ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

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INVENTORY OF REPAIR AND STRENGTHENING METHODS TIMBER

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ABSTRACT

The objective of this research was to produce an inventory on stabilization, repair and strengthening methods aiming at the structural restoration of timber structures. A parallel study on the properties of the material, its historical use on structures as well as the causes for the need of interventions had the objective of helping the accurate judgment on the suitability of the presented techniques. The research of both traditional and modern solutions, with the use of different materials, their practical applications, medium and long term performance, and compliance with conservation principles resulted in a compendium of repair and strengthening techniques with a sound discussion on advantages, limitations and ideal application, following the practice recommendations of the modern philosophy of conservation and restoration.

1. INTRODUCTION

It is common sense that Architectural Heritage, in its broad meaning, which involves singular architectural works, elements or structures of an archaeological nature and groups of separated or connected buildings, such as ancient city centres and historic urban textures have a great value and action should be undertake to conserve their intrinsic authenticity. Still, the extension of this inherent value and the authenticity of each kind of architectural heritage to be conserved are not yet satisfactorily understood by many of the agents parties involved in conservation engineering, decision making and legislation. Architectural Heritage, involving artistic, technical and spiritual merits is a cultural landmark that provides identity to cultures, world regions and towns. Therefore it is an essential contribution to cultural diversity and global cultural wealth as well as a living document on ancient knowledge, practices, cultures, technologies and history (Bláha and Roca, 2007).

(a) (b) (c)

Figure 1 – Some historical timber structures. (a) Horyu-ji Goju No To (Five-storey Pagoda) with Central pillar dendrochronologicaly dated to 594 AC, (b) Wooden Pagoda in Yingxian, CHINA, 1056, (c) Westminster Hall in London, ENGLAND: Built by carpenter Hugh Herland in 1399.

Although this dimension of the notion of value is generally clear when referring to singular, high value monuments like sculptures, palaces, cathedrals and others alike, in the case of ancient city centres, its extension is many times hard to understand. The fact that these are still centres of living in our societies and not just mere tourist attractions, and therefore have a destiny that depends on the desires, expectations and limitations of people living there their daily life, makes the conservation of their authenticity dependent on the increase of the awareness within the public of this fundamental dimension of architectural heritage.

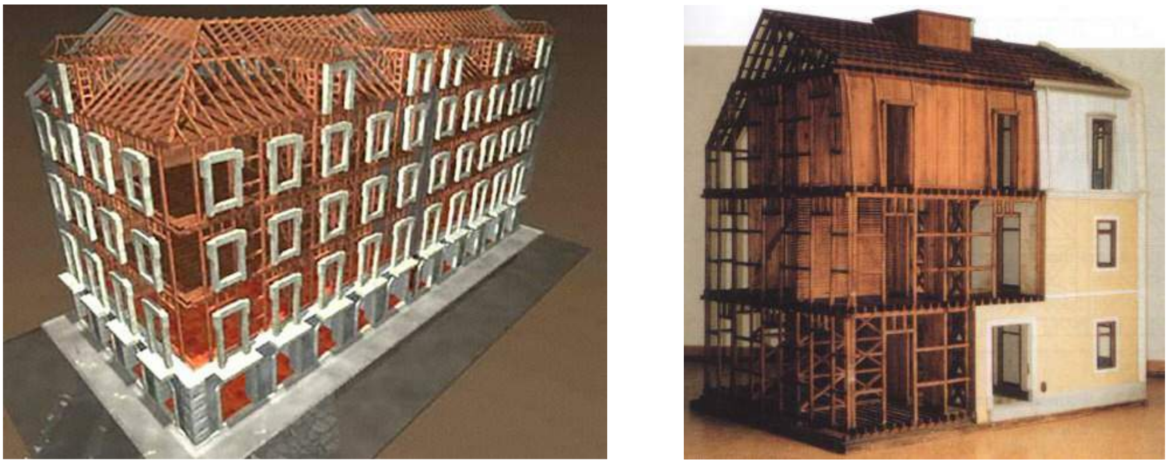


Figure 2 – Portuguese seismic resistant construction “gaiola pombalina” with mixed masonry and timber walls, which took advantage of the carpentry experience from naval construction.

