Learning from a case study: the great timber roof structures of the Cathedral of Vercelli

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Abstract The great timber roof structures of the Cathedral of Vercelli offer an extraordinary path of knowledge, diagnosis and conservation, through a collaboration between the architects of the Cultural Heritage Office of the Diocese of Vercelli – responsible for the restoration process – and experts in the field of timber structures.
The interest of the architectural complex is witnessed also by the contribution of renewed architects of Piedmont between the XVIth and XIXth centuries.
The paper goes beyond the diagnostic evaluation, giving an overview on the main consolidation interventions respectful of the conservation of the timber structure.

Keywords diagnosis, survey, timber grading, conservative restoration

1. INTRODUCTION

In general, the conservation of historical timber structures requires the knowledge both of the overall static behaviour, both of its single elements, so that the task of who is involved in its restoration/maintenance can be based on reliable data for a proper project.
Of great importance is the constructive knowledge and understanding of the structure that can be reached through a accurate geometric survey, both of the elements and their technological defects, both of the joints; on this survey is based the diagnosis for the evaluation and grading according to the resistance.
Built heritage wooden structures from past periods represent a specific category of artefacts that are of particular importance and recognized interest in the rich heritage of cultural goods relating to historic

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or traditional buildings. These historic buildings show diffusion at the local level, type of structure, technological characteristics, artistic and formal value, etc.
Sadly, in the majority of cases these structures, were not deemed worthy of the same attention as the buildings of which they were an integral part. They were frequently subject to inappropriate intervention, replacement, or, even worse, demolition.
It was not until fairly recently that it became generally recognized that, as far as possible, these structures should be renovated and conserved in terms of their static purpose and in a manner that is respectful of and coherent with their original concept as well as their material: wood.
Nevertheless, in practice many structural renovations carried out in recent times have betrayed the idea of conservation, sometimes even involving the unwarranted demolition of centuries-old roofs. Such arbitrary or "excessive" intervention frequently stems from difficulties in assessing the state of conservation of the material and of its real load – bearing capacity, the incorrect evaluation of the structural behaviour of these elements, or the adoption of superficial procedures guided by profit rather than by the real needs of the works in question. Despite the revival of interest in wood and the proliferation of studies on this material, its load bearing capacities continue to be questioned by operators whose inadequate knowledge and total lack of confidence are revealed in the use of consolidation techniques using supports made from innovative "new" materials thought to hold the answer to all structural problems. This is a short sighted approach that disregards the effects of such interventions in the medium and long term. Many techniques described in the current technical literature (though sometimes innovative) are failing to keep pace with a conservation trend that is emerging, not just with respect to monumental restoration but also as far as historic or merely traditional buildings are concerned.
There are too many cases of unjustifiable radical interventions where wooden ceilings have been consolidated with steel structures and layers of reinforced concrete, or roofs have been partially or completely reconstructed using steel or Glulam components.
Not only do such projects share a lack of confidence in the traditional materials, construction techniques and skills, but they frequently neglect one of the fundamental steps of structural renovation project management - the diagnostic phase. The historical knowledge is fundamental for any kind of intervention.

Figure 1 – Elements of the roof timber structure over the apse of the Cathedral of Vercelli Grading according to resistance

2. THE CATHEDRAL OF VERCELLI. HISTORY AND DESCRIPTION

The present Cathedral of St. Eusebio of Vercelli was rebuilt after 1570, when cardinal Ferrero gave order to demolish the choir of the great and ancient paleochristian basilica probably dating back to VIth century, that was build on the primitive church built for the will of St. Eusebio, protobishop of Vercelli and of Piedmont around 355, on the place of the burial of St. Teonesto.

