

Construction of structural schemes for ancient timber structures

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ABSTRACT: Historical trusses show many problems concerning definition of structural schemes, especially in relation to internal and external constraints, behaviour of elements in contact, effects of metal strengthening. This means little reliability of analytical results obtained without paying the necessary attention to those factors of uncertainty. The problem of stress distribution in simple and composed palladian trusses has been studied with special attention to principal and jack rafters behaviour in varying contact conditions. The research is composed of an experimental phase and a numerical one. In the first stage static loading tests on in scale models have been carried on: the distribution of stresses between principal and jack rafters in different contact conditions has been evaluated measuring deformations. Numerical schemes have been constructed in the second stage that reproduce the experimental behaviour with the best approximation. Results have been applied to the study of an historical truss of Naples Royal Palace coverings.

1 INTRODUCTION

The study of 15th and 16th centuries treatises and 18th and 19th centuries manuals, as well as analysis of ancient buildings surviving until nowadays, like the trusses of the church of Saint Catherine on Mount Sinai (6th century AC) or those of Cefalù Cathedral (12th century AC), allows tracing the historical evolution of timber trusses structural forms and of the structural concepts on which their construction was based, (Ceraldi et al. 2000).

From the simple shapes, like schemes reported by Jacopo Mariano, named Taccola, in his “*Liber Tertius de ingeneis hac aedifitius non usitatis*” (1427-1433) or by Francesco di Giorgio Martini in his “*Trattato di Architettura, Ingegneria ed Arte Militare*” (1481), more complex schemes were generated, like those illustrated by Sebastiano Serlio in “*I sette libri dell’architettura*” Libro VII (1584), Fig. 1.

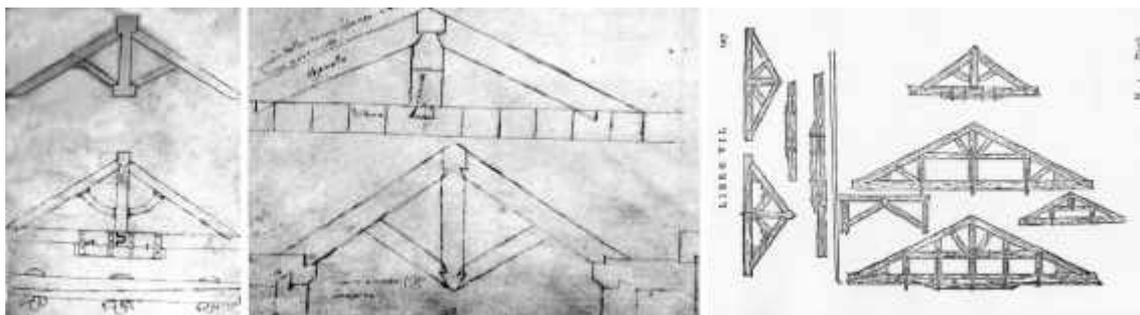


Figure 1 : Schemes of timber trusses from Taccola, Martini and Serlio.

Some of those last reported schemes can be found in the work of Andrea Palladio (1508-1580) whose designs are the starting point for the traditional classification of historical trusses as simple and composed palladian.

In Italy, the more used timber trusses typologies in historical heritage can be traced back to palladian trusses; the case of study presented in this work, the oldest timber trusses of Naples Royal Palace, Fig. 2, can be ascribed to the composed palladian typology.



Figure 2 : Naples Royal Palace truss.

The possibility of a reliable analysis of those ancient timber works depends upon a correct interpretation of their behaviour from a structural point of view, to evaluate real stress and deformation states as well as to design eventual restoring interventions.

Many different elements of uncertainty in the definition of the right structural scheme exist as:

- interpretation of external constraints behaviour;
- schematisation of joints, made of timber or with metal strengthening;
- evaluation of efficiency in the distribution of stresses of a more or less continuous contact between aligned structural elements, like principal and jack rafters.

In the present research the last aspect has been studied, comparing experimental data, obtained with tests on in scale models, with numerical data, coming from numerical calculus on schemes simulating the different kind of contact existing between principal and jack rafters.

