecuzione ed il Controllo delle Strutture di Legno, ROMA – CNR 28 novembre 2007 – rev. 7 ottobre 2008. p.92

[12] Circolare 617/09 Istruzioni per l'applicazione delle Norme Tecniche, relativa al DM 14-01-08 Norme tecniche per le costruzioni. p.389

[13] DOLCE, Mauro, MANFREDI, Gaetano, Linee guida per riparazione e rafforzamento di elementi strutturali, tamponature e partizioni, Doppiavoce Editore,2011-12, 2012-5,ISBN 978-88-89972-29-8

[14] RONDELET, G., 1833, Trattato teorico e pratico dell'arte di edificare, Basilio Soresina, Livorno.