Figure 2 – Nowadays image of the Cathedral's complex

The Dome of Vercelli, also called the cathedral of San Eusebio, is a symmetrical, latin coss- shaped building. The ground floor has a size of 3634 sqm. It consists of 3 aisles, of these the much larger one in the middle overpasses the two side aisles. Where the extremely high dome covers the cathedral, the two transepts intersect the main aisle. At this crossing point are modern multi liturgical objects placed, like the ambo, the altar and the Episcopal seat. The two side aisles end with flat chapels, while the main aisle continues with semicircular apses after the transept. Along each of the two side aisles are three minor chapels before the transept. On the right side are: the altar of the feretory, the altar of S. Onorato and the altar of S. Giovanni Nepomuceno. On the left side are: the altar with the baptistery, the altar of S. Emiliano (now dedicated to S.Elena) and the altar of S. Guglielmo. At the two ends of the transept are the much larger octagonal chapels of S. Eusebio and Beato Amedeo. Besides these, there are little chapels on the right side the altar of the crucifixion, and on the smaller side of the aisle the altar of S. Ambrogio. On the left side is the altar of S. Filippo Neriand and at the end of the aisle is the altar of the Madonna.

Figure 3 – Nowadays image of the Cathedral's complex

The five spans in divided aisles are covered with a ribbed vault, massive, quadratic posts and engaged columns. The two transepts on the other hand side are closed with barrel vaults. On the top of these vaults and the smaller cupolas are timber constructions mainly out of oak wood which carry a tile roof covering.
The dome and the larger cupolas are completely made of stone and covered with lead and copper.
The hipped roof is the part which has been retained nearly unchanged in the course of time (both structural technique and form). The form traces back to the four or more pitched roofs, with a primary structure out of trusses or beams and angle bars on the bisecting line. The main timber elements have been worked better and with more accuracy than the smaller elements with less importance for the structure. In other cases the different working techniques (for example sawn and not chopped) are indications that the elements have been replaced or added in later periods.

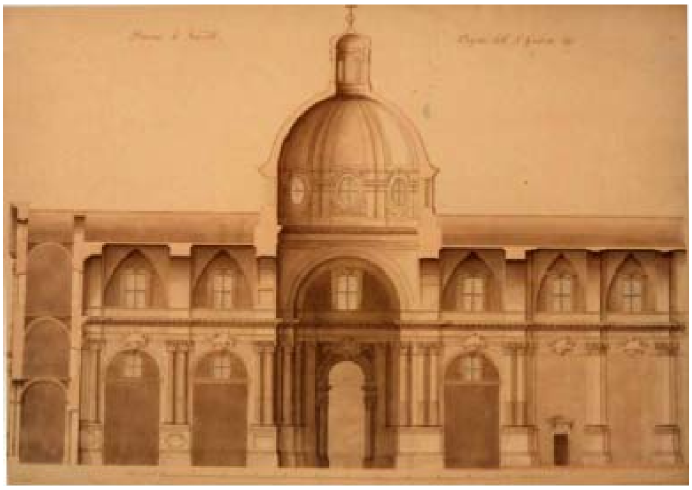


Figure 4 – Original project section attributed to Guibert (probably 1749)

At the middle of the XXth century, the cathedral already showed big problems of moisture and rainwater leaking, so that several maintenance works started of the timber roof structure. These works were concluded in the 1960's. In 1992 were substituted the covering surface of the St. Eusebio chapel with new lid plates.
In the recent years, thanks to the interest of Bishop Masseroni, maintenance works have been carried out on the roof structures of the sacristy.
The increasing problems of the last years, mainly due to raising humidity and spread rainwater leaking, brought to a general state of decay inside and outside the complex that brought the bishop to consider an overall restoration intervention.

