Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)

The XIX century opera theatre of Catania: Conservation and seismic strengthening interventions

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ABSTRACT: This paper presents a study carried out on the dome which covers the horseshoe shaped hall of the Massimo Bellini Theatre in Catania. The dome's painted surface shows a set of cracks whose pattern, probably come out as a consequence of a seismic action, seems to be depending on some features of its structural behavior which are related to its geometrical configuration. The structural behavior of the trussed dome is at present the subject of a numerical (via f.e.) analysis with the purpose to clarify the importance of the different mechanical parameters and, in case, to recognize potential weak points of the assembly. But a preliminary attempt has been made to understand, by means of simply logical reasoning and on the basis of the observation of the structure and of its damages, the mechanisms of the structural behaviour. The results of such an effort have been used as a guide in defining consistent intervention criteria.

1 INTRODUCTION

The Massimo Bellini Theatre in Catania was built during the XIX century and opened in 1890 according to the final design of Carlo Sada, a Northern Italy architect whom the actual shape of the theatre is due to. He intervened on a building whose erection dated from the early 1800 and magisterially completed it taking into account, within a unitary design, the yet realized structures.

In 2005, more than one hundred years later its completion – and having practically never lay a hand on it –, the theatre underwent a restoration design with the aim, among the other purposes, of improving its structural behaviour.

In that occasion the building has been carefully observed in order to recognize its pressing needs and consequently decide how better use the available funds. The attention was immediately captured by those portions whose conditions appeared worst than the ones pertaining the whole body and a collection of problems was pointed out.

The most relevant problem highlighted was undoubtedly the condition of the ceiling of the horseshoe shaped hall. The painted surface shows a set of cracks whose pattern, probably come out as a consequence of a seismic action, seems to be depending on some features of the structural behavior of the dome which are related to its geometrical configuration.

The dome shaped ceiling is realized according to a constructive typology quite spread in the lyrical theatres built in Italy during the XIX century; but the big flat dome of Massimo Bellini Theatre exhibit some interesting, and structurally relevant, features.

The preliminary analyses – carried out for the restoration design and consisting of the on field survey of geometry and state of material's conservation – clarified that the dome is made by a set of radial wooden trusses, and its painted intrados is realized by a thin layer of plaster hanged up to the above trusses.

The shell behaviour of the trusses' assembly is affected – and locally altered – by the radial asymmetry and different length of individual trusses, which do not converge in geometrical centre of the dome plan. Such a configuration makes more deformable the longest and less circumferentially contrasted trusses and can produce a crack pattern similar to the surveyed one.

The structural analyses performed until now, show that the surveyed crack pattern does not indicate a deep structural deficiency and cannot therefore prejudice the safety of the dome. However, the cracks introduce unacceptable discontinuities in the painted ceiling and can produce the detachment of relevant portions of it.

As a result it was possible to define consistent intervention criteria.

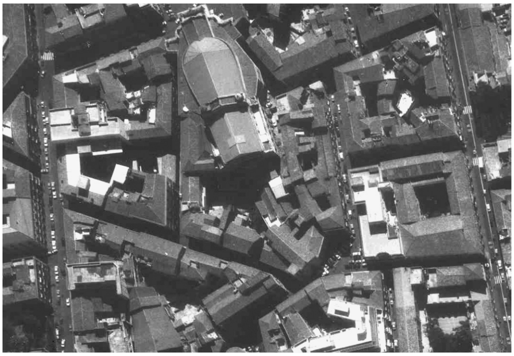

Figure 1. Aerial view of urban texture surrounding the theatre.

2 HISTORICAL ASPECTS

The history of both the designs and the construction of Massimo Bellini Theatre develops in almost eight decades, beginning from the former decision to build an important theatre that the municipality took in 1812 (figure 1).

The first project, with which the construction began, was due to Giuseppe Zahra, an architect from Malta. He designed a theatre with 1400 seats both in the hall and in the five levels of boxes.

The area chosen to build the theatre was in front of Nuovaluce square, placed at the border of the ancient city walls but now over passed by the growth of the city.