On the side of the valuable historic buildings, also on the restoration or rehabilitation of common old buildings, the techniques and philosophy of heritage conservation should be given a special attention. With the combination of lack of public sensitivity and appreciation of the ancient nature of buildings and the lack of preparation and knowledge by the intervention designer, it is relatively common that solutions get more destructive, invasive and less effective, bringing to later degradation due to incompatibilities of materials and misunderstanding of the behaviour of ancient structures, thus bringing to far more expensive solutions. Also the problem of the real value of the conservation projects is a great threat to more “scientific” approaches. The usual procedure of calculating the cost of projects has a percentage of the cost of the work done is completely against the best conservation practice, once the best intervention is the minimum required. The judgment of the needlessness of an intervention can require more studies and real costs than a recommendation for deep intervention (Translation from Lourenço 2005).

Timber, together with stone, is the oldest building material. Its capacity to resist both in tension and compression made it the most complete before steel became available. The heritage timber structures are immense and date back to millennia ago (Figure1), but by being very sensible to lack of maintenance, timber structures become the most vulnerable part of historical buildings, often suffering from a level of degradation that requires interventions of conservation. The objective of this dissertation is then to document an investigation on methods and technologies used for the structural conservation of timber constructions, focusing on floor and roof structures, keeping in mind the modern practice principles and methodology.

It starts by giving an idea of the modern principles and general concepts involving conservation, given by the ISCARSAH Committee. The 3rd chapter is dedicated to a brief description of the nature of the material and its common pathologies. The 4th chapter to the investigation and diagnosis, which is the essential phase of collecting all the information which is necessary to any scientifically-based intervention and finally the 6th chapter, which is dedicated to the inventory of the repair and strengthening methods, with the materials and techniques available to the designer.

2. FUNDAMENTAL CONCEPTS AND PRINCIPLES OF CONSERVATION

Prescriptions and principles for the conservation of historic timber structures have been the target of several developments along the last century until the present time, being clear that, although there is a common understanding on several generally accepted principles, diverse approaches and criteria still prevail and are the subject of wide discussion. Before any further development it is essential to clearly define the general concepts that concern restoration of historic structures.

The **authenticity** of a monumental building is a wide concept that, aside from its history, aesthetic value and social significance, is extended to the structure itself. By conceiving conservation as care for the authenticity of a structure, it should be clear what is implicit when the concept is applied to a load bearing structure. A possible definition might be:

> *"Authenticity is the original configuration thought by the Architect, the material specified in the contract and the assembly made by the carpenters according to the plans, the signs and witness of the failures, the past strengthening work; not excluding the object of accomplished historicizing such as the alterations and changes that were and still are consistent with the structure, therefore including also the changes of the configuration and behaviour when they were justified, for instance, as a successful strengthening measure."* (Tampone, 2001)

The load bearing structures of monumental buildings carry not only the aesthetical historic values but also their technological quality.