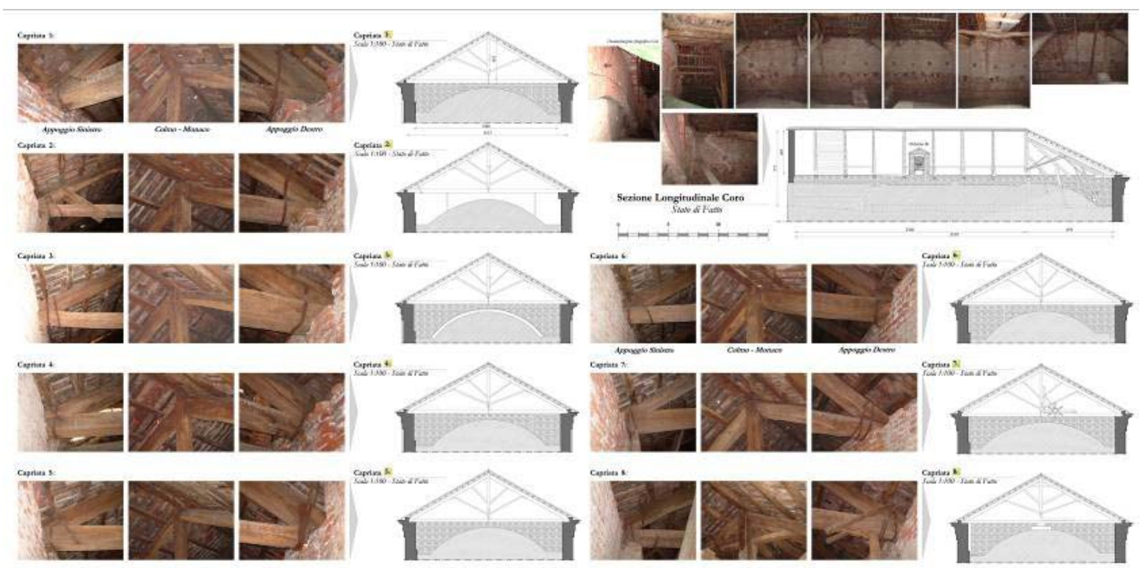
3. THE TIMBER ROOF STRUCTURE

The great timber roof structure of Vercelli's Cathedral covers an area of around 3.800 sq. m. and present different typologies between presbytery-choir, central nave, lateral naves and transept. The typology of reference is the truss. In general terms, the examined trusses have the function to support the roof of the religious building and are composed by a tie-beam and two rafters connected with the help of a king-post. Each single element composing the truss derives from a single trunk that was squared by axe. King-post and rafters are connected by two struts.
The span between the masonry walls on which lay the trusses is of approximately 15,50 m, the section of the timber elements is of approximately 30 x 30 cm or inferior: often the dimensions of the sections vary in the length of the element and between the elements within wide limits.

Figure 5 – Plan of the timber roof structure

4. GEOMETRICAL SURVEY

The conservation project was carried out though a hand survey carried out by arch. D. De Luca in collaboration with the architects G. Corradino and R. Pasquino.
Each single element of the timber structure was surveyed in its dimensions, classified and evaluated under the technical profile and located in the overall structure. The survey was therefore translated into graphical drawings of plans and sections (executed for each truss).



