The Timber Roof of Hagia Paraskevi Basilica in Chalkida, Greece: Multi-Disciplinary Methodological Approaches for the Understanding of the Structural Behaviour. Analysis and Diagnosis

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6 Dendrodata

1. Methodological introduction

The outstanding aspect of the study derives from the extraordinary combination of different factors that take part in making the contribution in its complex a real “lectio magistralis”. In fact, the involvement from one side of two European Universities (National Technical University of Athens and Politecnico di Torino) and on the other side of two National Board of Antiquities – Ministries of Culture (of Greece and of Venice), on the problem of conservation of cultural heritage has brought to the definition of a working methodology that integrates and sometimes opposes two different cultures, offering an international dialogue between specialists in the field of timber structure conservation in the Mediterranean Basin.

All this finds justification in the case study of the extraordinary timber roof of the church of Hagia Paraskevi. And it couldn’t be in a different way: the church was realised in Greece in 13th century, the constructive typology - and maybe also the materials – derive from the Venetian school. Undoubtedly the influence of the late gothic Venetian style on the Greek construction develops in this roof structure with rare efficacy: for the truss typology at three elements, for the “barbacani” corbels, for the stone corbels, for the decorations with the winged lion, etc.

Therefore, promoted by Prof. Panos Touliatos (NTUA), Dr A. Miltiadou-Fezans and N. Delinikolas (HMC), a wide Greek and Italian working team (about 20 people) was constituted, for the evaluation of the mechanical behaviour and failures of the great timber roof structure.

The components of the research represent scientifically qualified authorities in different fields, for e.g. architects, civil engineers, architecture historians, wood technologists, dendrochronologists, architectural survey. The collaboration developed in the past years proved to be absolutely necessary in order to reach valuable, useful and innovative results in the specific field of the preservation of timber structures, which are of historical interest. Politecnico di Torino was coordinator and NTUA partner of European project "Wooden Handwork/Wooden Carpentry: European Restoration Sites" in the frame of Culture 2000 programme, which compared at international level theoretical knowledge acquired in the different countries for the characterisation of wood, diagnosis and guidelines for conservation.

For the comprehension of mechanical behaviour have been used the recent Italian standards (UNI), result of a multi-annual work of the Working-group GL 20 "Wood and wood-based products in cultural heritage". The basic themes of restoration, reinforcing and maintenance of built heritage, with
particular attention to wood in cultural heritage, require new criteria based on multidisciplinary integrated competences, to support decisional and social complex processes.
Referring to these considerations, the interests of the proposed research are directed towards the innovation of methods, techniques and instruments, related to the organisation and management of interventions on built heritage, in order to develop an approach that is:
- multi-disciplinary, for the study of complex problems, such as the ones concerning cultural heritage;
- multi-scale, to take in account both single elements and the whole structure;
- multi-state, tailored to the different requirements of countries;
- multi-objective, customised to the different and integrated aims identified by a survey (diagnostics, conservation, restoration, maintenance, use, management);

2. Mechanical behaviour and failures of timber structure: comparison between roof structures of the Venice arsenal and Hagia Paraskevi Church

The mechanical behaviour of ancient timber roof structures highly influenced by degradation phenomenon, so that the structure results inadequate for its functions performance. In relation to the causes, to the environment and sites, the decay can sometimes be evident, in other cases can be more insidious and can be determined only with accurate surveys on the material, on the components and on the connections. The theme is therefore strictly linked to structural safety and to the actual requirements of a higher performance compared to the original one.
The timber roof structures of Venice (in particular of the Venice Arsenal) and the one of Hagia Paraskevi church do have a common aspect: the marine environment with thermo-hygrometric conditions often of high risk. In the Hagia Paraskevi church case we have to add the great seismic risk. (Fig. 1)

![Figure 1. Similar failures of the timber structure: roof trusses from the Venice Arsenal (top) and from Hagia Paraskevi church (bottom)](image)
The research intends to define a methodology that faces the restoration of roof structures of historical interest paying attention to the aspects of structural behaviour. The crucial scientific starting point keeps in consideration the coherence of data of mechanical behaviour of the timber on-site, in relation to the thermo-hygrometric and chemical ones.

3. The case-study: Hagia Paraskevi Church

3.1 Historical summary

During the period of Frankish rule, Chalkida was called Negreponte. (Fig. 2)

![Figure 2. Map of Greece with the location of Chalkida.](image)

Its strategic position for the conduct of trade in the Aegean and the wider area of the Eastern Mediterranean meant that often in its history it became a site of strife between many conquerors.

Contact between the town and the Westerners date back to the Byzantine period, when emperors of the Komnenian dynasty (Alexios I, John II and Manuel I), granted commercial privileges to the Venetians. In 1205, shortly after the capture of Constantinople by the Crusaders, Boniface of Montferrat, the ruler of the Latin kingdom of Thessaloniki, captured Euboea on his way to the Peloponnese. Boniface divided the island into three fiefs, which he granted to three *terziari* or triarchs, who were knights from Verona (Ravanno dalle Carceri, Percararo de Mercanuovo and Giberto dalle Carceri). In this way the island was divided into three parts, excluding Chalkida, which was jointly owned by all three.

