Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Static History and Structural Assessment of Masonry Domes: The Treasure of St. Gennaro's Chapel in Naples

V. Russo
University of Naples, Department of History of Architecture and Restoration, Naples, Italy

G.P. Lignola and E. Cosenza
University of Naples, Department of Analysis and Structural Design, Naples, Italy

G. Tucci
University of Florence, Department of Architectural Planning, Florence, Italy

ABSTRACT: The paper focuses the attention on an interdisciplinary research programme concerning the preservation of the double calotte dome of the Treasure of St. Gennaro's Chapel in the cathedral of Naples. Recurring to the correlation of archival and iconographical documentation with a precision survey and numerical analysis (3D F.E.M. analysis based on a continuum masonry elastic material), the contribution aims to demonstrate a methodological and interdisciplinary experience which, making use of a deep informative base, puts in evidence structural 'weak points' and problematic nodes for the conservation of the monument.

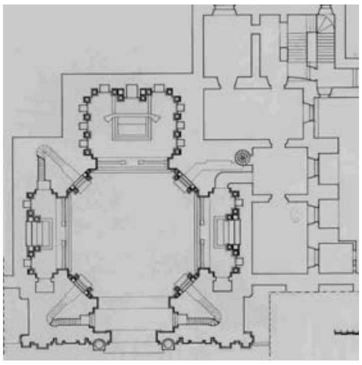
1 AN INTERDISCIPLINARY APPROACH

1.1 «Ars sine scientia nihil est»? The example of a four centuries'old dome

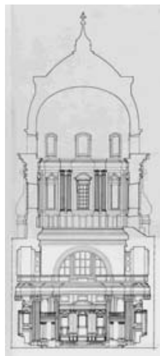
Avoiding preclusive attitudes regarding "intuitive" or, on the contrary, uncritically "quantitative" interpretations, the study concerning the Treasure of St. Gennaro Chapel's dome (Fig. 1) has been carried out with a strongly interdisciplinary approach in order to correlate the diacronic history of the monument with the structural behaviour undertaken by itself during past centuries. The complex variability of factors that have been involved in the structural analysis of the dome has not allowed rapid schematizations but it has demanded a punctual and deep analysis of the baroque dome: this also in order to reduce, in the future, any operation, however dangerous, on the ancient structure and in order to direct towards strengthening solutions which have to be compatible with the monument for materials and techniques. The still existing historical documentation, relative to the building site and to multiple, successive consolidation and restoration programmes, has supplied extremely detailed information about the static history of the building: a history of settlements, crackings and proposals regarding the structural and covering elements. It has been possible to construct an articulated database developed during four centuries which has represented an indispensable instrument for the analysis of the dome's present structural conditions. The knowledge of historical strengthening and repairing interventions and, moreover, an accurate knowledge of its geometry obtained by using a terrestrial laser scanning system, have constituted the first steps towards the evaluation of stresses and deformation states of the masonry. The extreme "variability" of ancient materials, whose evolution towards more sensitive and vulnerable progressive stages is well-known, has directed the research group to a "relative" approach rather than to "conclusive" interpretations of structural characteristics of the building. Taking into account that the dome, as explained later, has undertaken during time an architectural configuration extremely different from the initially designed one, the study has turned to distinct interpretative models; particularly, subsequent and significant strengthening interventions have been taken into account which, in some cases, have been only planned while, in other cases, have been effectively carried out with methods recorded in archival documents, too. The "variability" of parameters to consider has appeared very large, indeed; the decay of materials, measurable only by laboratory tests, matches with many imponderable factors dued to constructive “defects” of the dome; among these ones, no model can take properly into account realization irregularities (i.e. mortars thickness and inclination), elements’ toothings and intrinsic characteristics of materials, so different in relation to internal composition or to stones’ cutting and building directions. Moreover, residual weaknesses that the structure has accumulated after the frequent earthquakes of neapolitan area are all measurable in a difficult way.