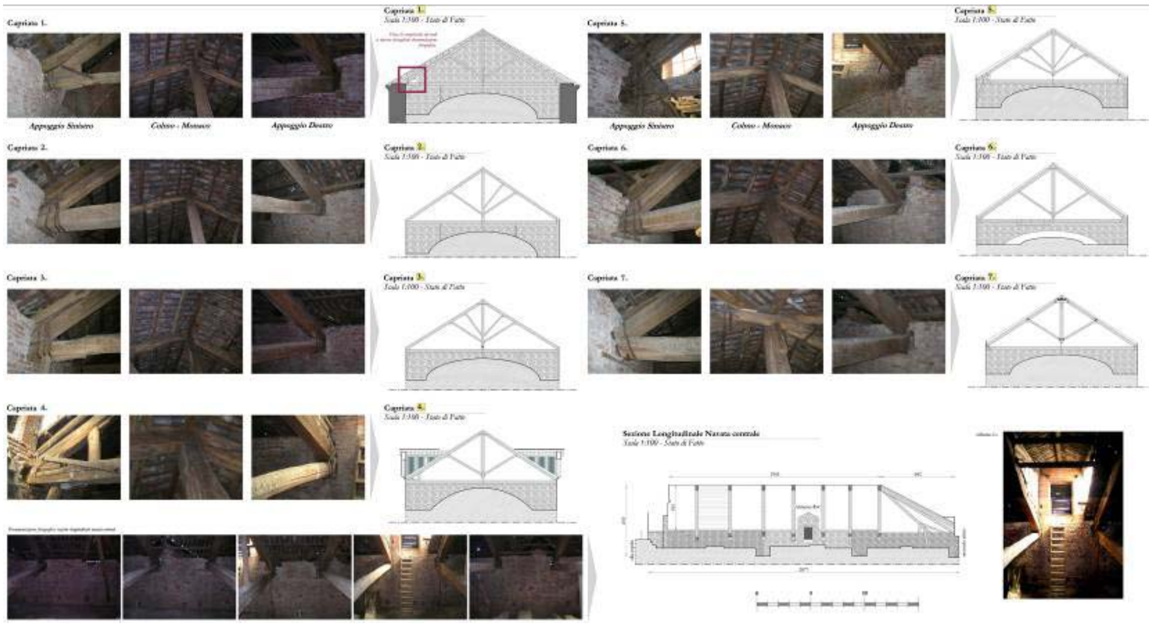


Figure 6 – Survey of the trusses of the transept-choir and of the central nave

The survey was also supported by an innovative survey technique through a “Laser Scanner” carried our by a Spin-off company of Politecnico di Torino. This work has allowed to located in the exact position all the hand survey without possibility of errors, if not minor ones. Afterwards, the work has been completed with the diagnostic survey on the main structure of the roof.

5. OPTIMISED STATIC MODEL RPLAN

The load bearing capacity of the truss has been modelled assuming an optimal condition of every single timber element. Because the forces in each of its two main girders are essentially planar, a truss has been modelled as a two-dimensional
plane frame. A truss is a structure comprising a triangular unit constructed with straight members whose ends are connected at joints referred to as nodes. External forces and reactions to those forces are considered to act only at the nodes and result in forces in the timber elements which are either tensile or compressive forces. This means that torsional forces (moments) are excluded because, doing the calculations, all the joints in a truss are treated as revolutes.
The load cases which have been calculated are: the one for the permanent death load, a combination of death and snow load, death and wind load and for a combination of death, wind, snow and living load. The connections are assumed as hinge joints. The values (max. stress, modulo of Elasticity…) for oak timber have been taken out of table from standard UNI 11119:2004 on Maximum stresses of on site timber of the load bearing system.

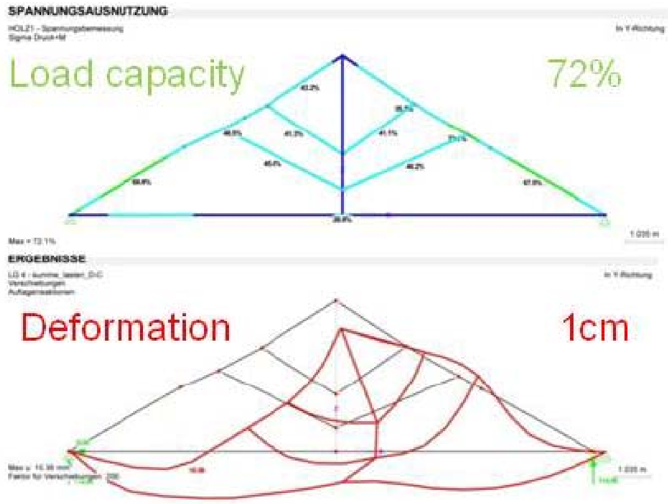
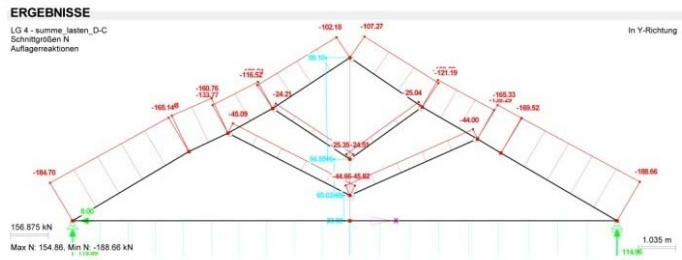
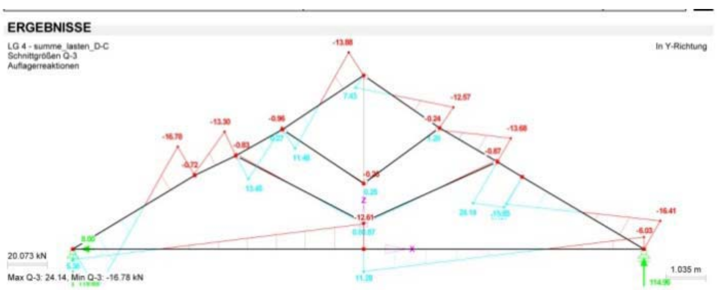