After the recapture of Constantinople (1261), Michael VIII Palaiologos entered into an agreement with the Genoese in order to confront the Franks and Venetians. This agreement did not produce the anticipated results. Relations between the Byzantines and the Venetians were regulated by treaties in 1302 and 1310, according to which Chalkida remained a Venetian possession. After 1390 the Venetians were the sole rulers of the
whole of the island. The Byzantines thus finally departed, while at the same time the Ottoman Turks began to make their presence strongly felt. They finally captured Chalkida in 1470 under Mohamed II.

Chalkida was the seat of an Orthodox bishoicpgic, but after 1261 Negreponte became the seat of the Latin Patriarchate. Because of its strategic and commercial significance, the Venetian part of the town was fortified in 1303 by Francesco Dandolo, and was completed in the 15th c. This fortification was kept and parts of it was renovated by the Turks, although Mohamed II destroyed a large part of the town when he captured it. Negreponte certainly had several Catholic churches, but most scholars are agreed that Hagia Paraskevi was the most important. According to the modern scholar J. Koder, it was not a parish church but a cathedral. Very few Catholic parish churches have survived in Greece. The majority of them were used by monastic orders who received the support of the Holy See. The Catholic communities were not numerous enough in every region to need many parish churches, while the Greek population preferred Orthodox churches. According to more recent researches and the identification of two of the sculptured monks on the great arch with the saints Dominic and Peter of Verona, it is most probable that the Venetians collaborated with the Dominican order in Negroponte to the building of this Church (MacKay, Delinikolas-Vemi).

### 3.2 Description of the church

The church is a three-aisled basilica. The central isle ends in a flat sanctuary, and the side isles in square chapels that have no apses. The site on which the modern church stands was occupied by a Byzantine church of the late 5th or early 6th century. In the period between its initial erection and its modification in the 13th century, there were probably other changes. The first basilica was probably destroyed during the course of the Frankish occupation in the 13th century. It was reconstructed involving modifications and additions to the ground plan and the superstructure. Some of the columns of the basilica were retained in situ and their basis were incorporated into the modern floor.

The west facade and the south wall were reconstructed in the 14th or 15th c. and the west façade was reconstructed again after the earthquake of 1853. At this time it was probably set about ten meters back, since two Early Christian columns are preserved now in front of the modern façade.

After 1853 a wooden upper gallery was added at the west end, which is supported by two built piers. (Fig. 3)

The construction style above the slightly pointed arches is an early example of the blending of Western and Byzantine forms and techniques. It is a free cloisonné system, in which decorative brick work is added here and there. The view has recently come to be accepted that this coexistence of western and Byzantine elements is “a deliberately anachronistic phenomenon”.

In the interior, the aisles led to the sanctuary and the chapels by way of three pointed arches. The side arches of the church are very simple. The only decoration they bear is a flat band, which emphasises the openings even further. The central arch is possibly the most impressive feature in the church, thanks to its highly elaborate sculpted decoration. It is a double arch, 5.50 metres high, decorated with two concentric relief bands.

The sanctuary before 1853 and the side chapels are roofed by ribbed cross-vaults. The ribs end in elongated corbels, richly decorated with lace pattern, which may be dated to the 13th century.

The corbels of the north side chapel exhibit a mixture of Western forms in the treatment of the volumes, with the Byzantine decorative style dominant in Central Greece at the end of the 12th and beginning of the 13th century. It is apparent that a historically very interest collaboration happened between Greek, Italian and French artisans.

Externally, the basilica was supported by four buttresses on the south side, the two of them of 14th or 15th c. and only two on the north.
Apart from its west end, Hagia Paraskevi is a Gothic church built on the foundations of an early Christian basilica. It was probably constructed during the last quarter of the 13th c. (Fig. 4)

Figure 3. General view of Hagia Paraskevi church
3.3 Roof construction

The pitched timber roof probably belongs to the 13th-century phase and has many parallels in western Europe, and also many similarities with some Italian roofs. (Fig. 5)
The aisles are covered with lean-to roofs which were reconstructed repeatedly in the 14th, 19th and 20th centuries. The trusses of the central roof with their corbel are excellent examples of Venetian art and were probably brought to Chalkida from Venice. Corresponding corbels dating from the 14th century can be found in buildings in Venice.

The wooden corbels of the roof are decorated with geometric and floral motifs, and enlivened with winged dragons and escutcheons. One of the escutcheons bears the winged lion of St Mark.

**Roof typology:**

The roof of the central nave was initially composed by a system of 21 trusses, 17 of which exist until today, in of about 8,50 m of span with an inter-axis of about 1,70 m. On the trusses there are timber joists (many of them seem substituted) and on them there are wooden boards on which lays the roof covering. Over the boarding lays the roof covering of Byzantine type tiles. The trusses are supported on the North and South stone masonry walls of the central nave of the church.

**The trusses:**

Each truss is made of only three elements, a horizontal tie beam and two rafters, directly jointed without the presence of a king post. All the three elements are derived from a single bolt transformed into sharp edge beam by manual sawing and axing, and are jointed together with the mortise and tenon system (see survey of single joints). Each truss lays on two brackets which are not included into the grading.

The span covered by the tie beams (distance between the two walls) is 8,50 m and the section of the timber elements is around 20x30 cm, but they are not perfectly constant all along the elements.