Results have been applied to the study of Royal Palace trusses.

2 EXPERIMENTATION

In classical trusses and in almost all timber structures of the past, resistant elements in mutual contact, as principal and jack rafters, are very frequent, Fig. 3.



Figure 3 : View of a model of Palladio's Cismone bridge.

This contact sometimes is strengthened by metal strips, "straps".

Interpreting static behaviour of those structural elements in contact is not easy as it is strongly influenced by jack rafter end constraints, presence of intermediate studs (inclined struts), friction between the elements in contact, action of the straps. Those factors condition stress distribution in

truss structural elements and also influence stress repartition between principal and jack rafters; so numerical simulating of their effects on structural behaviour needs experimental assessment.

To this aim an experimental program, based on static load tests in linear elastic range, has been arranged on in scale models, as experimentation on real structures would have been too difficult in respect to loading, too expensive in respect to acquisition data, and too uncertain in the interpretation of data, due to the addition of many variables unconnected with the studied problem.

2.1 Model

A wood derived, homogeneous and stable material has been chosen to make the models, to avoid adding to the numerous variables of the problem, those variables due to characteristic properties of wood (presence of knots, fiber deviation, etc.). Then MDF (Medium Density Fiber) rods of rectangular transversal section, with variable height and a fixed thickness of 16 mm, have been used.

MDF is a material formed from wood elements reduced in fibers and merged together with isocyanic resins; it is produced in panels of constant density in thickness. MDF characteristics, deduced from an extensive experimental research, (Ceraldi et al. 1999), show great stability in linear – elastic behaviour at a constant moisture content. Mean density of the used MDF is 710 kg/mc, axial compression rupture stress is 17 MPa, and elastic modulus is 2734 MPa.

The design of models refers to two truss prototypes of 20.00 m span, 30° pitch inclination, of fir wood (elastic modulus 11000 MPa), with joints made by steel pins. Prototypes schemes are those of palladian trusses with and without secondary posts and inclined struts.

MDF models of those prototypes, 1:10 scaled, Fig. 4, have been tested with static loads which simulate loads distributed on the principal rafters of the prototypes. Loads evaluation, based on mechanical similitude laws, has been made so that loads will induce on the models deformations readable with sufficient precision using a millesimal deformeter, but at the same time they will produce stresses in the linear elastic range, making tests repeatable more times on the same model.

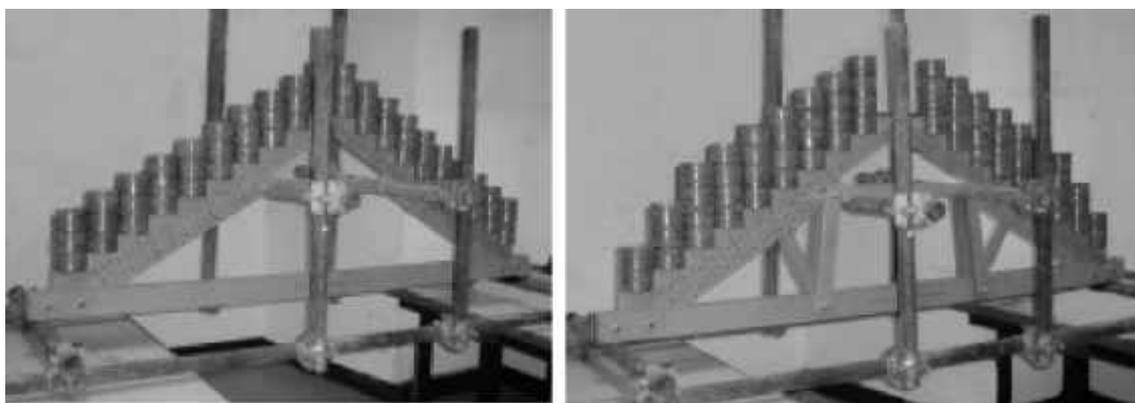


Figure 4 : Models of palladian trusses

2.2 Tests program and experimental results

Experimental research aim has been the study of the different distributions of axial stresses between principal and jack rafters, when their contact conditions vary, while loads are applied on the principal rafters.