The construction of the building was stopped a first time when the masonry walls were two metres high, probably for the occurrence of a strong earthquake in 1818. In fact, historical data tell us that the wooden beams collected in the construction site for the roof structure were used to back up damaged houses.

From the '30ies of the XIX century the news on the theatre construction stop for some decades along; but at the beginning of 1870 only the perimeter curved walls and eight big pillars are built.

The cause of the long stop in the construction of the theatre was the indecision of the municipality: during this period it calls some different architects, both local and foreign, to prepare alternative projects. It was even thought to change the place where the theatre should have been built, leaving he already begun construction site.

In 1872 the municipality calls from Milan Andrea Scala, a famous architect of theatres, to define a consistent site for the big and monumental theatre; it should be similar to the Opéra by Garnier and so isolated from the urban texture surrounding.

But only the following year it came back to the idea to continue the building in construction, transforming it in a "politeama", and therefore with a lot of seats formed as an amphitheatre.

The Andrea Scala project was approved in march of 1874 and the director of the construction site was designed in Carlo Sada, the architect who at the end will conclude the building.

The Scala project for the "politeama" is a transformation of the already existing portions of which the front part remains as it was (facade and foyer), while the boxes hall was strongly modified and the new squared plan scenic tower was added.

The goal of the project was to realize a more important theatre to satisfy the will of the citizen which wanted a monument for which be proud.

Carlo Sada worked tree years (1874–1876) in the construction site to realize the Scala project then the building was stopped again.

In the following there is the description of the condition of the theatre made by Sada in a note written in 1878:

> "the masonry walls surrounding the scene were finished in September 1874, while those of the hall in November 1875. Meanwhile the roof closing the horseshoe shake hall was built so that its construction was completed in august of the same 1875. The roof covering the scene was erected in the early 1876 and the tiles placed in July of the same year".

Two years later, in 1878, the municipality of Catania decided to ask to Sada to work at a completion project for the existing building modifying it in Lyrical theatre.

But before the beginning of this new construction phase, some experts realized an investigation to judge on the stability of the building (figure 2).

The opinion of the experts was positive: the building was well designed and correctly built both in the structural elements and in the assemblies. The cracks observed were explained as due to the different construction phases of the masonry walls.

In 1880 Sada presented his completion project (figures 3, 4) which was immediately approved from the municipality so that the construction site could start again. Modifications are not few: at the façade on the square an extension was added (portico) as well as two lateral volumes which connect the principal front to the close blocks; in the horseshoe shaped hall the disposition at amphitheatre was changed introducing five layers of boxes and covering the big hall with a flat dome.

The wooden structure of the dome is already built in 1883 as we can understand by reading the discussion on the intrados decoration reported on the city newspaper.

The construction of the theatre was completed in ten years and its opening performance took place on May 31th 1890.

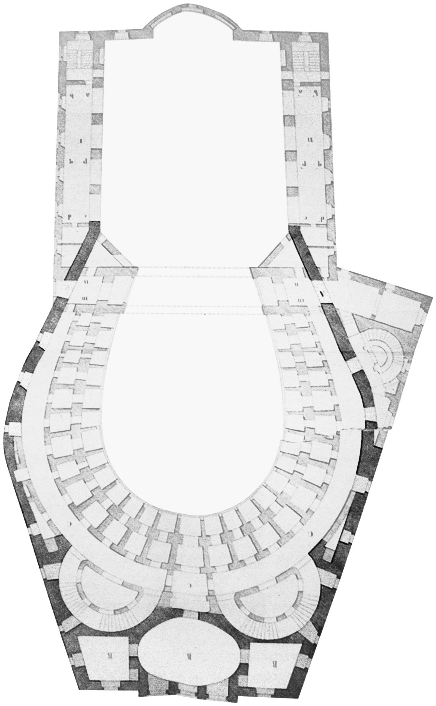

Figure 2. Constructive phases of the masonry walls in a plan made by professor C. Clericetti in 1876.