Figure 7– Results for the load case D-C (highest loads)



a



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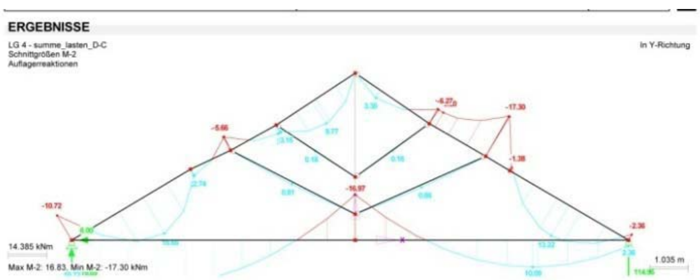

c

Figure 8 – Axial force working on the beams (a); shear force working on the beams (b); axial force working on the beams (c).

6. STATIC MODEL RPLAN DEFECTS

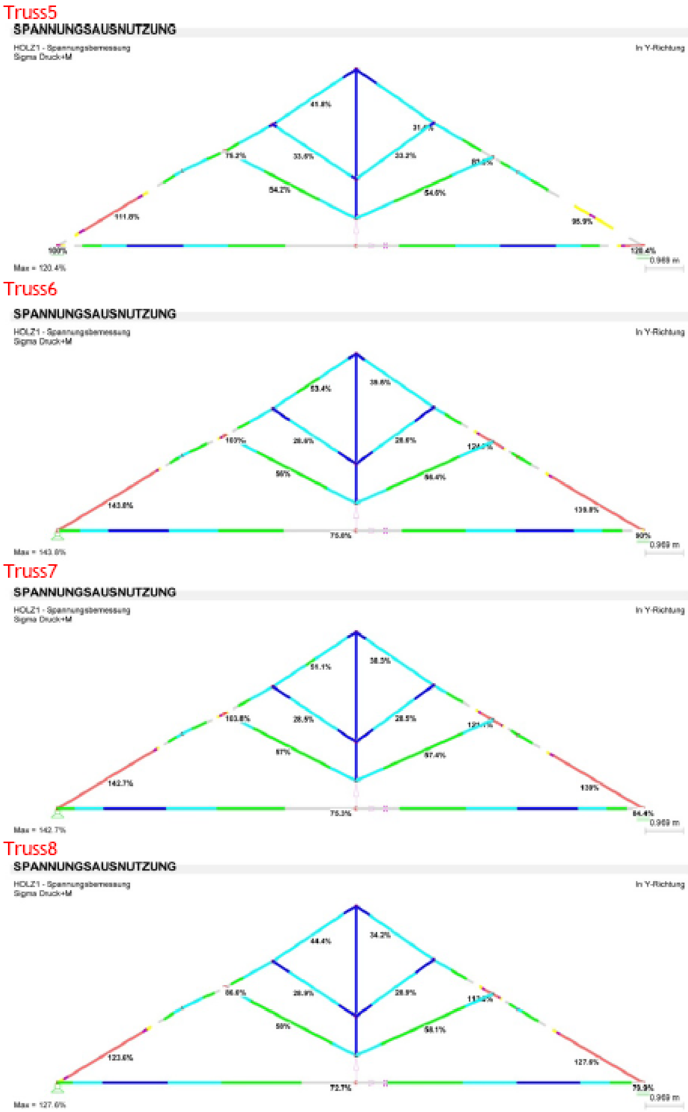

Figure 9 – Structural models reporting decays and defects of the components (stress in the lower part of the rafters is generally a too high)