All these remarks have addressed the research group towards an interpretation of the structural behaviour of the dome subdivided into sequential analysis corresponding to subsequent historical construction and repairing stages. The available archival documents, joined up with a constant *in situ* reading and precision surveying of the building, have enabled to identify progressive configurations resulting from unrealized plans of the eighteenth century. The investigation of these latter’s motivations and the evaluation of the impact that the same plans should have had on the structure if realized have enabled to understand the dome’s conditions in specific moments of its life; moreover, they have helped to understand which structural problems were put in evidence by historical “intuitive-empirical” interpretations of the complex baroque monuments. In addition, the available drawings concerning cracking patterns, made during 18th century, have provided the dome’s analysis with relevant modelling informative data regarding its diacronic cracking state. Compared stress readings allow to critically evaluate, today, the effectiveness of past centuries’ strengthenings and, similarly, the efficacy of planned but unrealized interventions. Such a compared analysis aims to give, of course, some indications – resulting from quali-quantitative interpretations – rather than “conclusive” solutions for the present conservation of the dome.

1



2(a)



2(b)

Figure 1 : Naples, The Treasure of St. Gennaro’s Chapel. South-east external side.
Figures 2(a,b) : Naples, The Treasure of St. Gennaro’s Chapel. Plan and cross section (Savarese 1986).

2 THE DOME’S CONSTRUCTION AND ITS HISTORICAL STREGHTENINGS

2.1 The seventeenth century plan and building site: materials and techniques

The Treasure of St. Gennaro’s dome, erected between 1608 and 1618, is composed of two groined masonry vaults with an internal diameter of about 14 metres. The instrumental survey has put in evidence an accentuated pointed curve of the calottoes, which was not noticeable in just published sections (Fig. 2b). The structure is comparable, so, with a long and narrow solid whose total height from ground is about 60 metres; it unloads its weight on four tuff masonry pillars connected by rounded arches (Fig. 4). The external masonries of the Chapel, inscribable into a square, are made of tuff, too, and externally covered by bricks. The dome continues this association of materials in its structure: it is constituted of a yellow tuff windowed drum with a brick courtain, internally regularly marked by Corinthian pilasters and, externally, by piperno and Sorrento’s grey tuff volutes (Fig. 3a). This latter material has been diffusely adopted in the baroque dome, perhaps because of its easy workability: decorative elements characterized by minute carvings, as modillons and masks aligned along the external perimeter, are constituted, in fact, of grey tuff. Instead, *piperno* – volcanic material widely used in the neapolitan ancient building site – is used in more stressed parts of the dome, as volutes, cornices and in the spiral staircase arranged in the drum's masonry (Fig. 5a). Eight rectangular windows, surrounded by grey tuff cornices and standing above the vaults, are placed around the "attic" (Fig. 3b); both the calottoes are connotated by a progressive reduction of their thickness which, as surveys have demonstrated, is about 70 centimeters near the upper part of the vaults. Finally, the upper vault's external surface is covered by compacted pumice stone and lead sheets. Perhaps during construction, the internal vault was connected to the external one by eight internal buttresses standing in correspondence of groins; a double circle of pillars, joined by a barrel vault, made up a lantern placed between the two vaults and unloading on a brick "oculus" (circle window), afterwards closed. The keystones of the groined vaults were distant, so, about 3.70 metres. Completed in the stone parts in 1618, the dome is concluded by an external pinnacle, planned by architect Dionisio Lazzari; this latter replaced an heavy piperno and brick lantern after the 1688's earthquake and it was lightened by a wooden structure between 1724 and 1726.


3(a)


3(b)


4

Figures 3(a,b) : Naples, The Treasure of St. Gennaro's Chapel.
External views of dome's drum and 'attic'.
Figure 4 : Naples, The Treasure of St. Gennaro's Chapel. Internal view.