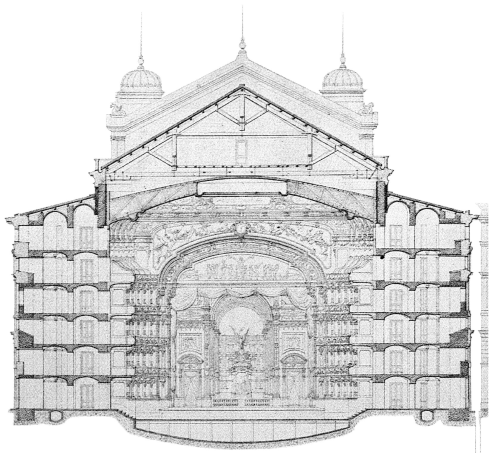

Figure 3. Transversal section through the scene from the Carlo Sada's project, 1880.

3 DESCRIPTION OF THE DOME'S WOODEN STRUCTURE

The horseshoe shaped hall is defined by the curved concentric walls which, together with the radial walls, realize the multilevel boxes.

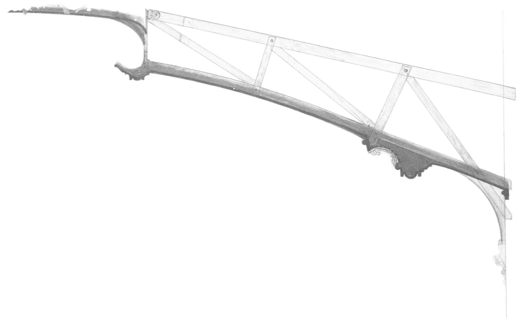

Figure 4. Wooden truss in a drawing made by Carlo Sada, 1880.

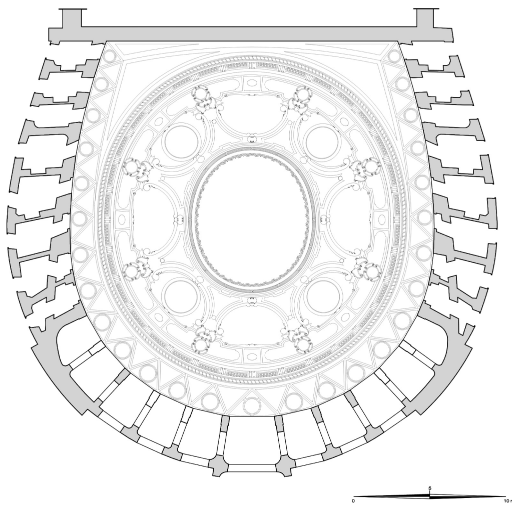

Figure 5. Balcony plan with the projection of the ceiling.

The ceiling presents an oval flat dome with a big central eye which is delimited by an important cornice. This latter connects the dome with the curved masonry wall through a set of lunettes and triangular flat surfaces (figure 5).

The length of the dome's principal axes measures 24.80 m × 23.90 m; they are wider than those of the lower hall (22.0 m × 19.5 m) because of the presence of the balcony gallery.

From the constructive point of view, the dome is a wooden and reed ceiling and it was realized by a constructive technique spread in XVIII and XIX century for the construction of theatre hall covering.

However, in this case the need to cover a relevant wide span introduced the use of an articulated bearing structure, quite different from the other reed ceilings' wooden forms spread in Sicily both in church and noble residential palace. These latter are generally hanged up to the wooden structure of the roof by metallic ties.

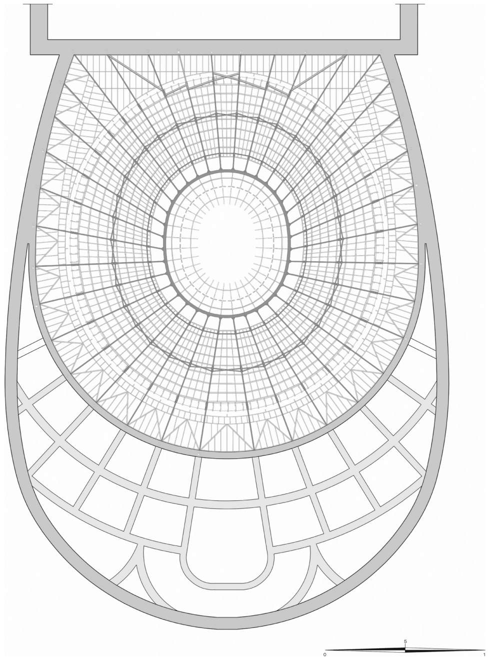

Figure 6. Disposition of wooden trusses and wooden centerings of the plaster shell.