7. DIAGNOSIS

The methodology adopted during the *in situ* inspection for the grading according to the resistance, are the one foreseen by the standard UNI 11119 (*Cultural Heritage - Wooden Artefacts - Load-bearing structures - On site inspections for the diagnosis of timber members*).
In the 4th paragraph of this UNI 11119 standard are listed the objectives of diagnosis whose final aim is to get informations on:

a) identification of wooden species. The identification had been carried out according to the criteria foressen by UNI 11118 (*Cultural Heritage - Wooden Artefacts – Criteria for the identification of wooden species*).
b) wood moisture;
c) classes of biological attack risk, according to UNI EN 335-1/2;
d) geometry and morphology of timber elements, including position and extension of the main defects, signs of decay and eventual damages;
e) position, form and dimension of the critical zone and critical section;

f) grading according to the resistance of timber elements as a whole structure and/or in single critical areas.

The visual inspection was integrated with instrumental inspection through resistographic drill. This instrument is necessary for the evaluation of the state of conservation of parts of the element that are enclosed inside the masonry.

Identification of wooden species
All the examined pieces of the trusses presented the following characteristics useful for the wood species identification::
- growth-rings easily distinguishable with the naked eye.
- brown colour of the heartwood differs from the colour of the sap wood (darkening from light gray-yellow to dark brown).
- timber vessels are particularly big and have a ring porous distortion.

All the elements constituting the trusses are in oak wood (*Quercus* sp.p.). The used oak wood are very heavy, with volume mass of around 800 kg/m^3. This wood is traditionally used for historical monumental structures in the Padana plain of northern Italy, where there were wide forests of oaks.

Climatic conditions under the roof
Wood assumes a different moisture of equilibrium according to different *in situ* conditions. Some conditions are favourable for biological decay of wood.
To be able to define the classes of risk of biological attack, the standard UNI EN 335 identifies 5 classes of risk. For each class are defined the situation of service vand the moisture conditions of wood in those situations.
In the specific case of the Cathedral of Vercelli, the temperature during the days of the survey was of 3-5°C and the air relative humidity was 80%. In these thermo-hygrometric conditions, wood assumes an equilibrium moisture of approximately 16%. Furthermore, the high value of environmental moisture content has to be connected with the water leaking that are clearly observable due to traces and spots visible on some elements.

Figure 10 – Elements of the roof timber structure over the apse of the Cathedral of Vercelli Overall state of conservation

Concerning the trusses object of the survey, an overall good state of conservation is present, except for some fungis and insects attack limited to portions of sapwood in some timber elements.
In any case the insects attack had ended since a lot of time.
In general, tie-beams are more decayed than rafters. This is probably due to material (i.e. concrete, pieces of tiles and bricks) that fills the space between the heads of the trusses and the masonry. This material becomes wet after rainwater leaking and provokes a high moisture content in wood that is therefore more subject to xilofagus fungis attack.
Each timber element of the trusses was classified according to resistance.
None of the head of the trusses (end transversal section) of the classified elements was visible at the monent of inspection. Tie-beams have been inspected on 4 sides. Rafters have been evaluated on 3 sides, excluding the upper one that was not directly visible. King-posts were evaluated on 4 sides. The state of conservation on some tie-beams was critical in the parts inside the masonry.

Biological decay	From fungi	Present in the part inside the masonry.	
	From insects	Absent	
Defects	Joints	The connection with the rafters seems to be in a good condition. The metal connection with the tie beam doesn't work anymore. The metal lengthened and doesn't support the tie beam anymore (no tension forces can be transmitted).	
	Ring-shakes		
	Twist		
Wooden species	Oak		
Moisture content	According to the surrounding air about 16%		
Average dimensions of the element	22 x 23 cm		
	Section	Rectangular	
	Geometric peculiarity	Wane	Knot and wane
		Deformations	
Other characteristics	The post is not lined up with the tie beam. The horizontal connections joining the king posts with each other caused a displacement of the timber element. The presence of the tenon in the connection with the tie-beam is evident in profiles 36a and 38a. From the profiles are not visible particular decay signs.		