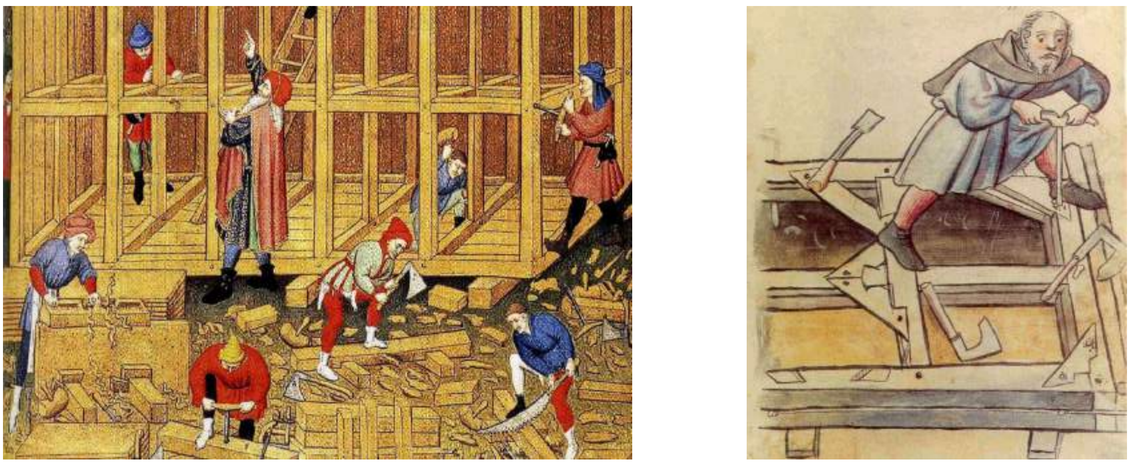


Figure 3 – Medieval carpentry in France.

These structures are precious witnesses of the efforts and inventiveness of mankind in search for more advanced techniques in the application of materials, idealization of new shapes and steadier configurations, taking the best profit from the available materials. The built heritage of the world caries in itself the history of architecture and engineering mechanics, making the efforts on the conservation of this heritage, both aesthetical and technological, one honourable task.

Another subject of frequent confusion and of hard clarification is the clear definition of the concepts that fall inside the general concept of conservation of historical structures.

Although conservation includes others levels of intervention such as preservation and reconstruction in this document I would like to give a special focus on the ones that, despite frequently used, are often misused and misunderstood – Consolidation, Restoration and Rehabilitation. It is easy to understand the general confusion once you start to research the official charters and communications on the subject and to confirm that it is not easy to find a clarification on the subject. It is possible to consult the Burra Charter for the concept of restoration. It states that *restoration means returning the existing fabric of a place to a known earlier state by removing accretions or by reassembling existing components without the introduction of new material.* It may comprehend cleaning, reintegration of details and features, replacement of missing or decayed parts and re-erection of dismantled or destroyed structures or fallen fragments. Consolidation on the other hand implies an addiction of material, strange to the original, in order to restore its original structural functions. Following these definitions, the next step of intervention is the rehabilitation. This is the more invasive intervention within these concepts. While the others may be understood as a repair, rehabilitation corresponds to the strengthening of a structure or part, in order to make it suitable for higher requirements which can be either a change in use with more exigent loads, the increase of safety, or an adaptive alteration. Rehabilitation is many times associated with interventions on historical urban sites and special attention should also be given to these cases (Drdácký, 2007). The level of freedom for the designer shouldn't imply less regard to the intervention principles but a higher responsibility and sensibility to them, therefore it is important for engineers implicated in these actions to have present the modern perspective towards conservation, as well as the techniques that allow interventions to be coherent with those practice principles, taking the cultural dimension of conservation to the same level as the technical one.

Having these concepts clarified, the approach on the principles of conservation of historical timber structures may start with the recommendations given by the ICOMOS committee for timber structures in the *Principles for Restoration of Timber Structures*:

- *recognise the importance of timber structures from all periods as part of the cultural heritage of the world;*
- *take into account the great diversity of historic timber structures;*
- *take into account the various species and qualities of wood used to build them;*
- *recognize the vulnerability of structures wholly or partially in timber due to material decay and degradation in varying environmental and climatic conditions, caused by humidity fluctuations, light, fungal and insect attacks, wear and tear, fire and other disasters;*
- *recognize the increasing scarcity of historic timber structures due to vulnerability, misuse and the loss of skills and knowledge of traditional design and construction technology;*
- *take into account the great variety of actions and treatments required for the preservation and conservation of these heritage resources;*
- *note the Venice Charter, the Burra Charter and related UNESCO and ICOMOS doctrine, and seek to apply these general principles to the protection and preservation of historic timber structures."*

Among the guidelines to intervention, three very important recommendations should always be present designer's mind. It is stated that intervention works should be recognizable, reversible and always follow the principle of minimum intervention. These are widely accepted principles, and are core of the modern approach on conservation. Being any intervention a threat to the authenticity of a structure it is obvious that it should be extended to a minimum, in order to preserve as far as possible the originality of the fabric and structural behaviour. The fact that they should be recognizable is one more way of keeping their intrinsic authenticity, once it should be clear what is truly original from what is added or changed, keeping invasion to a minimum, avoiding hurting the aesthetical value of the original structure. The reversibility of an intervention allows future substitution for more suitable or advanced solutions without sacrificing original fabric or leaving strong traces of past interventions.