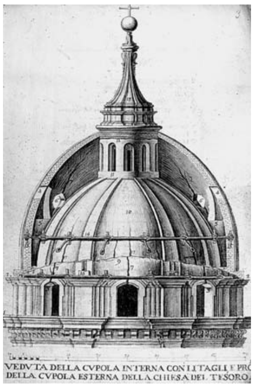
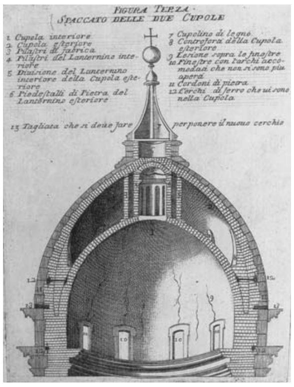
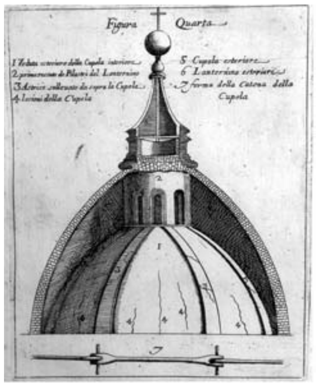

5(a)


5(b)

Figures 5(a,b): Naples, The Treasure of St. Gennaro's Chapel.
The spiral staircase in the drum and the double chain which connects the two vaults.

2.2 The vaults' enchainings

Archival documents have made clear that the Treasure of St. Gennaro's dome was circled by an iron chain placed at the base of the 'attic' in 1612 (de Martino, Russo 2005); this pre-reinforcement project, all put into the masonry, will demonstrate its insufficiency soon and it will require further reinforcements. The first strengthening, planned by Giovan Giacomo Conforto, was executed after the earthquakes of 1626 and 1627: a double hoop-iron bond was placed in five months at about 40 degrees from the vaults' impost (1628); the bond was made of a chain put on the external vault, connected by crossbars to another chain put on the internal vault's extrados (Fig. 5b). The debate which followed the 1694's earthquake can be considered as a very significant occasion for the knowledge of reinforcements' history and, particularly, in relation to the static history of the dome (Russo 2006); the analysis of the structure's damages induced many neapolitan technicians to propose the execution of a third hoop-iron bond to be placed on the external vault and on the upper part of the attic's windows.

6(a) 6(b) 7(a) 7(b)

Figures 6(a,b): G. Lucchese, Treasure of St. Gennaro's Chapel's sections (1707).
Figures 7(a,b): F. Sanfelice, Treasure of St. Gennaro's Chapel's sections (1708).

The new chain, realized before 1698, was never carried out and it constituted cause for debate still during the next century. In relation to this matter, particularly, the opinions of the architects G. Lucchese and F. Sanfelice faced each other respectively in 1707 and 1708 (Russo 2006); the first technician, after an accurate survey of the dome (Figs. 6a, b), thought that the insufficient thickness of drum's masonry in correspondence with the imposts of the vaults was the main cause of observed cracks. Against the vertical walls inability to absorb drifts, Lucchese proposed to add two new chains to the existing ones: the first chain was to put at the lower vault's impost – because of crackings maximum amplitude – and a thinner second one, eventually, to place some palms upper the external vault's impost. Ferdinando Sanfelice's opinion was connotated by a more optimistic approach to the structural problems of the dome; againsts the same cracking pattern, he showed, in fact, a very different interpretation of the cause of the damage. As his collegue did, Sanfelice made up a careful graphic description of the state of the dome (Figs. 7a, b): he drew attention to crackings of the internal vault in correspondence to windows of the attic and to small cracks on the latter's cornice. Sanfelice's criticisms to Lucchese's project were referable to three important issues, among which he noted the weight's increase that iron bonds should have determined. In addition, Sanfelice thought that the necessary embedment of the chains could be dangerous for the ancient structure and, essentially, he referred the cause of damages to the internal lantern's weight rather than to the drifts of the vaults. Finally, his proposals were based on the necessity of a careful demolition of the external circle of pillars standing among the vaults in order to reduce weights on the lower vault.