On the first palladian truss model, three different contact conditions have been simulated, inserting little metal square plates, side 16 mm, as spacers between principal and jack rafters.

1. The first condition has been created inserting two plates in correspondence of jack rafter ends; this configuration simulates absence of longitudinal contact between the two structural elements but at the same time loads transferring from principal rafters to the arch constituted by collar beam and jack rafters is guaranteed.

An alternative scheme has been obtained enlarging plates dimensions to simulate more efficient constraints at the ends of jack rafters.

2. The second condition has been obtained adding a third plates in the middle of jack rafter ends. This scheme can simulate the presence of a discontinuous longitudinal contact which, in a real prototype, can occur when scarcely rectilinear rods touch each other in a discrete number of points, or when the two separated structural elements, are forced inserting wedges or metal strips.
3. The third condition has been realized putting principal and jack rafters in continuous contact.

MDF panels making process gives smooth and uniform external layers, while transversal sections show great roughness. As MDF rods in the model are in contact along those transversal surfaces, there is a strong impediment to mutual sliding, as can be seen from lateral confined slipping tests. Those tests gave a slipping coefficient of 2.17 for MDF, while the corresponding value for wood is 0.45.

Finding a so strong contact condition in existing typologies of historical buildings is very difficult; consequently experimental values obtained in this third condition can be considered as an upper bound.

On the second palladian truss model, only two contact conditions have been tested.

1. The first condition has been realized inserting the metal plates at the superior ends of inclined struts and at both ends of jack rafters, obtaining contact absence in free tracts. Short length of those tracts makes meaningless the contact condition that in the first model corresponds to the inserting of three plates.
2. The second condition is that corresponding to the absence of plates, putting structural elements in touch for their global length.

For each contact condition three tests have been made, loading models with cast iron blocks and reading induced deformations by principal and jack rafters axes on a gage length of 50 mm. For each test axial stresses corresponding to those deformations have been calculated and then weighted averaged stresses in the jack rafters and in the matching tract of principal rafters have been obtained. The diagram of axial stresses for a test in the first contact condition on the second model of composed palladian truss is shown in Fig. 5.

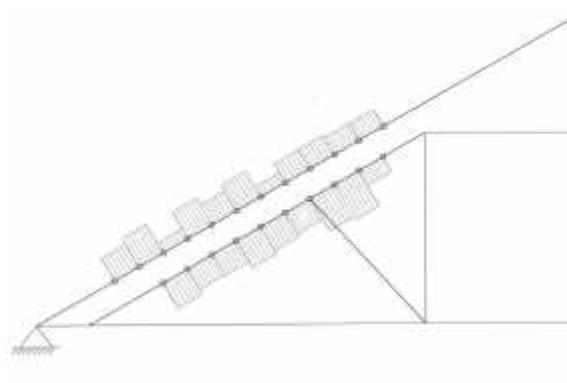


Figure 5 : Experimental diagram of axial stresses

Stress mean values for the jack rafter and the corresponding tract of principal rafter are expressed as rates of the total stress taken up from pitch structures.

In Table 1 the percentage mean values of the three tests made for each kind of contact condition are given.

Experimental data in Table 1 show that the behaviour of the first palladian scheme in absence of contact is such that loads applied on the principal rafter are carried on the junction between jack rafter and collar beam, which is the natural middle support of the principal rafter and consequently bears the most of the load, diving it between jack rafter and collar beam.

When joint efficiency increases, load carried by the jack rafter tends to move on principal rafter. This effect is mainly due to the position of the end bearing of the truss at the inferior end of

the principal rafters, while the jack rafters are pinned to the tie beam, so principal rafters end bearings are stiffer than that of jack rafters.