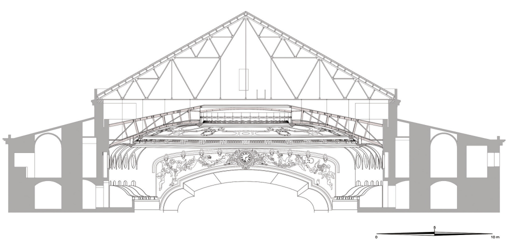

Figure 7. Transversal section.

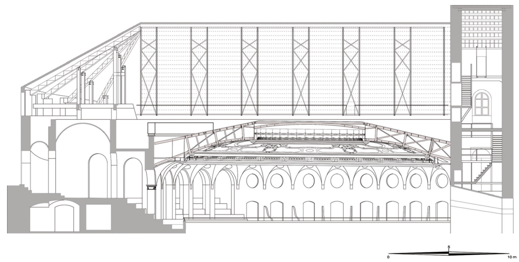

Figure 8. Longitudinal section.

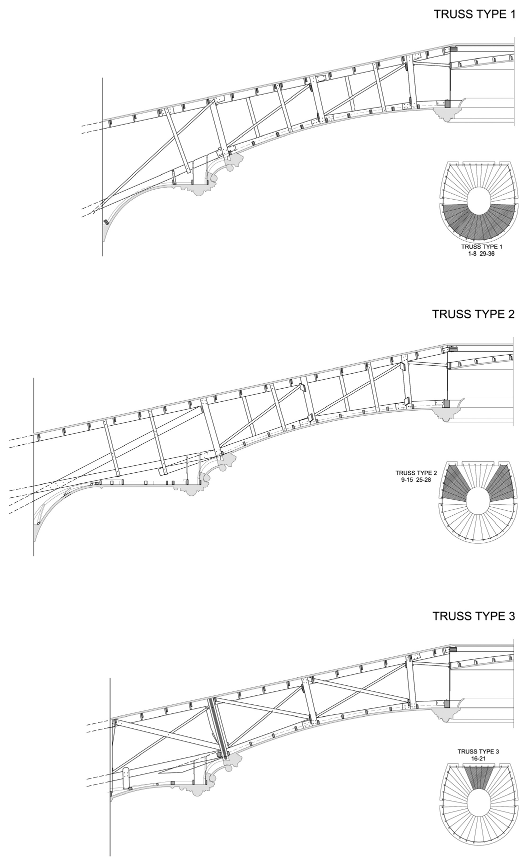

Figure 9. Truss types observed in the dome's structure.

The structural design of the Bellini's dome is quite similar to that of the metallic trusses in use from the second half of XIX century in Europe.

In fact, the ceiling structure is independent from the above closing roof, being realized with a spatial system of 36 radial wooden trusses. The trusses, supported by the masonry walls, converge in a wooden ring, which defines the intrados dome's eye (figures 6, 7, 8, 9).

The trusses' arrangement shows a symmetry with respect to the longitudinal axis of the dome, but not to the other principal direction.

This particular disposition is due to constructive reasons; in fact it is possible to observe first of all that the start of the trusses from the curved masonry wall is in correlation with the radial masonry walls of the boxes (best position to restrain the trusses thrust to the wall). Secondly the upper wooden ring, which collects all the trusses, is divided in 36 equal parts in order to make easier the placing of the trusses themselves.

Because of this double constraint, structural and constructive, imposed to the trusses' extremities, the trusses can follow the direction of the radial walls only in the part in front to the stage, explaining in this way the above mentioned asymmetry.