Some squared horizontal elements lay (jointed with nails) by the tie beams both near the tie beam – rafter joints and at mid-span. The mid-span elements are bearing the church’s chandeliers. (Fig. 6)
4. Architectural survey

In general, survey is the first real inspection aimed to identify quality and characteristics of each element. The conducted survey concerned all the joints tie-beam/rafter of the trusses. The geometric characteristics of the whole structure and the joints are reported on accurate drawings in scale 1:50 and 1:10. A part of the diagnostic survey was the

**Figure 7.** Constructive survey, detail of the connection between tie-beam and rafter in the masonry.
systematic constructional analysis of every joint that could be reached. Mainly axonometric sketches and drawings were used, for the recording of the original constructional details, the pathology and in many cases the previous interventions. This survey was supported by a punctual inspection with Resistograph, that has allowed not only to verify the conservation state of the material, but also and mainly, the characteristics of the joint, this permitting to give dimensions of the tenons and mortises, where present. With the combination of observations and the performed tests, it was possible to determine the functionality of the connections, their alterations, the passed interventions, with the aim of determining the real efficiency (or not) of the connections. (Fig. 7)

In all the trusses, the connections among the rafters on the top of the roof have been visually examined. In some cases, densitometric tests have also been made in order to determine geometric characteristics of the joint, otherwise not possible to be verified. From such survey it was possible to verify that all the original joints of the structure where tenon and mortise, both for tie-beam/rafter, and for rafter/rafter at the top of the truss (the dimensions of the parts respect the values around of 1/3, 1/3, 1/3). The drawings report both the original section, and its reduction due to decay. (Fig. 8)

Figure 8. Constructive survey, detail of the connection between tie-beam and rafter in the masonry and detail of longitudinal timber elements.
In very few selected areas the part of the masonry that was around the timber elements was removed, in order to verify visually the results of the Resistograph. These cases were limited because the top of the walls that the roof rests should not to be disturbed especially in a seismic area like Chalkida, without first taking securing measures.

5. Diagnosis survey

On the timber roof of Hagia Paraskevi Church, both inspection and grading methodologies were carried out following the Italian standard UNI 11119:2004 Load-bearing structures – On site inspections for the diagnosis of timber members. This standard establishes objectives, procedures and requirements for the state of conservation diagnosis and for the strength and durability evaluation of timber members in load-bearing structures, through the execution of in situ inspections and the use of non-destructive techniques and methods.

Following this procedure, the inspection was carried out in order to obtain information about:

1. wood species of the elements composing the structure. Through wood identification the wood mechanical profile became knowable for that precise wooden specie composing the structure.

2. Wood moisture content estimation. The knowledge in wood moisture content is important because it is a limiting factor for the development of fungi and wood boring insects able to damaging wood. The wood moisture content was estimated by pin type moisture meter.

3. Class of biological risk of the timber members. In order to establish the hazard classes of biological attack the UNI EN 335:2006 was followed. In this standard five classes of biological attack are identified, each one is defined by its service situation and the moisture condition of the wood in that situation.

4. Geometry and morphology of the timber members indicating the position and extension of main defects, decay or possible damage were surveyed and checked

5. Position, shape and dimension of the critical zone and critical section. Critical section is defined as the cross section which is representative of a critical zone. All the defects, anomalies, alterations, damages and other characteristics that are present in the critical zone and have an influence on its strength are attributed to the critical section. Critical zone is defined as the part of a timber element with longitudinal axes no less than 150 mm of lenght, which is considered to be relevant for the diagnosis because of defects, position, state of conservation and also stress conditions which are determined by structural analysis.

6. Strength grading of the timber member as a whole and/or in single critical zones. The strength grading was carried out on each structural wooden element because of high wood characteristic variability.

In case of alterations which were not visible on the surface of the timber member, but which were supposed to be present inside, the survey must proceed with the execution of non destructive tests. A dynamometric drill was employed for the diagnosis of defects or not visible wood damages. The instrument system is based on a drilling resistance measuring method. A drilling needle with a diameter of 1,5 to 3,00 mm penetrates into the wooden object with a regular advance, and the drilling resistance is indirectly estimated. The data are recorded on a paper or wax paper strip at a scale of 1:1 or instantly printed out by a printer. The wood will only be insignificantly injured, the more as the borings will remain in the drill hole and thus close it.
Figure 9. Diagnosis Thematic Fiche

A special computer software serves for creating measuring profiles, on the basis of which the data collected may be rapidly and exactly analyzed and catalogued.

Through the knowledge on wooden specie, geometry and morphology of the beam, defect position and extension and with the results from non destructive instrumental inspection the strength grading was possible. Through an accurate inspection the parts that show visible alterations on the surface were detected, besides various types of alterations, also the origin, dimension and position of peculiar defects which may influence strength and stiffness characteristics, as well as the mechanical performance of the timber member, were taken into consideration. Every single structural timber member was graded according to strength. Any time when alterations were found, their position and extension in relation to the length of the timber member and if possible, in relation to its cross section was established; in this last case, the “efficient section” was determined, which is the cross section minus the areas with decay.