2.3 A too heavy structure? The eighteenth century lightening

A final state of the debate concerning the structural conditions of the dome can be identified in 1724, when it was decided to totally demolish the masonry lantern existing between the vaults.

(a) (b)

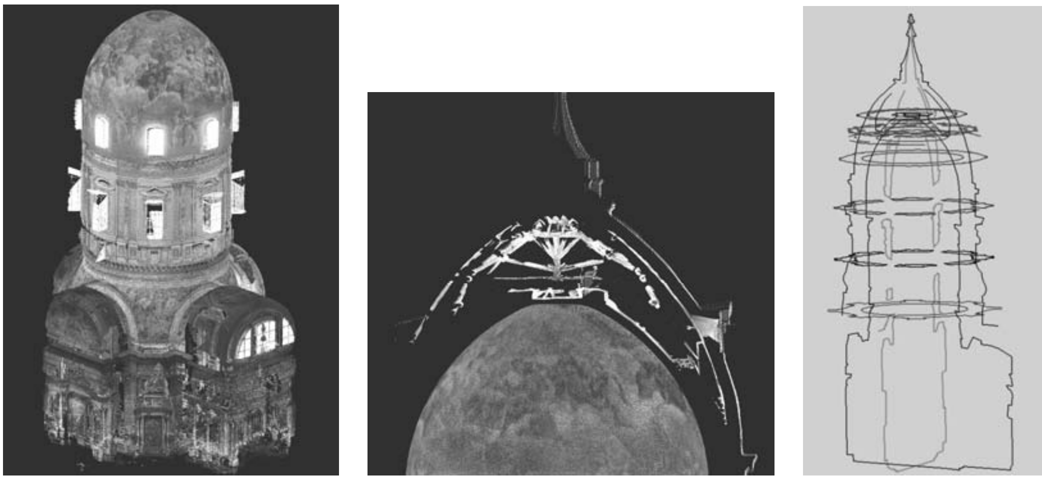
Figures 8(a,b) : Naples, The Treasure of St. Gennaro's Chapel. The wooden truss between the vaults

The aim of this intervention (arch. D. Gallarano, 1724-1726) was to concentrate the weight of the upper vault directly on the pillars of the drum and, consequently, to unload the internal vault from the weight concentrated on its keystone "oculus". Gallarano's aim was obtained with the demolition of the internal lantern and with the placing of a three-dimensional wooden and iron truss in the cavity between the vaults. Eight timber trusses were connected to a central wooden pier (Fig. 8a), recurring to eight corresponding iron tie-beams, too; the same trusses were connected to the internal buttresses on the opposite side in order to punctually unload the weight of the external dome (Fig. 8b). This latter one was partially covered, at intrados, by a complex wooden carpentry which concentrates upper weights on singular wooden nodes.

