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Timber Strengthening Systems Operated on the Vasari's Ceiling in Palazzo Vecchio

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ABSTRACT: The structural analysis started for the trusses designed by Giorgio Vasari in 1563 for the Sala Nova in Palazzo Vecchio proves that they became suitable to support not only the roof but the false ceiling as well only when a significant alteration to the original design was made, i.e. the rigid connection of the kingpost to the chord. The deformation of the ceiling are therefore due to lack of structural consistency of the unit, excessive (for the ceiling) bay, creep. The numerical analysis of the new series of trusses added by Domenico Giraldi in 1854 to strengthen the vasarian system gives evidence of the perfect sizing and efficacy of these units; also the slight deformations occurred fit with the theoretic behaviour of the system.

1 INTRODUCTION

The enormous hall in Palazzo Vecchio was first built and covered in 1495 by Architect Simone del Pollajolo said "il Cronaca" and co-operators; later in 1563, at the instigation of Duke Cosimo I dei Medici, the hall was decorated, enlarged and increased in height (dismantling the Cronaca's ceiling and roof and reconstructing them with new structures in the new position), decorated with paintings at the walls and on the ceiling, by Giorgio Vasari, the father of the modern artistic historiography and an architect and artist. Called since then Sala Nova or Salone dei Cinquecento, it became the largest Hall in Europe.

The most important representation place in the city, the hall hosted the most significant events of the social and political activity in the city of Florence as well in Tuscany till the XIX c. and also later.

The roof was constructed with 12 traditional kingpost and struts trusses on a span of 24 m c. and a bay of circa 5 m; the false ceiling, suspended to the chords of the trusses, was a free interpretation of the classical lacunars or boxes ceiling type, with apparent principal and secondary wooden beams, in reality empty boxes of well arranged boards, which determined lacunars or "*quadr*i" of different size. The lacunars were, as all the walls, decorated with paintings made by the same Vasari with *aiuti*.

Today the construction also includes smaller trusses designed in a very original way, inserted between the main ones, at a different level.

It has already been discussed (Tampone, Derinaldis, 2005, cit.) the fact that the circumstances and the technical aspects of the construction of the Vasari's invention had been neglected, as a field of research, by the historians because the historical (the Vasari's paintings represent the *res gestae* of the Medici Family) and artistic sides of the arrangement are prominent. As a consequence, there were a few inexactitudes and mistakes in the official historiography: for instance, all the trusses, the major and minor ones, were considered the Vasari's work; furthermore, it was the general opinion that Vasari had invented a new technique for the realization of ceilings, entrusting to the traditional trusses the duty to carry the roof and to minor trusses, of new design, stiffer than the previous ones, the duty to carry the ceiling. The cited authors demonstrated (2005, cit.), on the base of yet (in 2005) unpublished documents, that the minor trusses are a strengthening device of the vasarian false ceiling work and that they had been installed by the Architect Domenico Giraldi in the half of the XIX century.

It is of fundamental importance to say that Vasari, suspending the false ceiling to the chords of the trusses which also carry the roof, was following a well consolidated technical tradition which continued long after.

We ought to remember that the Saint Catharine Church in the Sinai desert, built by the Emperor Justinian, received a very light false ceiling in the XVIII c., suspended to the chords of the trusses; the Florentine Saint Barnaba Church, built in the third decade of the XIV c., was furnished wit a false ceiling in the XVIII c., the same for the Saint Mark church in Florence, the roof of which, built in the XIV c., was completed with a ceiling suspended to the chords in the XVIII c. In Florence, at the beginning of the XVIII c., the roof carpentry of the Church of the Spedale degli Innocenti, the work by Filippo Brunelleschi and the “manifesto” of the Renaissance, was concealed by a very nice ribbed false ceiling; the vaults which cover the Central Hall of the Building hosting the Archaeological Museum in Naples, XVIII c., are to be mentioned as well as an example of a self supporting vault built in the de l’Orme system (see over) but also suspended to a two-slopes lattice girder.