PHOTO

n. Photo	IMG_0687 Truss 2	IMG_0730 Knot (king post - rafter)

PHOTO

n. Photo	IMG_0729 Knot (king post - chord member)	IMG_0731 / IMG_0732 Knot (rafter - chord member)

Figure 11 – Example of Thematic Fiche

IDENTIFICATION DATA OF THE STRUCTURE	
Date of inspection	3rd/4th /12th Dec. 08, 6th/9th Mar. 09, 6th/12th May 09
Place	Vercelli - Italy
Site	Dome Vercelli
Team	Prof. Clara Bertolini Cestari (Co-ordinatore), Arch. Gianoreste Biglione, Dott. Alan Crivellaro (CNR-IVALSA), Luciana Cestari (restauratrice), DI. Pia Panosch, Arch. Daniele De Luca
	Evaluation of the conservation state of the wooden material and of timber joints

Truss	N. 8	Choir		
Tie-beam				
Biological decay	From fungi	Nothing visible		
	From insects	Absent		
Defects	Joints	See rafter		
	Ring-shakes	Nothing observed		
	Twist			
Wooden species	Oak			
Humidity	According to the surrounding air about 16%			
Average dimensions of the element	27 x 30 cm			
	Section	Rectangular		
	Geometric peculiarity	Wane	Absent	
		Deformations	Absent	
Other characteristics	There is a problem at the joint tie beam- rafter, because of the heavy degrade, the tie beam seemed to be flattened (crushed) by the weight of the slightly moved and curved rafter. A group of knots is visible.			
Resistographic profiles				
Data	Profile N°	from	Direction	Observations
3.12.08	R 15	front end south side	perpendicular to grain	Drill 15 (executed on soft timber): the test has been taken perpendicular to grain on the tie beam. There are only 6cm of good timber, after that there is nearly no resistance. <u>The result couldn't have been much worse.</u>

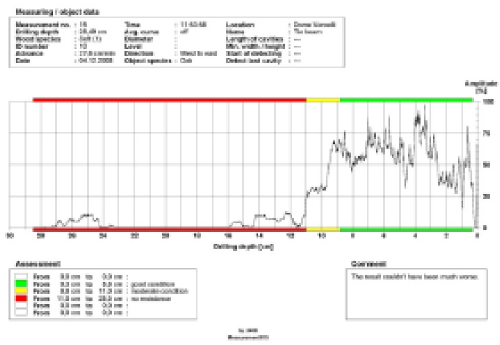

PHOTO		
n. Photo	IMG_7034 Truss 8	IMG_7344 Knot (king post - rafter)

Figure 12 – Example of Thematic Fiche

Intervention proposals

The results of the visual grading of the timber elements of the examined trusses have been integrated with the instrumental analysis carried on in the timber parts included inside the masonry walls.

With the aim of bringing back thermo-hygrometric conditions of wood below the limit that is favourable to fungis attack, is indicated to facilitate air circulation around the wooden parts inside the masonry, so that it will be possible to reach better moisture conditions.

It is also advisable an accurate cleaning of the horizontal timber elements with the removal of dust and various deposits.