3 A DOME INSIDE A DOME: PROBLEMS OF MEASURING

3.1 Methodology and aims of the instrumental survey

The survey of the St. Gennaro's Chapel dome has been focused, in this first step, on the study of the shape of the dome aimed at a structural behaviour analysis, leaving out architectonic details. In order to be able to understand this complex structure, which is still being studied, a LIDAR technique, integrated by classic topographic methodologies, has been applied. One main problem has been soon evident: the difficulty in referencing of the data of the interspaces between the calottes, as it was not possible to connect them by network vertices, neither through the small spiral staircase nor through the dormer windows in the upper vault. So, the connections among the vertices of the traverse, useful to establish a unique reference system for the whole dome, have been planned entirely on the surrounding roofs with only one side across the chapel, linking one vertex on the threshold of the unique existing passageway at the impost of the drum, with the arrival in the attic of the spiral staircase. In this way the reference for the intrados of the inner vault and the extrados of the upper vault has been guaranteed. The measuring operations have been carried out using a help-assist total station; the survey coordinates of the net were adjusted. During the survey campaign, 25 cylindrical targets have been placed on the internal and external prospects and between the vaults, aimed both at controlling the registration of the range maps and the global alignment of the complete model. The coordinates of the targets have been acquired using tacheometry method from the traverse vertices. At the same time, other natural points have been measured, above all the corners of the dormer windows, which were the unique way to reference the interspaces between the calottes in the local coordinate system, set up with the traverse; the same points, in fact, have been acquired by high resolution scans from inside the interspaces. The material of the targets was characterized by a high level of reflectivity in order to be automatically recognized by the laser scanner. To obtain the entire model of the dome, both intrados and extrados of the two calottes, 24 range maps have been acquired by a RIEGL LMS-Z420i "time of flight" laser scanner. This hybrid sensor is composed of high-performance long-range laser with a wide field-of-view (360x80 degrees) and a calibrated high-resolution digital camera firmly mounted onto the scanning head of the laserscanner. As for every image taken with the camera, the position and orientation of the camera is measured with high accuracy within the scanner's own coordinate system, so that scan data and image data can be combined in a straightforward way without the need of user interaction. The scanner used has been combined with a calibrated Nikon D100 digital camera (6.1 Megapixel). It produces a point cloud of recorded points with 3D coordinates and the intensity of each reflected laser pulse. All acquired points' cloud consists of about 50 million measurements; at the same time, high-resolution digital images have been available, too, without the need of registration work as the internal and external orientation of the camera is known. Data acquisition, sensor configuration, data processing and storage have been done by the software RiSCAN PRO. In this way the intrados of the inner vault (from the doors in the drum and attic and from the floor of the Chapel), the extrados of the upper vault (from different scanner positions on the surrounding roofs), and the more critical interspaces (from different scanner positions on the extrados of the inner vault) have been surveyed (Figs. 9a, 9b). Data collected can be postprocessed in numerous way. According to the aim of the research, the first product - useful to the structural analysis - are horizontal and vertical sections. In this first step the whole point cloud has been considered as a detailed storage of geometric information to make shape analysis and to define different cutting plane position in order to extract the required sections. These sections have been exported and elaborated in CAD environment, maintaining the same local reference system (Fig. 9c).



(a) (b) (c)

Figures 9(a,b,c) : Scanner digital images of the dome and plan and sections in Cad environment.

4 HISTORICAL DATA AND PRESENT CONDITIONS: THE NUMERICAL STUDY

4.1 Finite-Element Modelling

With reference to above mentioned methodological and historical questions, an accurate analysis has been performed modelling the various historical phases using the multipurpose finite-element analysis software DIANA v9.1, which can handle accurate three-dimensional phased analysis (de Witte and Kikstra 2005). Starting from detailed geometric and structural surveys, the dome has been modelled by 124928 eight-node, three-dimensional solid brick element, based on continuum masonry material in order to have a reasonable run time for the program. The knowledge of the geometry obtained using laser scanner and the correlation of historical documentation to identify internal iron chains and removed structural parts have allowed to model accurately the dome in each phase of its history (chains insertions, substitution of the internal lantern with truss, etc.). The dome has been considered as composed by six different materials (Table 1) for the structural and ornamental elements: old tuff masonry for the main structure, low modulus iron for the chains, timber for the truss (in the last phase) and, neglecting the mechanical properties of non-structural elements, the weight of lead for the top coating, piperno for the former lantern and wood for the rebuilt one. The analyses have been performed for the dead load only and the F.E.M. mesh has been designed to account for openings, ribs on the inner internal dome, buttresses at the bottom drum, iron chains (Fig. 10) and the timber truss modelled with 512 two-node truss elements since the internal lantern was removed (*phase* 5).

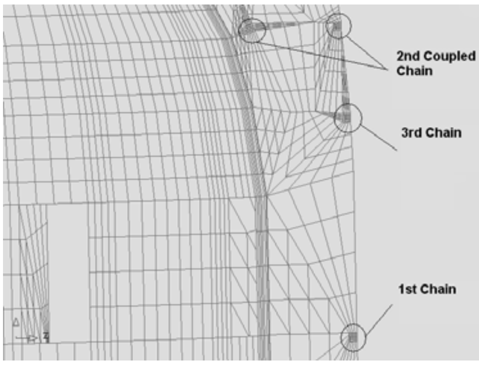
Table 1 : Materials Properties.