An other very interesting item to complete the frame of the technical setting in which Vasari was operating, is the publication, 1561 at Paris, of the Philibert de l’Orme’s Treatise “*Nouvelle inventions pour bien bastir et à petit fraiz*”.The system, also quoted by Sebastiano Serlio as “*armamenti alla francese*”, was disseminated to an extraordinary extent in Italy therefore the two systems, the traditional one and the innovative proposed by de l’Orme, continued to be used at the same time.

2 DESIGN OF THE STRUCTURE AND ITS PECULIARITIES

Although Palladio invented and built in the same years the wooden bridge over the Cismon River nearby Vicenza, with an only enormous span of 33 m circa (amongst the others, for the technical aspects of the Palladio’s wooden bridges see Tampone, 2000, cit.), the vasarian trusses are extremely audacious for the time in the field of civil constructions, due to the very large span. Furthermore they present a few peculiar design details and devices.

The chords are made, in account of the length, 24 m average, of two elements connected in the middle by a seal joint (a simplified “Jupiter’s arrow joint”) the contact surfaces of which are resting in vertical planes, also inclusive of a superior and a slightly longer inferior element. These, acting as brackets, are intended to stiffen the connection and to make it suitable to resist also to bending moment: this is generated by the not negligible self weight of the chord and by the weight of the false ceiling. The central connection is completed with nails and bolts of various types set untidily (a sign of multiple interventions) which stop any mutual motion and do not allow adjustment; very sophisticated the bolts, which are to be attributed to the Vasari’s time. Besides, the four pieces are tightened by two end iron ties. These have no wedges (today) but a single upper horizontal connector and they can be tightened to the woods only inserting wooden thicknesses.

The kingposts does not touch the chord, therefore the trusses are conceived as true trusses of the Mediterranean traditional type. At the time being, the iron stirrup which is suspended to the kingpost and generally wraps loosely the chord, has been connected with a lot of nails to all the elements, included the brackets. Therefore, the truss is acting as a lattice girder; thus the deformations of the chord are efficaciously prevented. This is confirmed by the document written by Engineer Martelli (see over) after the inspection he made to the garret in 1854, the first technical one in a modern sense, where he remarked that he found the chord already nailed to the post; therefore the connection is not the work of modern times. The most probable hypothesis is that the arrangement was made at the Vasari’s time as soon as the carpenters who were constructing and suspending the ceiling became aware that it was sinking because of the mutual rotation of the middle end of the chord (see over).

The main nodes (rafter-chord) include a wooden cantilever to stiffen the chord and an iron collar; the upper branch of the collar is made of the wedge-shaped rulers, the one laid upon the other, set into eyelets of the collar, to ensure connection and adjustment.
Similar iron devices will be adopted all along the following centuries, as examples we can quote those of the floor of the Sala di Minerva, Accademia di Belle Arti in Florence established at the end of the XVIII c., and those set by Giuseppe Valadier to connect, by means of adjustable ties, the radial walls of the Coliseum, after 1823.
An interesting feature of the vasarian trusses is the fact that a good amount of the entire main node, that is to say the connection of the rafter to the chord, rests on the masonry support of the wall with evident benefit for the stability of the node; besides that the wrought iron collar connecting bracket, chord and rafter is very inclined in the direction of the possible motion of the rafter when this is sliding along the chord; the device is thus active, since its application, in the prevention of the sliding.
The similar collars of the chord junction are inclined too but oriented in the wrong direction.
The almost obvious accuracy needed to do these details is generally neglected in the timber trusses design, for various reasons such as deliberate choice for economy, difficulties in finding timbers of suitable size (for the length of the rafters), insufficient understanding of the structure, others; on the contrary they are essential for the stability of the units. By their presence one can assume that Vasari and his co-operators (the carpenter Mastro Botticelli first of all) were concerned about the behaviour of the single members as well as that of the units – motion, deformation, stress condition etc. – and took their measures to ensure stability to the carpentry.
The trusses of the classical type (except the cited alteration) designed by Vasari, in spite of a few inconsistencies, show a deep concern of the designer for the not negligible loads (the ceiling weighs 0.072 N/cm^2) and they are well sized; in fact they do not present any crack or failure except for a few breaks of minor importance that can be considered typical and physiologic: slight deformation of the inferior part going from strut to chord, of the rafters, little breaks at the indentation of the rafter to the chord. The timbers (fir tree, *Abies alba*) are excellent, with a straight grain, little number of knots. But the trusses designed were not suitable to carry a loading system acting partially on the rafters and partially on the chord, also because this last fundamental member is made of two main pieces and the collars are inefficient.