An important phase of the work has focused on the inspection of the joints tiebeam/rafter and, where possible, rafter/rafter. The data plotting and reporting has been organized in thematic fiches, catalogue of all structural elements, considerations of reliability, assessment of residual resistant section and initial intervention indication. Local decay has been identified and explained in terms of a prolonged lack of maintenance, responsible for partial loss of material.

The aim of the investigation was to assess, quantitatively, the resistance of constructive materials, according to the criteria and recommendations of the new law about to come into force – and to ascertain the extent of decay together with the risks of...
deterioration of the individual elements (and connections), bearing in mind the preservation/conservation perspective. A conservation, which is vital, due to the high value of the building where the roof is located.

The identification and inspection phase, preceded by partial drawing (in particular of the joints) up of the diagnostic investigation project, included:

- recognising the wood species (mainly larch for the trusses and oak for the timber laccings embedded in the walls);
- determining their natural durability and class of biological risk;
- locating and technically evaluating their main defects,
- identifying alterations and critical zones; the singling out of pathologies, either under way or non active;
- surveying of environmental and wood moisture conditions via non destructive testing (NDT) measurements;
- evaluating the residual bearing resistance of the individual items by means of penetration resistance tests in the areas of decay;
- classifying either real or suspected zones not directly accessible, such as at the bearing points and plotting and reporting is articulated on the basis of thematic fiches and – in correspondence of the joints – of thematic maps (in scale 1:10), as follow:
  1. the classification of larch wooden item in a catalogue;
  2. assessment of residual resistant sections
  3. and the initial intervention indications.

The number of elements inspected amounted to more than 18, To these the inspections are added to 12 connections between tie-beam/rafter and rafter/rafter. (Fig. 9)

5.1 Visual inspection

5.1.1 Macroscopic identification of the wood

The identification of the wood species was carried out by means of macroscopic inspection method (UNI 4390 1950, UNI EN 844-7 1999,) by recognition procedures using the naked eye, to determinate the presence or absence of anatomic elements. Sometimes these macro elements are so obvious that identification of the species - or, at least, of the order, genus and family - is very likely. Such markers include: wood porosity and colour differences between annular rings; differences between sapwood and heartwood; visibility, shape and dimensions of the rays; the presence of resin and/or pitch pockets; distinctive smells; wood colour and pattern, etc.

Regarding the wood species is related to the analogies of the wood material used in some churches in Venice. Therefore some cores have been taken with the Pressler drill, to have a better precision in the identification. Careful examinations identified Larix decidua Mill, with very similar characteristics with the ancient Venetian wood.

5.1.2 Wood quality and workmanship

The UNI and UNI EN standards grade the timber quality (UNI EN 518 1997, UNI EN 975-1 1999, UNI 11035-1 2003, UNI 11035-2 2003, UNI ISO 1039 1984) on the basis of a number of parameters including the abundance of defects. They are mainly:
- quality of workmanship;
- lack of homogeneity and defects such as knots, angle grain, deformations, checks.

Regarding the timber elements, which make up the main roof, the quality of the workmanship is mixed (UNI EN 844-3 1998); purlins and ridge beams are of rough-hewn timber with wane edges; while in the trusses, principal rafters are sawn and frequently planed. Even on the worked pieces, edges are frequently not straight. In such cases there are irregular, prismatic sections or rough-edged sections with taper greater than one tenth of the section.

Large knots are common (larger than 50 mm diameter) and also knot nests (diameter smaller than the section height). Unsound knots and knotholes have also been observed.
In these situations, a reduction coefficient of 0.75 was suggested in the calculations of residual bearing resistance.

5.1.3 Grain direction and shrinkage shake
Equally frequent are members with angle grain (between 10° - 15°), wavy grain or, in the case of some logs, spiral grain. At times, shrinkage shakes have been observed, in some cases, cracks are passing through the element, in others there are ring shakes. The more evident twistings are in the “barbacani”, where the rotation of the section is sometimes more than 20°. Occasionally, damage due to angle grain was detected, near knots in traction area. For those members with angle grain, reduction coefficients of bearing resistance will be recommended. In particular, “barbacani” which should give support to the tie-beams, very often are too much twisted to consider them as load-bearing elements. It is suggested, as a precaution, not to consider their action in relation to the truss, in correspondence of the joint.

5.1.4 Natural resistance
According to current standards (UNI EN 335-1 1993, UNI EN 335-2 1993), the natural durability of the in-situ members is as follows:
- Larix decidua Mill., medium resistance to fungi attacks, not resistant to wood borers (anobium punctatum and hylotrupes bajulus).

5.1.5 Class of biological risk
Biological risk is the hygiene-health state of wood preservation in-situ. It is necessary to determine the adverse situations in which wood may risk bio-attack, due to moisture. Regarding biological risk, it is standard to rate from 1 to 5 (1 being protected wood, 5 being material in salt water). In the building which has been inspected, ventilation is furnished by windows. The following situations have been observed during inspection:
- in general, the biological risk rating is type 1 (protected wood and low risk of direct wetting, wood moisture normally below 20 %), and the only kind of rot is that associated with wood borers.
- locally, where water leaks inside because of roofing rot, the class of biological risk rises to 3 (the wood is not completely protected and moisture content is frequently greater than the secondary risk with insects. The bearing of the trusses in the masonry walls are also to be included in class 3, although at present they are not moist. It is suggested, for the heads of the tie-beams and rafters, as well as of “barbacani”, to make a proper ventilation of the heads so to protect the material from fungi’s attack.