Table 1 : Mean experimental values of percentage incidences

| | Principal rafter (%) | Jack rafter (%) |
|---------------------|-------------------------|--------------------|
| First model | | |
| n.2 plates 16x16 mm | 43 | 57 |
| n.2 plates 16x32 mm | 51 | 49 |
| n.3 plates 16x16 mm | 56 | 44 |
| Continuous contact | 66 | 34 |
| Second model | | |
| n.3 plates 16x16 mm | 43 | 57 |
| Continuous contact | 52 | 48 |

In the second palladian scheme, the presence of inclined struts and secondary posts alters significantly the simplicity of stresses distribution mechanism and tends to distribute stresses equally between principal and jack rafters. As a consequence, variation in contact conditions becomes quite irrelevant.

3 NUMERICAL SIMULATION

The numerical simulation has been done with a finite element program (Nolian by Softing) in a mono-dimensional schematisation.

Numerical computation has been made on the structural schemes of the prototypes, Fig. 6.

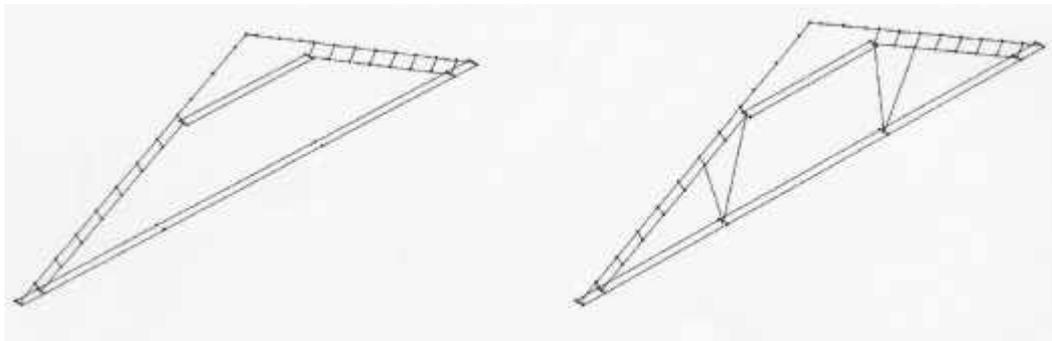


Figure 6 : Computational schemes of the prototypes

Numerical modelling of contact variations between principal and jack rafters to obtain numerical data comparable with experimental ones has been achieved inserting structural elements of square transversal section, made of the same wood as prototypes, clamped at the ends and spaced of about 1.00 m. Variability in contact conditions has been reproduced varying transversal dimensions of those timber rods.

Clamped linking rods are an obstacle to mutual translation between principal and jack rafter; so increasing their stiffness makes shear components that they transfer from principal to jack rafter larger.

Stress mean values for the jack rafter and the corresponding tract of principal rafter, expressed as rates of the total stress taken up from pitch structures, are recorded in Table 2.

Comparison between Tab. 1 and Tab. 2 shows that the introduced schematisation can well simulate contact between principal and jack rafters.

The gradual passage in prototypes from a scheme without linking rods to a scheme with rods of 150 mm of transversal dimension reproduces the whole range of the experimental data.

| | Principal rafter (%) | Jack rafter (%) |
|----------------------|-------------------------|--------------------|
| First prototype | | |
| Without linking rods | 44 | 56 |
| Rods of 50x50 mm | 53 | 47 |
| Rods of 100x100 mm | 60 | 40 |
| Rods of 150x150 mm | 68 | 32 |
| Second prototype | | |
| Without linking rods | 45 | 55 |
| Rods of 50x50 mm | 46 | 54 |
| Rods of 100x100 mm | 48 | 52 |
| Rods of 150x150 mm | 51 | 49 |

The axial stress diagrams reported in Fig. 7, corresponding to contact simulations obtained with linking rods of 50x50 mm and 100x100 mm transversal section dimensions, respectively, reveal the huge transfer from jack to principal rafters, when linking rods become stiffer.