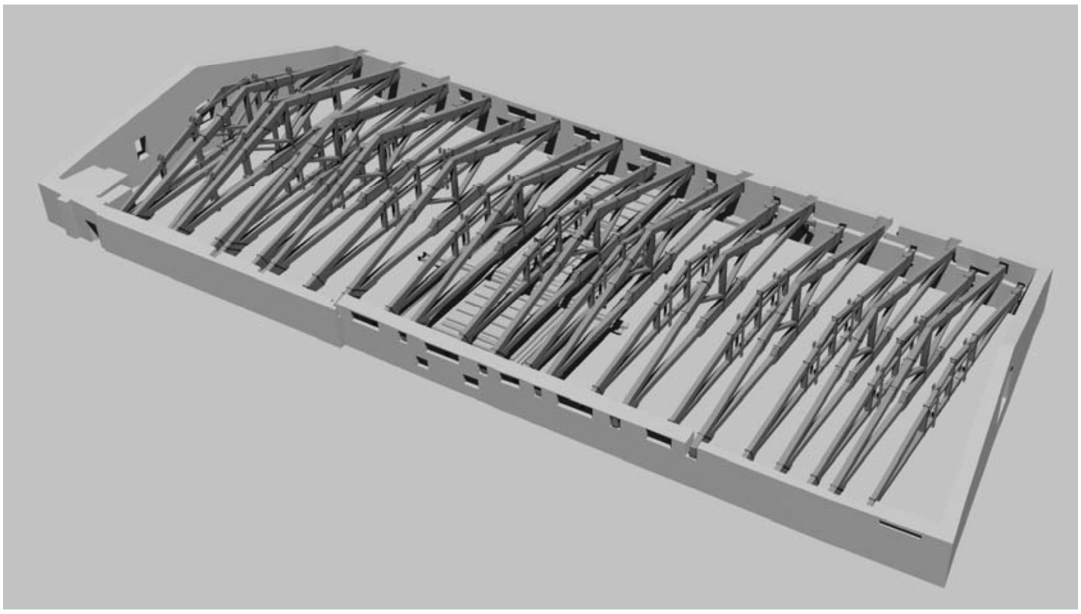

Figure 1 : “Salone dei 500”. Perspective view of the garret

Figure 2 : Panoramic view of the “Salone dei 500” garret, in the middle the vasarian trusses.

3 THE GIRALDI’S TRUSSES

The real change in the stability of the ceiling happened with the intervention operated by Domenico Giraldi, who inserted in the year from 1854 on, between the Vasari’s trusses, a new row of shorter, stiffer trusses which are true lattice girders due to the fact that all the connections between the three posts and the chord are absolutely rigid. It is evident that the author intended to design a very stiff frame, with fixed joints, able to carry the loads applied at the chord. As a coeval bibliographical reference it is possible to quote the Colonel Emy’s treatise on Carpentry.
The success is due to the division of the original bay in two parts. The ceiling is anchored everywhere to steady supports.
The unusual shape and configuration of the Giraldi’s trusses has at least one antecedent in the trusses which since the construction (end of the XVIII c.) co-operate to support the ribbed vault of the central hall (25 m span) of the Naples archaeological Museum (see Tampone, 1996, cit.), arranged to host the tallest sculptures found in the excavations of Ercolano and Pompei. Here the trusses are of the modified Palladian system; they show an almost complete similarity to the Giraldi’s trusses even for the smooth slope, the lower positioning etc.
The structural analysis for the Giraldi’s trusses shows that the stresses in the wood vary in a very narrow range and the values are small (see Table 4). A deformation curve of the rafter different from that of the under rafter and a tendency of these members to share have been observed.