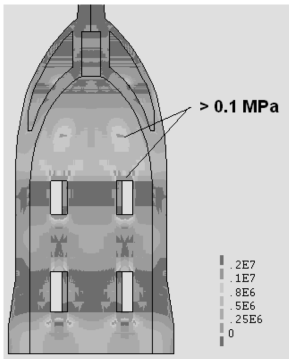
	Young Modulus MPa	Poisson Ratio -	Unit Weight kN/m^3
Old tuff masonry	1000	0.1	20.0
Iron for chains	100000	0.3	77.0
Timber for truss	6000	0.3	5.0
Lead	-	-	115.0
Piperno stone	-	-	25.0
Wood	-	-	5.0

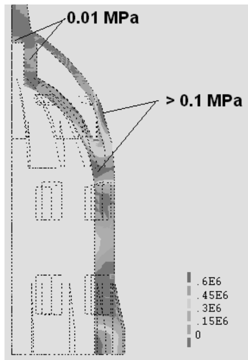
The dome rises up over the roof of the Chapel; this latter is strictly connected to other buildings and forms with them a single structure. To avoid modelling all the complex structures below the dome, two limit cases have been considered for the base constraints, depending on stiffness of the under-structure compared to stiffness of the dome: in the former one the dome has slider supports, while in the latter one it is fixed at the base. In the following, results for the former conservative, safe side case will be reported only. In the fixed support case, main differences are in the lower half of the drum where circumferential principal tensile stresses become compressive. In the other parts tensile stresses are generally reduced of about 50% and the stress field is much more homogeneous.

4.1.1 Phase 1. Building site (1608-1618)

At building site the structure was made by tuff masonry, the external lantern was made by piperno, the internal lantern was made by two rows of columns connecting internal and external domes and the external coating was made by lead. A first iron chain was already placed at the base of the second windows row. In Fig. 11a there is a map of the maximum principal stresses looking the intrados surface of the domes from inside the Chapel and in Fig. 11b across the thickness of the walls. As it can be seen, the maximum value in the dome is bigger than 0.1 MPa, higher than the tensile strength of an ancient tuff masonry, thus resulting in crack pattern evolution. Maximum tensile stresses zones, that are cracking prone, are located on the inner dome over the windows and these are reduced where groins increase the cross section. These high tensile stresses cross the thickness of the wall rising also close to the third windows row.







10 11(a) 11(b)

Figure 10 : Mesh refinements.

Figures 11a, b : Phase 1 - Tensile Stress Map over the walls (a) and across the thickness of the wall (b).

4.1.2 Phase 2. Second coupled chain insertion (1628)

When a second coupled chain was inserted close to the third row of windows (1628) where high stresses where previously found, it can be seen that the maximum tensile stress is reduced to 0.8 MPa (Figs. 12a, b); narrow tensile stresses (compatible with crack patterns observed in 18th century) are also still present in the upper part of the internal drum.

4.1.3 Phase 3. Substitution of piperno stone with wood for the external lantern (1688)

When the external lantern made of piperno stone was substituted with one made by wood, a significant reduction in the applied load at the top of the structure was achieved. Therefore, a reduction of about 3% only is found in principal compressive stresses. The maximum compressive stress is about 2.5 MPa close to the windows, but the average value in the drum is about 0.5 MPa.

4.1.4 Phase 4a. First consolidation hypothesis: the third chain

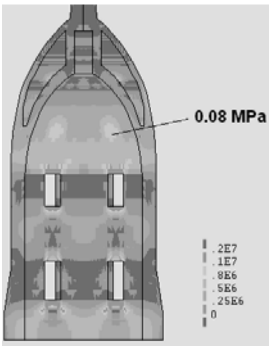
A third chain close to the first one surmounting the second windows row was designed by Giuseppe Lucchese (1707) where a tensile weakness was correctly located in that part of the structure. In this case the maximum tensile stress could be reduced to 0.6 MPa.