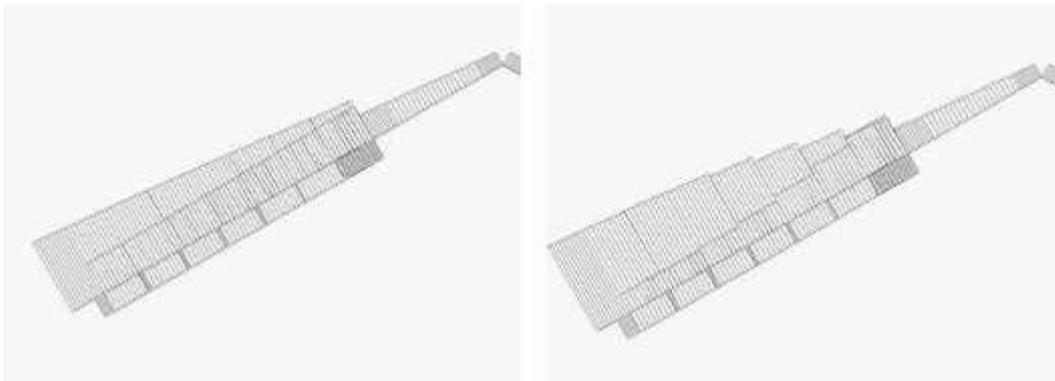


Figure 7 : Axial stress diagrams on prototypes with different contact conditions

4 NAPLES ROYAL PALACE TRUSSES

Covering system of Naples Royal Palace is constituted of many different structures varying for constituent materials (wood, glulam, steel, reinforced concrete) and for typological schemes.

In the Palace western block there are timber trusses that presumably were built during the former setting up of the 17th and 18th centuries. Their typology is that of composed palladian truss, with king post and inclined struts, queen posts and lateral inclined struts, collar beam and tie beam. In this area there are three different versions of the same palladian scheme, with different spans. The trusses studied in the present work, in number of 36, cover the largest area.

They have a span of 19.90 m, between perimeter walls with a mutual distance of 1.90 m. Pitch planes have about 31° slope and the inside height in correspondence of ridge is 5.56 m, Fig. 8.

The truss typology and the large height and transversal dimension allowed the construction of an attic, building a floor carried by the tie beams. The counterlath consists of purlins spaced about 0.30 m, which carry timber planking, water proofing sheath and tiles. The wood specie of the trusses is fir of Sila, named “zappino”, a wood frequently used between 17th and 18th centuries, to make covering timber structures of large span. Most of the joints are timber on timber mortising joints, while principal and jack rafters in some points are linked by forged iron straps. Other metal jointing elements are the traditional U-bolt which connect queen and king posts to the tie beam. On principal rafters longitudinal timber rods lean, which share out covering loads without cooperating to the structural scheme as they are in no ways jointed to the principal structure. The end joints of principal and secondary rafters to the tie beams, which are put inside masonry almost everywhere, are visible only where aeration niches have been cut off in perimeter walls.

Tie beams and supporting timber corbels aren't visible as they are under pattering floor.

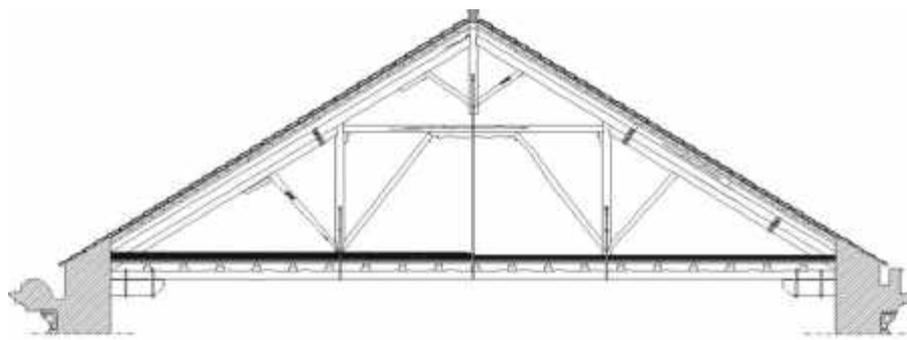


Figure 8 : Front view of the studied truss

4.1 Decay analysis

Only one of the 36 trusses has been analysed, which for its decay conditions seemed representative of the state of the whole structural set.

To evaluate truss decay a visual analysis has been made to survey: biotic decay (fungin attack, woodworm presence, etc.); timber defects (splits, knots, fiber deviations, shrinkage racks, etc.); gaps and detachments; hygrometric conditions of each timber element; conservation state of joints.