4 STRUCTURAL ANALYSIS

To make the analysis of the structural system which supports the ceiling some FEM models have been created using the numerical codex STRAUS 7. Monodimensional elements like *beam* and *truss* have been applied to the structure. The *beam* elements have been associated to the timber members and the *truss* elements are used in order to simulate the iron joints that connect the kingpost to the tie beam.
To evaluate the difference between the structural behaviour, in relation to the different definition of internal constraints, for the last ones both rigid and hinge behaviour have been considered.
In any case the external constraints have been respectively considered a hinge and a movable hinge.

The comparison of the results obtained with the two internal restraint conditions did not show substantial differences from the point of view of the stresses.
As regards the deformed state, more consistent displacements have been found in the case of smaller multiconnection between the timber members: in particular the difference has been stimated in 1 centimetre.
In the analysis of a single structural element the overload that depends on the ceiling, the whole beams system and the suspension devices have been simulated with concentrated loads positioned where the timber frame transfers to the tie beam its action with that one deriving from the suspension devices and the lacunar ceiling.
In the complete structural model, defined by the parallel collection of wooden trusses, a system of the wooden joists has been considered arranged among the singles structural units. Both the self weigth load of the ceiling and the loads trasmitted by the metallic and timber suspension devices have been applied directly to the wooden joists.
In order to simulate the post-elastic behaviour of the structural unities an elastic linear analysis and a geometrically non linear analysis have been performed. The results obtained in the two cases, small differences have been shown both in terms of stresses and in terms of displacements.
The results obtained with each model performed suggest that, at present, the XIX century trusses are subjected to a state of stress which respects the admissible range values of the materials.
The rational geometrical design of the truss is remarkable: the lateral kingposts and the structural elements called “cavalieri” are positioned in the area which corresponds to the maximum concentration of the material (because of the lacunar ceiling profile) and consequently of maxmum load.

Table 1 : Mechanical characteristics of the materials used for the calculation.

Material	Modulus of Elasticity N/cm^2	Density kg/cm^3	Thermal Expansion $°C^{-1}$
Abies alba (category III)	1.10×10^{6}	6.00×10^{-4}	3.50×10^{-6}
Iron	2.00×10^{7}	7.85×10^{-3}	1.17×10^{-5}

Table 2 : Domenico Giraldi’s 7th truss positioned in 1854.

Self weigth load kN	Ceiling’s load N/cm^2	Ceiling load acting on the single structural element kN
43.5	0.072	80

Table 3 : Trusses sustaining the false celing.

Maximun overload (5 th wooden truss) kN	Minimun overload (1 th wooden truss) kN
82	29

Table 4 : Domenico Giraldi’s 7th truss positioned in 1854.

With internal fixed joints		With internal joints like hinges	
Stress N/cm^2	Displacement max (y) cm	Stress N/cm^2	Displacement max (y) cm
1593.88 (metallic elements) -349.33	-1.7	1650.18 (metallic elements) -480.45	-2.5