The building is subject to condensation phenomena which increment both the environmental and the wood moisture content.

5.1.6 Pathologies
Wood pathologies are included in the visual grading of the elements considered. The visual inspection of active and non-active pathologies revealed the presence, extent and nature of aggressors, together with the characteristics of the damage found (UNI EN 844-10 2000, UNI EN 844-11 2000, UNI EN 1311 1999); saprophyte and parasitic insect attack (shape, dimension and colour of flight holes and bore dust) co-exist with the typical aggressors of the species present on the site. Likewise, when possible, stains were examined to ascertain the presence of pathologies (infections) or harmless alterations. Possible rot infections were evaluated with the aid of a penetration method (Resistograph®). In addition, a gimlet was used to test wood solidity and a chisel to evaluate locally the
depth of attacks first level examination (visual inspection). The preservation state of material at some bearing points in the masonry was assessed using invasive investigation techniques. More detailed explanations are provided below.

Appart detailed evaluation used to classify the single items, the following general observation can be made:

- *Larix decidua* Mill members have been attacked by saprophyte anobium coleopters (*Anobium punctatum* and/or *Oligomerus ptilinoides*) up to 10-15 mm depth, limited to edge areas (remains of sap wood). Active attacks have not been found, only passed attacks. This is important in the evaluation of possible conservation interventions.
- Infection are local and non-active. More serious attacks have been found close to the truss bearings, where stagnation and lack of ventilation have favoured spore taking root and hyphae proliferation (in particular in the joints tie-beam/rafter inside the masonry).

(Figures 10-11-12-13-14-15)
5.2 Instrumental survey

In addition to the above mentioned visual inspections, other investigations were undertaken with the aid of an electronic hygrometer for wood and of 2 instrumented for penetration tests.

Wood humidity detected in the examined trusses, was always lower of the risk of xilofagus attack. Tests were executed with electronic hygrometer.

The scope of the penetration resistance test (or instrumented drill) is to verify presence of inner wood holes and shakes, and fungi attack. The 3 mm diameter tip, 400 mm length needle, (or 300 mm), proceeds by a combined forward and rotation movement at constant speed. As the drill bores into the tested material, a chart or profile is created on chemical paper. The penetration depth (in mm) is reported on the x- axis, whilst the drill resistance is to be found on the y-axes. The variable instrument speed, from 0 to 500 mm/minutes, is set according to the wood species. The results are not readily interpretable and a wood expert is needed for evaluation purposes. In particular tests have been conducted in the joints tie-beam/rafter, at different height levels and different distances from the wall. For the first five trusses a total of 114 resistographic profiles have been made with the aim of determining the consistence state of the material and the geometry of the connections, their alterations or passed interventions. The penetration directions are indicated as follows in Fig. 16.

The tests were designed to verify the level of attack in the wood, as a preliminary examination to the formulation of a hypothesis, about the actual state of preservation and consequently about how to restore these ancient structures.

It was important to quantify the damage to establish whether it would be necessary to substitute parts of the wooden structure.
The use of the Resistograph allowed obtaining the density profile of the used tests specimens. For all specimens, as function of the obtained graphs with the Resistograph, a resistographic measure (RM) was determined. The selected resistographic measure represents the ratio between the integral of the area of the diagram and the height of the tests specimens.

**Figure 16.** Instrumental survey with Resistograph

### 6. Results of diagnosis survey

The timber roof of Hagia Paraskevi Basilica in Chalkida is composed by trusses. Each one of them is made of only three elements: a horizontal tie beam and two rafters directly connected with half-lap joint and two nails without the presence of a king post. Each truss lays on two brackets which are not included into the grading. The structure as a whole is in a good conservation state, taking into account the directly visible elements, disregarding some minor insect attacks in the small sapwood portions. All the insect attacks are at present concluded by a long time. The wooden parts into the walls are on the contrary generally attacked by brown rot fungi, in the best situation the attack is only on the external portions of the section. (Fig. 17)

Table 1 presents the results of the visual strength grading, showing the features of each timber member of each truss.
Table 1. Principal features of each timber member and grading classes.

<table>
<thead>
<tr>
<th>Member abbreviation</th>
<th>defects disconnections breakages</th>
<th>Biological decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>C = tie beam; P = rafter</td>
<td>Through ring shake up to 340 cm in span side B (picture 1) Section reduced by a mechanical damage on side O (picture 2)</td>
<td>Minor surface rot on the West face (side N) close to the tie beam – rafter joint.</td>
</tr>
<tr>
<td>C4</td>
<td>Close to the N wall 2 big shrinkage checks cause a detachment of a 7 x 13 cm section. Surface ring shake (picture 3)</td>
<td>N. I. III I</td>
</tr>
<tr>
<td>C6</td>
<td>Rot on face O and surface insect attack on side N</td>
<td>I III I</td>
</tr>
<tr>
<td>C7</td>
<td>Relevant grain deviation</td>
<td>I II II</td>
</tr>
<tr>
<td>C8</td>
<td>Multiple breakages close to the side B joint The breakages are for sure also on the sector B, even if they are directly visible.</td>
<td>N. V. N. I. N. I.</td>
</tr>
<tr>
<td>P4 B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5 B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P6 B</td>
<td>Surface decay by insects and fungi due to an ancient water infiltration from the roof. Instrumented inspection were not possible.</td>
<td></td>
</tr>
<tr>
<td>P7 B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P8 B</td>
<td>Divided by two by a through shrinkage check.</td>
<td>N. I.</td>
</tr>
<tr>
<td>P4 N</td>
<td>A big knot of 15 cm in diameter insist on a face 28 cm high</td>
<td>N. I.</td>
</tr>
<tr>
<td>P5 N</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>P6 N</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>P7 N</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>P8 N</td>
<td></td>
<td>III</td>
</tr>
</tbody>
</table>