To detect eventual decay presence inside the timber elements and to survey the real dimensions of unapproachable parts, the resistographic method has been employed. This method is based on the use of an electric penetrometer, the Resistograph[®], manufactured by IML (Rinn, 1998).

Resistographic inspection has been made particularly on the tie beam placed under the floor, which has been reached opening four trapdoors cut off the planking. So surveying of the structural elements of the planking has been possible: timber rods leaning on the tie beams, and disposed in the orthogonal direction, spaced of about 0.90 m; a wood floor 0.04 m thick; double layer of terracotta tiles, an expanded clay layer of variable thickness and finishing bitumen sheeting.

The resistographic inspection also allowed survey of timber corbels whose dimensions are 1.30x0.26x0.40 m. Resistographic tests made in different sections of structural elements, together with material decay detachment, Fig. 9, has allowed asserting that inspected elements are in a good state.

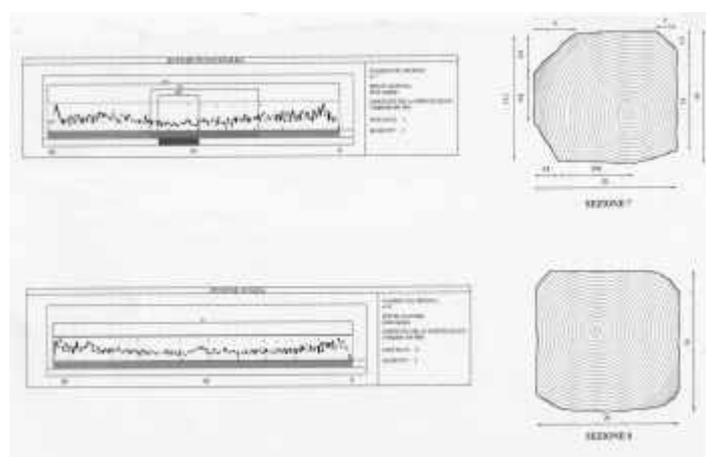


Figure 9 : Example of geometrical and resistographic survey on rafters

Analysis of joints and structural elements state has shown: biotic decay and gaps on lower left inclined strut, in the north-west pitch; little biotic decay on north-east principal and jack rafters; knots, fiber deviations and shrinkage racks on many elements.

Results of decay analysis have been considered in making structural analysis, with reference to dimensioning real resistant sections, and schematising internal constraints.

4.2 Numerical analysis

To make numerical analysis of the chosen truss, load analysis has been carried out, taking into account principal as well as secondary structures (purlins, planking, sheet, tiles, etc.), and respecting criteria and values prescribed by in force Italian laws. Accidental overloads on attic floor have been put equal to zero to obtain real load conditions, as this space isn't used now.

Snow overloads determine two different load conditions.

Defining as well as possible the structural scheme on which numerical simulation will be made, employing a finite element program, with mono-dimensional schemes, needs the interpretation of the kind of jointing existing between principal and jack rafters.

Visual inspection shows that contact between principal and jack rafters is quite discontinuous due to many factors, as:

- simple rough-hewing of used trunks, which leaves section profile partially rounded, reducing contact area largeness, Fig. 9;
- presence of few straps, which also are almost released, Fig. 10.

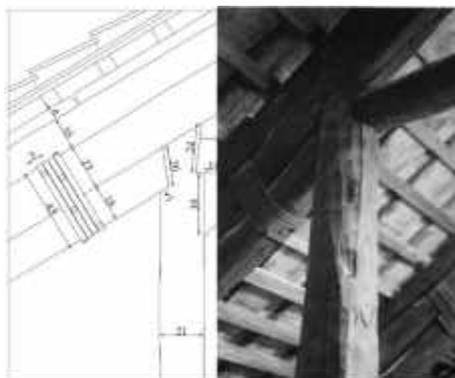


Figure 10 : Strap joint on left pitch plane

Comparison between numerical and experimental results, quoted in the preceding paragraph, allows inferring that simulation of contact conditions for the inspected truss can be made as follows:

- for the lower part of left jack rafter, as there aren't straps, quite a small obstacle to mutual sliding can be supposed; consequently clamped linking rods of 25x25 mm section, spaced about 1.00 m, are introduced in the calculation scheme;
- for the remaining part of left jack rafter, and for the whole right jack rafter, section of those linking rods has been put equal to 50x50 mm, taking in account strap presence.