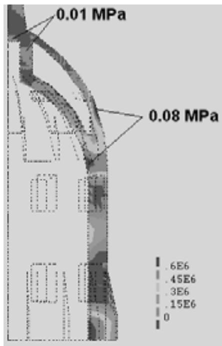
4.1.5 Phase 4b. Second hypothesis: external pillars' row removal in the internal lantern

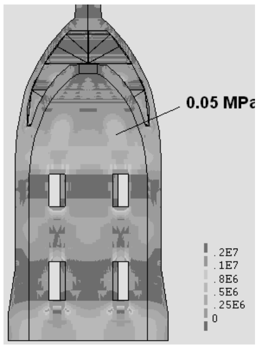
When the removal of the external pillars' row in the internal lantern was designed by F. Sanfelice (1708), the idea was to reduce the load on the internal structure but keeping the connection between the two domes. It is noticed that the reduction of the maximum tensile stress would be smaller than in previous case. Nevertheless a reduction in traction in the window's lintels of the second and third row can be noticed in both cases.

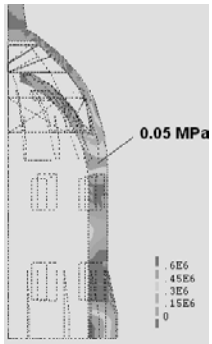
4.1.6 Phase 5. Present situation: substitution of the internal lantern with a timber and iron made truss (1724-1726)

This brave intervention allowed to virtually separate the domes and to push all the thrust close to the buttresses of the domes. It was a decisive intervention because it reduced principal tensile and compressive stresses more than 50% in the inner dome and partially in the outer dome (Figs. 13a, b). Although some stress concentrations raised at the supports of timber truss, a favourable reduction of stresses is gained all across the thickness of the walls. However, a weak tensile zone is still present just above the second windows row, where a third chain was designed (*phase 4a*).









12(a) 12(b) 13(a) 13(b)

Figures 12(a,b) : Phase 2 - Tensile Stress Map over the walls (a) and across the thickness of the wall (b).
Figures 13(a,b) : Phase 5 - Tensile Stress Map over the walls (a) and across the thickness of the wall (b).

5 CONCLUSIONS

A comparison of the dimensional stress fields and deformation states from historical, *in-situ* and F.E.M. analyses has shown that the dome underwent effective consolidation interventions during past centuries: the chain positions where accurately identified and the need to reduce weight was rightly specified. It is remarkable the skill and cleverness of the ancient technicians who designed proper and accurate interventions. Once a reliable model is generated, it will be possible to completely simulate the behaviour of historical structures after a newly designed intervention or subjected to different types of load, i.e. seismic loads.

ACKNOWLEDGEMENTS

The authors want to give special thanks to Valentina Bonora (Univ. of Turin) for sections'elaboration and to technicians of Tecno In (Naples) for the ability in the use of 3D Riegl Laser Scanner.

REFERENCES

de Martino, G. and Russo, V. 2005. Structural damage prevention in the historical building site. Theory and praxis in the eighteenth century in Campania. In Modena, C., Lourenço, P.B., Roca, P. (eds), *Structural Analysis of Historical Constructions, Proc. intern. symp., Padova, 10-13 Nov. 2004*, p. 153-158. Leiden: Balkema.

de Witte, F.C. and Kikstra, W.P. 2005. DIANA 9. Finite Element Analysis. User's Manual. Analysis Procedures. Delft, The Netherlands. TNO DIANA bv.

Russo, V. 2006. Il doppio 'artificio'. Costruzione e restauri della cupola della Cappella del Tesoro di San Gennaro nel duomo di Napoli. *Napoli nobilissima* (in press).

Savarese, S. 1986. *Francesco Grimaldi e l'architettura della Controriforma a Napoli*. Roma: Officina.