The timber species was determined through the macroscopic characteristics visible by naked eye: the whole structure is made of larch (Larix decidua Mill.) wood. Table 2 shows the maximum stresses of larch wood for the different grades.

Table 2. Maximum stresses, per each grade, of larch wood.

<table>
<thead>
<tr>
<th>Species</th>
<th>Grade</th>
<th>Maximum stresses [N·mm⁻²]</th>
<th>Compression Parallel to the grain</th>
<th>Compression Perpendicular to the grain</th>
<th>Static bending</th>
<th>Tension parallel to the grain</th>
<th>Shear (parallel to the grain)</th>
<th>Bending MOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larch</td>
<td>I</td>
<td>12 10 7,5</td>
<td>2,5 2,2 2,0</td>
<td>13 10 8,5</td>
<td>12 9,5 7</td>
<td>1,1 1,0 09</td>
<td>15 500 14 500 13 500</td>
<td></td>
</tr>
</tbody>
</table>
Figure 17. Draws of the most important defects valuable by visual inspection

Figure 18. Map of the decay and failures on connections and elements
Figures 19-20. Draws of the decay and failure survey
7. Numerical analysis verification

The European standards (Eurocode 5), the National Codes for the loads and the above described grading of the existing timbers have been used for the numerical analysis. The calculations concerning the load bearing capacity of the timber members and the connections verified the static efficiency of the authentic system.

8. Presentation of the alternative intervention proposals

8.1 Immediate non permanent safety measures

A very important result from the above analysis and assessment of the timber roof was the need for immediate, non permanent, safety measures at the bearing area of the roof on the walls. The immediate safety measures have already been designed, proposed and accepted from the Hellenic Ministry of Culture. It is a passive system, that will work if the connection of the rafter to the tie-beam is destroyed, and the horizontal forces from the rafter will be transferred to the walls, situation quite dangerous for the integrity of a wall especially in a seismic area. A metal strap placed inside the walls, will prevent the rafter from sliding on the tie beam, transferring the horizontal forces of the rafters on new steel chords. A timber wedge connected to the steel strap will transfer the vertical forces to the tie beam. The above described system can be used without causing any damage to the timber elements and without removing either the coating of the roof or the surrounding masonry at the bearing area or the timber elements and In parallel at the external side of the walls, a steel construction will be constructed that will tie the perimeter walls, like a belt, in order to help the building in a strong seismic event, till the whole study for the restoration of the church will be completed.

Figure 21. Overall scheme of the immediate non permanent safety interventions
Figures 22-23-24. Details

B2.3.a Όταν ο ξύλινος ελαστικός δεν είναι σε θέση να παραλάβει με σωφράλεια τις εφαλκωτικές δυνάμεις που επιβάλλονται από τους αμεβόντες στοις ελαστικούς γιατί οι τελευταίοι είναι κοιμητές είπε έχουν γίνει τη διαπίεσιμη παραταξία της οριζόντιας δύναμης λόγω καταστροφής της σύνδεσης τους με τους αμεβόντες, τότε προτείνεται η χρήση δύο χαλαρών ελαστικών (δ1) παράλληλα με τους ξύλινους.

Οι μεταλλικοί ελαστικοί αυτοί, μπορούν να σταθούν τις προβλεπόμενες γ’ αντί υποδοχές (γ) της χαλαρών βάσης (α).

Η μετατροπή των αφιξόντων φορτίων από τον αμεβόντα στους μεταλλικούς ελαστικούς προτείνεται να γίνει μέσω μεταλλικού M16 το οποίο θα τοποθετηθεί σε από προκαταρκτική στην μεταλλική βάση α2 (βλ. B2 και Χαρακτήρα).

B2.3.b Περίπτωση χρήσης ελαστικών (δ1) χωρίς χρήση ξύλινης σφήνας
8.2 Definitive interventions

8.2.1. Criteria for the choice of intervention techniques.

On the basis of the accurate diagnostic survey and classification according to the resistance conducted by the group of research of the Polytechnic of Turin in the period January-May 2006 and of the consequent inspection in the restoration site of Isolotto in Venice, various alternative structural restoration interventions were proposed to be applied to the decayed parts of the trusses in object. In the following part the proposed alternative interventions techniques are presented and their advantages and disadvantages are commented upon. Some indications for the execution of the project are given as well, together with characteristic executive drawings for interventions.