At the aim of verifying coherence of this choice with results obtained for the prototypes, as structural scheme of the second prototype, Fig.6, is simpler than that of studied truss, Fig. 8, this last one has been modified suppressing upper inclined struts, the king post and metal tie-rod, and removing permanent overloads on the tie beam, which there aren't in the prototype.

Percentage incidence values of axial stresses absorbed by principal and jack rafters, in this transformed schemes, are 47% and 53%, respectively, which sufficiently agree with theoretical results of Tab.2 (46% and 54%), for linking rods of 50x50 mm. The little difference in percentage values can be ascribed to the unavoidable differences between the two schemes.

Numerical calculus on the complete scheme of the studied truss shows a larger difference in percentage values between the two structural elements, 56% in the principal rafter and 44% in the jack rafter, than the simplified scheme. This behaviour is clearly due to the central metal tie-rod which, supporting the tie beam in its more inflected point, transfers the loads directly on the principal rafter.

In the end, applying the overloads that really rest on the tie beam, obtaining the real calculus scheme, significant variations in the reported percentage values can't be seen while obviously there is a relevant increase in axial stresses.

In Fig.11 axial stress and bending moment diagrams for the real calculus scheme are reported.

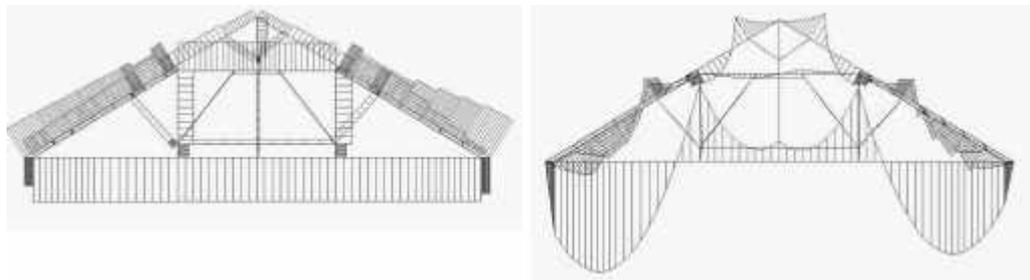


Figure 11 : Stress diagrams of the real scheme

Safety verifications of structural elements have been made with the maximum allowable stress criterion. No reference has been done to limit state verification criterion reported in Eurocode 5 (UNI ENV 1995 – 1–1 Eurocode 5 Design of timber structures), as this normative is still not in force in Italy.

For fir timber classified of II category, allowable normal stress, parallel to fibers, is $\sigma_{D//}=9\text{MPa}$ (Giordano, 1999).

Truss elements in which maximum normal stress is greater than allowable value, for all loading conditions, are the tie beam and the principal rafters:

- in the tie beam $\sigma_{\max}=13.85\text{ MPa}$
- in the principal rafter $\sigma_{\max}=12.96\text{ MPa}$.

From those values it is evident that the studied truss isn't in safety conditions.

4.3 Restoration proposals

Examining the stress state quoted in the preceding paragraph, it can be inferred that the structural elements that need an intervention to bring stresses back to allowable values are principal rafters and tie beam.

As inspections have revealed that wood is in a good state, it is believed that the optimal solution will consist of a redistribution of stresses in the truss elements, and of an increase in resistant section dimensions, retaining all original rods without inserting prosthesis. At the aim of reducing stresses in the tie beam, insertion of a system of forces generated by metal tie rods appropriately disposed is proposed. First of all the intervention concerns the attic floor, which loads tie beam too much, as it has been subjected to many works directed to increasing water proofing and insulation. It is appropriate noting that under the tie beams there are the carrying structures of the ceilings of the Royal Palace apartments, rich of frescos of great value. This circumstance obliges to intervene from above, as buttressing tie beams isn't possible, and suggests to reinforce the trusses without removing them.