Among the lower cords of the trusses is placed a system of wooden elements, which realizes together

with the lower cords, the mesh on which the reeds are nailed. The intrados surface is completed by a two layers of plaster which support the pictorial decoration.

Similar wooden elements are placed among upper cords of the trusses, also these supporting the reeds and plaster covering.

It is just this double system of wooden elements that guaranties, by virtue of the continuity realized by the plaster layers, an efficient connection among the trusses.

In addition other connections are offered (i) by the closing wooden ring, (ii) by two levels of cross braces and, only near the stage zone, (iii) by inclined braces probably introduced to absorb the additional thrusts produced by the aforementioned radial asymmetry of the trusses arrangement.

Eventually, it is possible to say that the decorated flat dome (as well as the covering at the level of the upper cords), although realized by a warp of reeds and a thin plaster layer, cannot be considered unrelated to the structure, because it gives its contribute to the whole stability.

Concerning this last point it can be noticed that in the dome's portion close to the impost, precisely between the cornice and the perimeter curved wall, the trusses are not connected by transversal wooden elements. Therefore both transversal wooden elements and the intrados plaster layer are hanged up to the trusses by metallic and wooden ties.

This different arrangement introduces a lack of connections in the direction of dome hoops which has been controlled with attention above all because of the contemporary lack in the same zone of cross braces.

In seventies of last century the wooden roof made by Palladian trusses, was substituted by a set of metallic trusses; during the same set of work wooden footbridges were placed among the wooden trusses of the dome.

These footbridges are hanged up by steel cables to the metallic structure of the new roof, so they do not weigh on the dome. Anyway the steel cables pass through the extrados plaster layer so that every movement of the footbridges, even during maintenance inspections, could affect the dome.

4 STRUCTURAL BEHAVIOUR AND CRACK PATTERN

From the even short description of the previous section, it appears that, as the architectural and constructive body of the theatre, the dome which covers the horseshoe shaped hall is an uncommonly complex machine.

Different materials and elements, assembled by means of various and proper connections, create a device whose functioning is due to the precise interaction of its components but which, because of its own complexity, reveals an extreme fragility.

Figure 10. Typical connections observed in the reticular structure of the dome.

The structural behavior of this machine is not trivial.

The apparent simplicity of the connections between the elements, simply supported or nailed together, makes it difficult to understand how the machine works and introduces practically insurmountable problems in numerical analysis (figure 10).

In such cases, nevertheless rather frequent in the structural field, what is asked to the mathematical modeling is not the thorough evaluation of the structural response but just the individuation of the role of the different parameters – geometrical, mechanical, etc. – in defining the value of the response and the most probable way in which the response itself may develop.

The heavier are the uncertainties in the analytical phase, the deeper must be the attempt to preliminarily understanding, even by means of simply logical reasoning, the mechanisms of the structural behavior. These can often be imagined on the basis of the observation of the structure and of its damages.

It's exactly the way this work is going to be performed.

A 3D finite element model of the dome structure has been prepared and some preliminary analyses have been executed. But in building the model, as well as in interpreting the results, great care has been taken of all the aspects, geometrical and constructive, which although hardly to put in quantitative terms, nevertheless logically derive from the way the structural elements are built and connected together.

From the structural point of view the assembly of the wooden trusses realizes a system whose behavior can be assimilated to the one of a reticular dome because of the interaction between the single trusses assured by: (i) the cross braces disposed at two different levels along the dome's circumference (one of them is placed near the central eye), and (ii) the wooden centering

Figure 11. Internal view of dome's structure: it can be noticed next to the truss, one of the circumferential cross braces and the recently added footbridge.

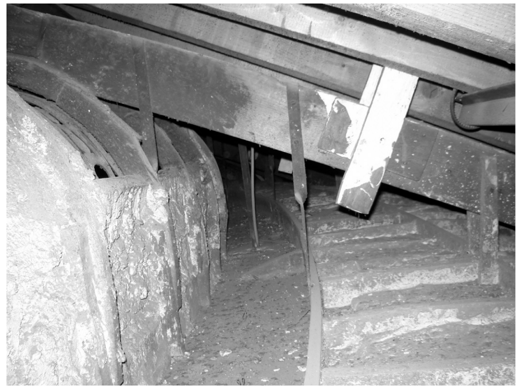

Figure 12. View of dome's the suspension system in the area close to the perimeter masonry wall.

disposed between the upper and lower cords of the trusses and nailed to them (figure 11).