The proposed techniques of intervention are substantially local reconstructions (wooden prosthesis) of decayed parts or lacking or inefficient parts, with the apposition of wood boards of larch of first quality with thickness 2 or 4 cm in function of the necessity of each intervention.

Such substitutions are dimensioned from the constructive details and assembled with the system of gluing with bi-components resins (as specified below) in combination with a mechanical system of connection, constituted by self-threading stainless steel screws of 6 or 8 cm length, according to the size of the boards to be connected. Besides, the interventions on the inefficient elements foresee the integration with metallic components.

In prevalence, the use of wood for the repair and the consolidation of wooden trusses, constitutes the most largely applied solution in the past. It is not for instance rare to meet in the old structures repaired elements or partially reconstructed through wooden prosthesis, joined through “dart of Jupiter” joints. This technique requires an accurate execution of the work.

The wooden prostheses or the element of reinforcement are sometimes mechanically joined together through metallic elements as nails, bolts, screws, bands and metallic plates.

In prevalence, the selected solutions are prosthesis with mechanical unions and glued. In general, wooden prostheses are to be preferred to those of other materials (as for instance reinforced epoxy betons) because, even being impossible to find wood prosthesis with the same characteristics physical-mechanical of the rest of the existing structures, following thermo-hygrometric environmental variations, the deformations of wooden prostheses are surely more similar to those of the rest of the structure, in comparison to another material that doesn't deform itself.

In fact, the prostheses in epoxy conglomerate have the disadvantage to require for great volumes of resin with elevated costs. Moreover, they develop big quantities of heat during the process of reticulation. Such heat can provoke strong gradients of humidity in proximity of the extremity of the beam with consequent anomalous creeks.

Besides, impossibility to be deformed during thermo-hygrometric variations can provoke disconnections to middle or long term among effected prosthesis and original material.

The proposed technique is a technique of prosthesis to be realised in-situ.

7.2.2 The structural glueing

Since some years, instead of the traditional materials, material of synthetic origin have been used; among these the bi-components epoxy resins that, thanks to some peculiar characteristics, constitute the adhesive more broadly used.

The epoxy resins are also used with fine inert mineral filler to glue parts of wood or of steel. In other cases they are loaded with inert of varying granulometry from fine to big for the realization of conglomerates to fill missing parts.

When the prosthesis is realized with the material wood, epoxy products are used for the junction whose specific techniques are in the attached fiches.

The products with epoxy resin base are generally very sensitive:
- to the proportions measuring
- to the conditions of conservation of the material of base
- to the external temperature
- to the excessive humidity of wood (never above 12-15%)
- to the time that intervenes between the mixing of the bi-components and the use
- to the temperature during the maturation
- in every case the epoxy mortars cannot be used with too low temperatures (normally 10°C), therefore in the winter periods is not suggested the use of this technique; it is not suggested even for outside temperatures higher than 33°C
- structural glueing are sensitive to Ultra-Violet rays
- and other factors as dust, dirt etc. that must have checked in the restoration site

For these motives it is suggested to have these products used by experienced personnel under the supervision of a Technician.

Besides it is good to use resins loaded in way to reach the tixotropic consistence (epoxy mortars spatulable in way that doesn't strain); too much liquid resins have the tendency to strain and to empty the glueing, moreover they penetrate in shrinkage creeks of the wood, preventing the natural movements, such circumstance can provoke self-tensions dangerous for the structural stability.

Small reconstructions of decayed parts can be performed through the glueing of wooden boards with epoxy mortar (technique of in-situ glulam). Such technique can be applied on wider volumes watching out for not to oppose the natural movements and however is advisable to assist the glue of the boards with mechanical union through self-threading screws.

### 7.2.3 Constructive details

For this technique the constructive details have to be well planned to confer the durability of the work; besides it is important to keep in mind the following basic rules:

- The biological decay of the wood from the xilofagis agents (mushrooms and insects) happens when the humidity of the wood overcomes 20%; in the structures well ventilated and well protected from the weather agents, such value is normally not reached. It therefore important to provide natural ventilation of the places with wooden structures, avoiding the "humidity traps" for instance not tucking in with mortar of cement the heading of the beams inserted in the walls, avoiding that the metallic elements in direct contact with the wood will end outside, acting therefore of thermal bridge and therefore object of it condenses. It is suggested to maintain the original constructive technology of the ventilation: with the small brick elements.
- Direct exposures to the rain, especially during the phases of workmanship in the restoration sites, must be avoided.
- Some wooden species are more durable then others. For the prostheses it is good therefore to choose a durable wood species, as the original one (boards of first quality larch), also for the compatibility of the material.
- The wood, because of its hygroscopicity, exchanges humidity with the environment; consequently it suffers some movements that if prevented they produce dangerous self-tensions; it is therefore necessary to leave in the native position the wooden elements that have moved (as the barbacani) and that freely "move"; it must be avoided the transformation of connections among the different elements from hinges to joints; systems of junction not too much rigid must be used.
- The movements of the wood due to the variation of humidity are greater in the direction perpendicular to the fibres in comparison to those in parallel direction; it is therefore important to watch out for not to oppose them.

### 7.2.4 Operative techniques and equipments

The intervention of prosthesis both on the head of the rafter both on the truss, requires the access from the upper side at least in the area of heading.