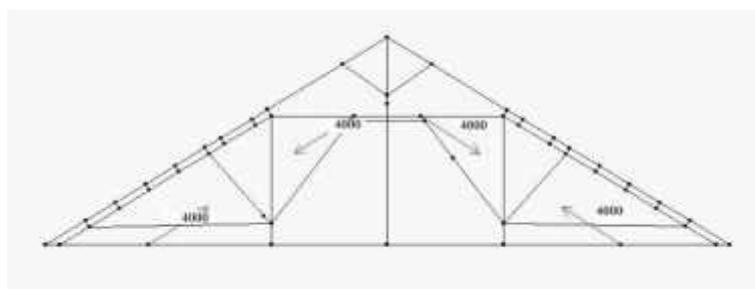


Figure 12 : Positioning of tie rods

So attic floor removal is planned; then supporting corbels must be made integral with tie beam ends, through the use of bolted steel plates, and at the same time two steel tie rods will be inserted,

subject to a pulling tension of 4000 daN, Fig. 12. Tie rods will be made with steel round bars of 24 mm of diameter, pulled by metal turnbuckles, alike those employed for tensile structures.

Calculations made tacking into account a new planking, constituted of double wood floor, upper reinforced concrete slab 0.04 m thick, water proofing sheet and overloads of 100 kg/mq, to guarantee safety during the next phases of the intervention and during ordinary maintenance operations, have given in any structural elements stresses less than the allowable stress.

Relating to stress diagrams of Fig. 13 next values have been obtained:

- in the tie beam $\sigma_{\max} = 2.10 \text{ MPa}$
- in the principal rafter $\sigma_{\max} = 8.01 \text{ MPa}$.

where the very low value in the tie beam is due to jointing with supporting corbels.

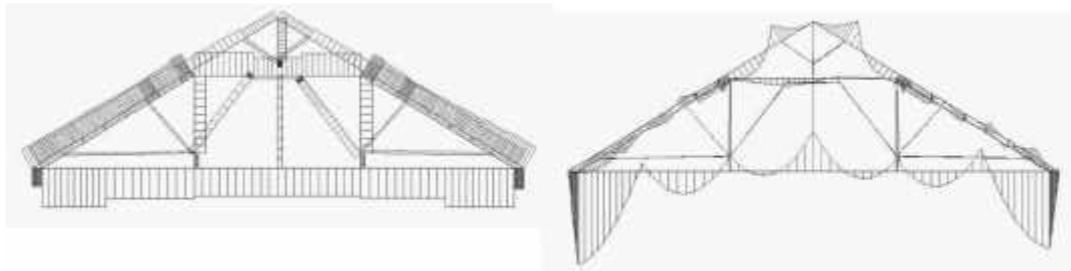


Figure 13: Stress diagrams of the real scheme after the intervention

5 CONCLUDING REMARKS

The proposed methodology for the restoration of timber trusses seems the easiest from a constructive point of view, tacking in account the peculiarity of the area (presence of the a fresco ceilings which doesn't allow the intervention from the above). But this methodology, based upon the redistribution of the stresses in the structural elements, needs knowing the real static scheme of the existing structure. To this aim a theoretical–experimental study on the behaviour of timber trusses in presence of resistant elements in contact has been made. Particularly, the simulation of principal and jack rafters behaviour in presence of different contact conditions can be obtained inserting in the mono-dimensional calculus scheme rods with different stiffness depending upon the different degree of mutual sliding. The efficiency of this simulation is confirmed by experimental data.

Obviously the structural scheme of a truss basically relies upon its typological scheme. This research is devoted only to examining composed palladian trusses; extension to different typologies will necessitate a specific experimental study. Another delicate question is the numerical modulation of internal constraints in historical structures, which are not specifically dealt with in the present research and which in any case can't be easily generalized. The study of the influence of all this factors enriches the comprehension of the behaviour of complex structures as ancient timber trusses and is essential in designing any restoring intervention.

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