The trusses can be thought, therefore, as the meridians of an ideal dome whose hoops can be identified in the braces and in the centering.

According to this explanation of the structural system, both the dome of the hall's ceiling and the upper covering cannot be considered as not structural parts, respectively suspended and superimposed to the radial trusses. On the contrary, they are essential elements of the global bracing system whose effectiveness significantly relies on their presence which ensures a smeared action much more powerful than the lumped one pertaining to the main wooden elements (cords, posts, braces).

In this sense, some constructive features of the dome achieve a stringently structural meaning. First of all, the radial asymmetry of the wooden trusses, but also the different suspension system of the dome nearby the border walls (because of which the lower cords of the trusses cannot count on the bracing effect of the centering) and the simultaneous lack, in the same zone, of the cross braces (figure 12).

These geometrical and constructive features affect, and locally modify, the shell behavior of the trusses' assembly – a typical biaxial stress state, with internal action both in the meridian direction (in this case, the trusses) and in the hoop one (braces and centering) – and can produce, as a consequence, a crack pattern similar to the surveyed one (figures 13, 14).

The circumferential layout of some of the fractures – which are almost perfectly disposed along the dome's hoops – seems indeed classical.

Domes struck by seismic action frequently crack horizontally, and it's undoubtedly not by chance that such cracks came out, in the painted dome of the Bellini theatre, after the 1990 earthquake (the so called "Santa Lucia" earthquake).

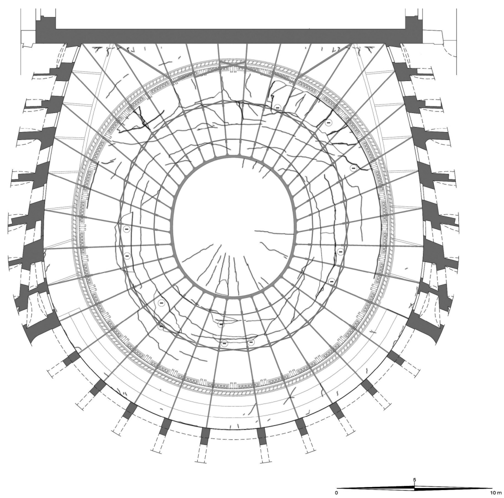

Figure 13. Relationship among wooden trusses, masonry walls and crack pattern of the plaster.

Furthermore these cracks are localized in the zone of the dome where the suspension system passes from wooden centering to metallic ties.

The meridian cracks that are mainly located in the zone of the dome nearby the stage walls seem instead consistent with the radial asymmetry of the wooden trusses.

If the dome was spherical and the trusses perfectly radial, the braces and the centering would transmit constant compressive actions to the trusses which would be consequently subjected to the same forces, both in vertical (dead and live loads) and horizontal (hoop forces) directions.

The dome is however oval and, furthermore, the trusses do not converge in its geometrical centre (because of the aforementioned radial asymmetry).

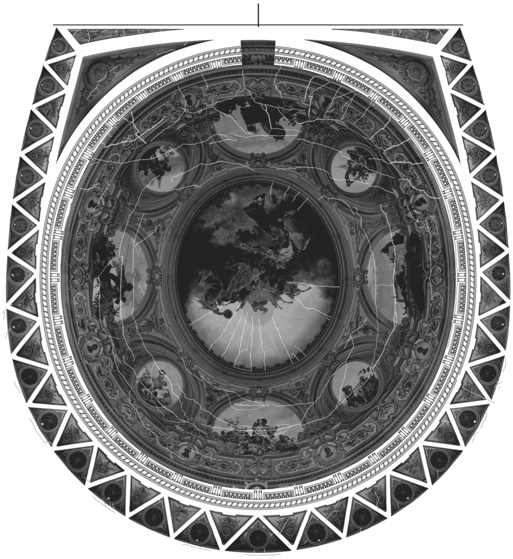

Figure 14. View of the crack pattern from the bottom.