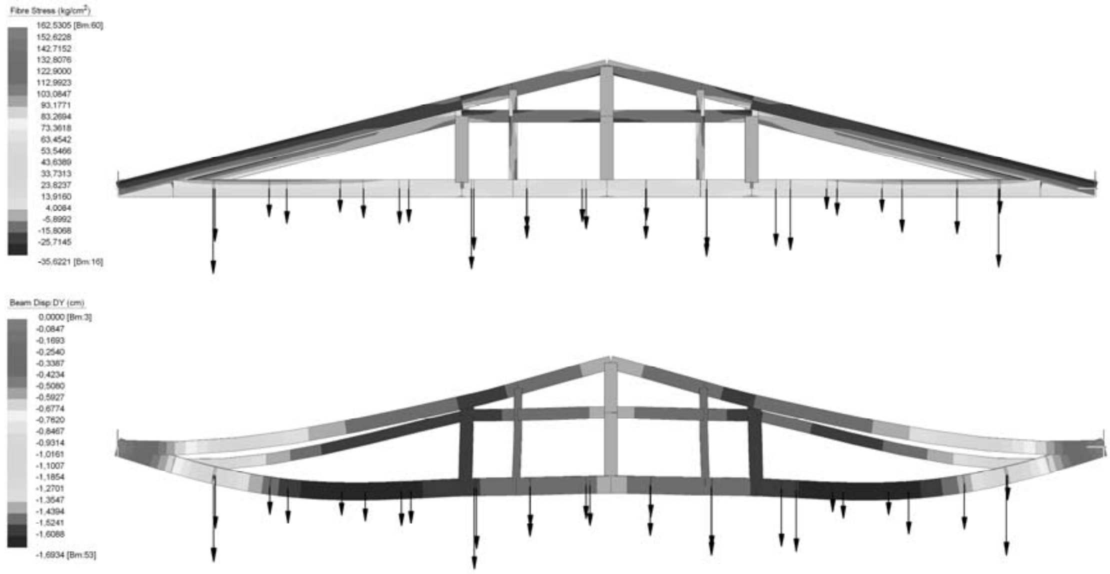

Figure 3 : Numerical model of the 7th Graldi's truss. The painted ceiling is suspended from this truss. Structural unit subjected to statical loads. Stresses (up). Vertical displacements (down).

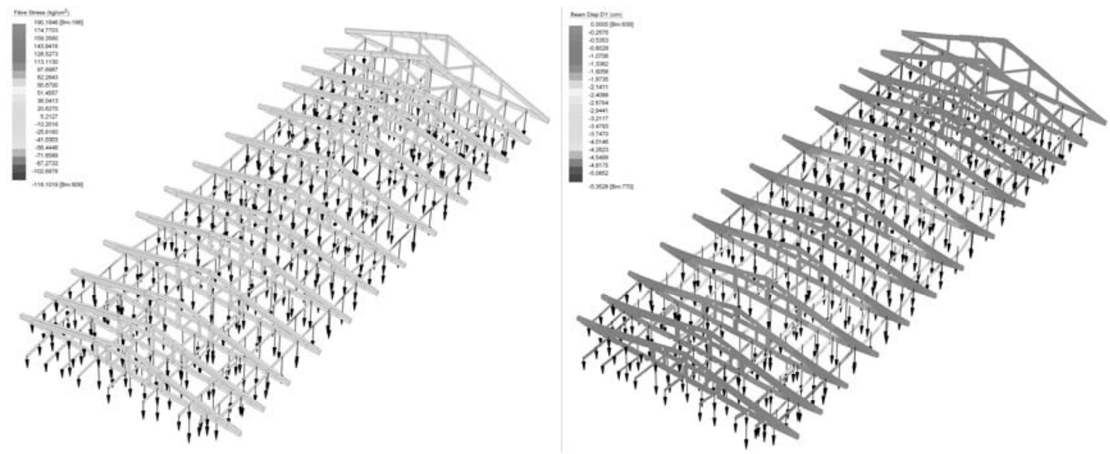

Figure 4 : Numerical model of the trusses which sustain the false celing and of the interposed joists. Structural system subjected to statical loads. Stresses (right). Vertical displacements (left).

5 DEDUCTIONS

Three numerical models of configuration for the vasarian trusses have been supposed: a) truss with post and chord not connected, chord of an only piece, b) truss with post and chord connected, chord of an only piece, c) truss as case b, chord made of two pieces. The constraint on the supports is the bi-dimensional hinges one of them being movable.

The results are that in case a) the stresses are not excessive, inferior anyhow to the today's admissible ones; very high, on the contrary, the deformations. In case b. the compression tensions are 468 N/cm^2, tension 553 N/cm^2; deformations are very low and do not exceed 1.6 cm. In case c) stresses rather; deformations are not excessive (3 cm).

We can deduce that the two rulers of the chords have been nailed at their connection at several times: there are many chances that the nailing of the kingposts to the chord is the extreme act of the stiffening attempts, posterior to the last unsuccessful nailing of the two rulers. All we can say is that this happened before modern era. The structural analysis in the new configuration shows that the stresses are rather low and anyhow absolutely admissible for fir tree.