After opportunely having supported with scaffolds the truss, it is performed a cut of the rafter at 90° respect the extrados; the cuts must follow the direction of the decayed part according to the project drawings. Such cut is performed with chain electric-saw or disk
saw. The cut in the tie-beam is opportune that is performed with a disk saw, performing a cut and eventual deepening of cut with hand saw. It must be remembered that it is opportune to aspirate both dusts both sawdust before the intervention with epoxy glues. The cut of the tie-beam must be regulated according to the indications of project of every truss (see attached executive drawings).

The thickness of the boards of larch must be cut according to the project, glued to the part of the existing structure and therefore furnished of self-threading screws according to the scheme of project.

It must be remembered that the package of the tables glued and provided of screws must be opportunely kept shut with vices that prevent the relative movements during the period of hardening of the glue. Such vices must be maintained in position - in the case of the temperatures recommended by the manufacturing firm - at least 24 hours. Structures can be loaded (or put in exercise) after about 20 days, except different prescription from the firm producer of the glues.

The realisation of the punctual intervention, except unforeseen events, requires from two to four hours of work for two specialized workers, in relation to the dimension and complexity of the prosthesis.

7.2.5 Reconstruction of heading through prosthesis of wooden boards glued and connected with self-threading screws for wood

This solution foresees a wooden prosthesis instead of a decayed head of tie-beam or of rafter.

The joint among old and new wood is realized with degrading course with the glueing among old wood and new board and self-threading screws of coherent dimensions with the thickness of the suitable boards indicated in project (Fig. 25).

Figure 25. Proposal of intervention of reconstruction of the head of the tie-beam
In any case, it is suggested to use non-planed boards to have a better setting of the glue. The self-threading screws, work to shear stress, and they transfer the stresses from one board to the other one assuring the pairing of the joint, guaranteed also from the presence of the epoxy mortar. For this technique it must be realized the cut on the element (tie-beam or rafter) so to insert by step the boards and possible eventual adjustments can be performed with a disk saw. However the prosthesis must correspond in more then satisfactory way and after the spreading of the glue to insert the screws made the trace with a wood drill whose drill has to be coherent the dimensions of the screw. The alternation of the boards implicates a different distribution of the self-threading screws according to the scheme that follows (Fig. 26).

Suggested methods of calculation: The method of calculation in this case is reduced to the calculation of the elements of connection that work to shear stress, over obviously the verification of the carving between rafter and tie-beam as for a normal truss. The main stress is that of traction that can be divided for the present connectors (self-threading screws). The stresses of bending and shear of the tie-beam due to its own weight are usually negligible or non influential. The method of the admissible tensions can be used. In the calculation are assumed the worse mechanical characteristics between existing wood and new wood. For this it has to be compared the mechanical characterization of the elements at the end of the diagnosis activity. (Fig. 27)
Figure 27. Proposal of intervention of reconstruction of the head of the rafter and partial substitution of the tie-beam with glulam.

8. Conclusions

Who has the assignment to evaluate the characteristics of elasticity and resistance of the structural elements and the efficiency of the connections of ancient wooden structures, with the purpose to evaluate the load-bearing capacity of the structures of which they belong to, it has to pick up all the information on the material wood, on its principal characteristics physical-mechanics, of its defects and of the agents that could have caused the deterioration. Furthermore the expert has to analyse with attention the systems of mutual connection among the structures, in relationship to the geometric characteristics of the structural system which they belong and to their possible decay. Finally it is important to recognize the interventions of consolidation made in the time and to know how to evaluate its real effectiveness (i.e. prosthesis, additions of wooden parts, metallic parts etc.). Considering the great number of variables present and the difficulty to carefully explore the whole volume of every wooden element (i.e. a rafter or a tie-beam), it would be illusory to pretend to evaluate all the factors above mentioned, or to foresee the breaking load of every element.

On the opposite, through an accurate examination and maintaining a certain safety degree, it is possible to reasonably esteem the elements current state (resistant section, admissible tensions, elastic module, etc.) and to give realistic data to the planner of the intervention on the existing structure.

Furthermore, the actual debate at European level linked to the conservation of timber structures and to the restoration interventions, highlights the high importance of the research theme, in which technical efficiency, professional execution, documental
transparency and economical compatibility are melted with the objective of assuring a long life performance of load-bearing wooden handworks. The methodology applied for the investigation of the Hagia Paraskevi timber roof has proven once again the great role of preventive diagnosis. In fact generally an accurate diagnosis gives the possibility to avoid unnecessary and expensive interventions. In cases of structures belonging to our cultural heritage preventive diagnosis is even more important and absolutely necessary in order to ensure an optimum intervention that takes into account both safety requirements and all the other values of each specific historic structure. This is the only way to avoid the loss of ancient timber structures that are part of our cultural heritage.

The peculiarity of this international experience is evident also from the presented results that have found a common “language” both in the diagnosis phase, both in the intervention proposal. The work of transferring the knowledge between the two working group is highlighted also by the graphical documentation in three languages.

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Bibliographical References

- Coronelli M., 1695, Historia del Regno di Negreponte et sue Isole Adjacenti, Venice, 208.
From Material to Structure - Mechanical Behaviour and Failures of the Timber Structures