Consequently, if we assume that the resultant of the hoop forces applied on each truss cannot act out of the truss's plane (because of the extremely small out-of-plane stiffness of the truss itself), it follows that the hoop forces are not constant.

This circumstance causes a different deformability in the different zones of the dome's structure, in such a way that the zones where trusses are acted upon by smaller hoop forces exhibit, for the same load condition, greater vertical displacements. Relative displacements between contiguous trusses can produce cracks directed along the dome's meridians.

Such a behavior is obviously amplified nearby the stage walls where the trusses are respectively longer and shorter than the mean length they show in the remaining portions of the dome.

As for the circumferential cracks, it is possible that the meridian cracks too came out after the "Santa Lucia" earthquake. In fact, most of the relative vertical displacements between the trusses could have produced gradually during the building of the dome, and further settlements, caused by the completion of the intrados, could have been absorbed by the elasticity of the plaster.

In such an hypothesis, however, the thin plaster layer of the dome would have been subjected to a self stress state that the occurrence of an even weak seismic action could have relaxed generating the meridian surveyed cracks.

On the basis of the proposed interpretation, moreover confirmed by the preliminary results of the numerical analyses, it seems reasonable to affirm that the crack pattern surveyed on the dome does not highlight particular weakness neither of the dome nor of its suspending structure.

Indeed, the fractures may have reduced the self stress state previously described bringing the structure to a new equilibrium configuration. On the one hand this circumstance may be regarded as a value, because it could allow the structure to follow, without further damages, the vibrations of the heavy perimeter walls induced by seismic action; but on the other hand it induces a remark on the fragility of the whole bracing system that could be partially weakened by a further increasing of the present crack pattern.

5 INTERVENTION CRITERIA

From the structural point of view, the necessary interventions finalized to the safe conservation of the painted dome concern both (A) the reticular structure and (B) the plaster layer of the dome.

(A) The trusses' assembly is safe against the eventuality of both a buckling collapse and a material crisis – as pointed out by the numerical analyses – provided the wood is in a good state of conservation.

With regard to this aspect, the widespread presence of little cavities, probably due to an infesting action of biologic nature (no matter if historical or recent), suggests as necessary a protecting treatment that should be extended also to the lower cords of the trusses and to the lower centering, unlike a previous treatment carried out fifteen years ago, limited to the upper parts of the trusses because of the presence of the footbridges.

Some centering elements, mainly belonging to the upper covering, are broken and some elements of the trusses are cracked, in a more or less serious way: it can be foreseen the substitution of the broken or seriously damaged elements and the repairing of the others – for example by nailing or bandaging them.

(B) Although the crack pattern of the dome does not imply serious structural lacks, it is nevertheless to worry about (i) both for the possibility of detachment of plaster portions delimited by cracks' intersection (ii) and for the weakening that it could introduce in the bracing system.

Therefore, one of the purposes of the intervention should be to assure the adhesion of the precarious portions of plaster layer to its reed upper support; while it is not evident at present if it would be convenient to restore the continuity of the plaster layer.

6 CONCLUSION

In this paper has been presented a study carried out on the wide span dome which covers the horseshoe shaped hall of the Massimo Bellini Theatre in Catania.

During the preliminary analyses, both historical and in situ, the dome appeared as a constructive and typological "unicum". The main difference with respect to other similar ceilings – in which the decorated intrados is suspended to the roof structure – is due to the combined behaviour of the reticular trusses and the upper and lower plaster shells.

This circumstance required a very deep comprehension effort in order to evaluate both the constructive connection devices and the assembly's functioning. Such a comprehension was necessary to attempt a realistic interpretation of the surveyed damages, taking into account the complete lack of reference models.

Nevertheless it deserved to define an appropriate numerical model able to account for the essential mechanical features of the structure.

The until now acquired data and results enable an aware definition of the most respectful structural interventions.

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