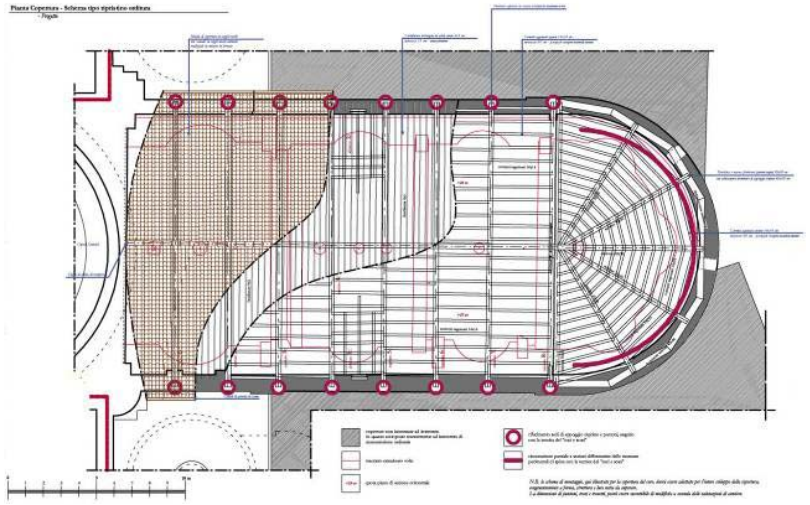

Figure 13 – Plan of the presbytery-choir. Scheme of the restoration project for the roof structure.

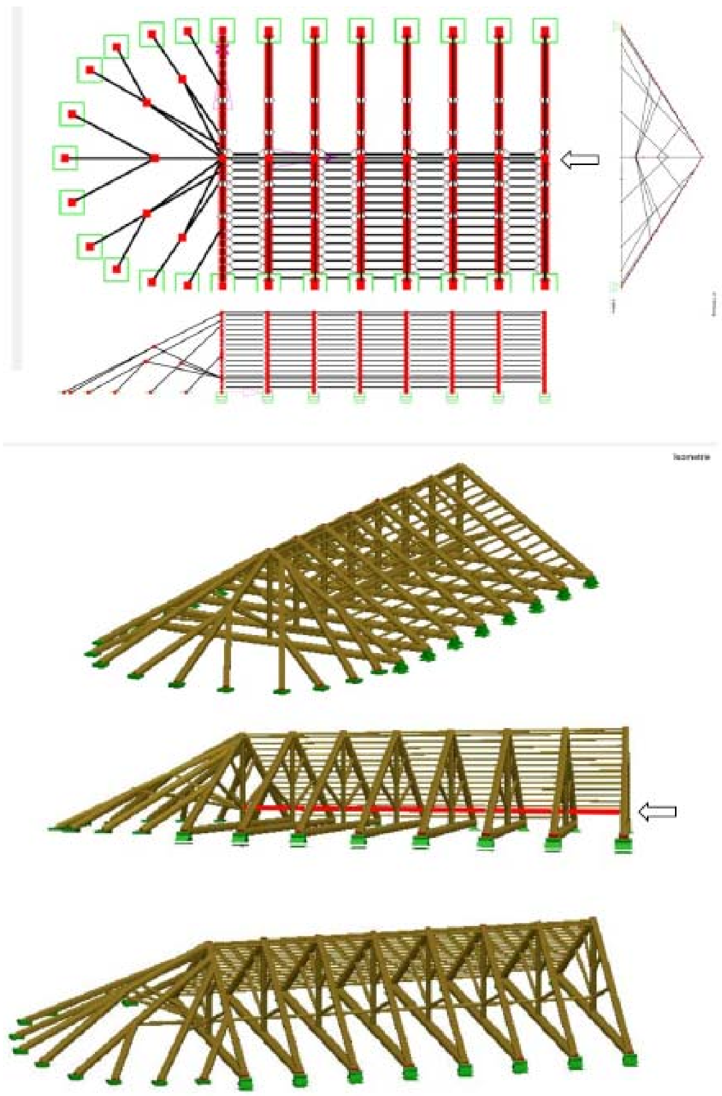

Figure 14 – Sketches of intervention proposal

8. CONCLUSIONS

The great timber roof structure of the Cathedral constitute the first part of restoration works of the whole architectural complex. The works are followed directly by the Cultural Heritage Office of the Diocese of Vercelli, and are aimed at the conservation and restoration of the timber roof structure, adopting techniques that are very few invasive and suitable to give back structural consistency to the whole structure, without loosing the important characteristics of the building: its impressive structure, also considering the skilled carpenters, the importance of royal architects and the traditional rules of the art that those structures still preserve.
The intervention foresees the rehabilitation of all the great trusses and the relative metallic elements; also the secondary structure, where possible, will be preserved. While it is foreseen the only substitution of the covering. Part of the tiles will be preserved and an accurate maintenance will be carried out also on the copper and lid cupolas.

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