The ceiling itself has no structure except for the boxing of the boards, no stiffness, it is deformable. The longitudinal beams resting on the chords and carrying in the middle of each bay the hangers to support the ceiling were highly deformable. And the boards as well were deformable, especially because they warped, disconnected and became unsteady. One can assume that in a first stage the ceiling sunk due to the deformation in the middle of the chord; to a second stage belong the rigid connection of the kingpost to the chord by means of nails; the deformation, also caused by creep, of the beams and of the ceiling occurred in a third phase which includes the increase of number of joists to support the ceiling. But then the situation was very confused and misleading due to the large number of supplementary beams and hangers.
Many documents (see Tampone, Derinaldis, 2005, cit.) are available that record the phases of the increasing deformation of the ceiling, the concern of the Officers of the Municipality, in charge of the Palazzo Vecchio, for the danger that a few elements of the ceiling could fall down during events or visits. What one can deduce from these documents is that the damage consisted of a significant sinking of the ceiling, especially in the middle of the Hall. None of the available documents, except a late one (see over), reaches a suitable technical level, none of them points on the understanding of the structure, on the causes of the failure, on the possible effects of the disease, on the correct way to do the repairs up to Martelli's report. The long period up to the XIX c. is characterized by irrational measures taken on the ceiling such as supplementary wooden beams set on the chords of the original trusses to keep the hangers.
After the inspection in 1854, the Engineer Giuseppe Martelli designed and built, as a remedy, two additional trusses at the head of the garret; they are, anyhow, of the old type even if stiffer and they work in the same way as the Vasari's. But they were not the solution of the problem.

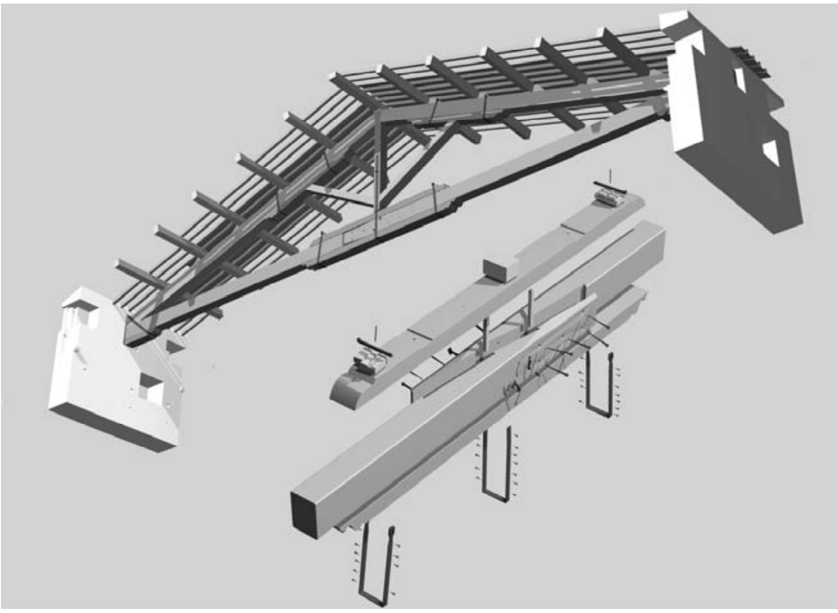

Figure 5 : The vasarian truss; exploded view of the chord.

6 CONCLUSIONS

The Vasarian trusses are in perfect order. This is due to the general factors quoted before and also to the connection of the post to the chord, operated as an early remedy of a previous not suitable configuration.
The real damage of the false ceiling was caused by the lack of self-structure of the ceiling, the deflection of the too long joists resting on the chords and sustaining the ceiling and, to this respect, by the too large bay of the trusses; the creep effect influenced in the long term the set-up as well.
The built up or engineered structures are subject to deform more than the massive pieces or the structures made of a little number of members; the excessive deformation of a structure as well

of the members is an important cause of instability. The ancient structures are often very deformed therefore unsteady due to the presence of creep effects.
The trusses of new configuration set in place by Domenico Giraldi are suitable for the purpose because they are very stiff and divide in two parts the original bay of the trusses.
The Giraldi's intervention does only add new units to the vasarian ancient carpentry, considered a masterpiece since the beginning, without subtracting anything; besides is deliberately respectful for the Vasari's architecture and construction. After one century and a half, it can still be considered a very good example of correct strengthening work of an ancient structural system.
The structural analysis proved to be a powerful mean to assess not only the condition of a structural system but also, when combined with the historical research and the direct survey, the reason of some alterations to the configuration and their sequence.

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