> *"3.8 At times the difficulty of evaluating the real safety levels and the possible benefits of interventions may suggest "an observational method", i.e. an incremental approach, starting from a minimum level of intervention, with the possible subsequent adoption of a series of supplementary or corrective measures."*
>
> *"3.9 Where possible, any measures adopted should be "reversible" so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not completely reversible, interventions should not limit further interventions."*
>
> *"3.12 Each intervention should, as far as possible, respect the concept, techniques and historical value of the original or earlier states of the structure and leaves evidence that can be recognised in the future."*

Frequently, when designers apply the practice codes for the design of new structures in conservation interventions these recommendations are forced to be set to a secondary role. By not recognizing the need for a different methodology, the compliance of interventions with the building codes may take to devastating interventions on the case of timber structures. The accentuated viscoelastic properties of wood result in strong deformations that should be assessed carefully, recognizing that this is the nature of the material and that often and that despite the strong deformations observed, there is a reduced danger of collapse. The fact that historical structures have resisted and performed their functions until the present times should be taken in account before any intervention and the idea of improvement should be preferred to total compliance with the building codes. As an example, if permanent, variable and accidental loads are determined with accuracy for each specific situation the safety coefficients can be justifiably reduced. With these ideas in mind, generally interventions become lighter, less invasive and more economic.

There is a strong discussion among conservation specialists on the use of recent techniques and materials on conservation interventions versus the reproduction of ancient knowledge and practice. Although at first sight, these seem to be two opposing points of view, both approaches are reasonable as long as the fundamental objectives of conservation explained above don't fall to a secondary role. Conservation should always have a greater care for the original structure than the intervention itself, although these can be a source of great pride for the designer. The following quotes summarize the different points of view.

> *"Many historic structures manifest a high ability of ancient carpenters in solving complex technical tasks and challenges. Such knowledge has been supporting the author's belief that traditional carpentry should be reintroduced into conservation*

> *practice to a larger extent, namely in cases where historic timber structures are to be strengthened or repaired. In such cases, high performance carpentry helps to solve material incompatibility problems and prevents wood deterioration due to differential physical interface effects."* (Drdácký, 2006)
>
> *"(..) it is the skill in using the most advanced techniques for conservation work, where advanced, in this case means that they are based on the knowledge of the ancient technique and reach the planned results with minimum of damage to the authenticity of the monument, made in compliance with the conception of the structure, the real task of the present times. It is a skill of this kind that must be improved and disseminated amongst workers, not the obtuse repetition of techniques of the past; what does not exclude the possibility of simple, traditional interventions when possible, appropriate and efficient."* (Tampone, 2007)

It is easy to understand that each singular case imposes singular difficulties to overpass. In some cases the knowledge and application of traditional techniques might be a lot more efficient than the application of a modern technology or material, while in others the opposite would be the best solution.

(a) (b)

Figure 4 – (a) Prosthesisation of a damaged beam extremity by means of timber carpentry, (b) alternative to a prosthesisation in the case of a decayed support of a truss.

Both interventions shown on the figure 4 can be considered examples of good practice although different approaches were taken. While in the case of Figure 4 (a) the ideal method for prothesisation was used (all timber intervention by means of carpentry techniques) assuring compatibility of materials, in the case of Figure 4 (b) an alternative to prosthesisation, by using a stainless steel tie, allowed the intervention to be extended to an absolute minimum.

> *"3.7 The choice between "traditional" and "innovative" techniques should be weighed up on a case-by-case basis and preference given to those that are least invasive and most compatible with heritage values, bearing in mind safety and durability requirements."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)
>
> *"Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any technique for conservation and construction, the efficiency of which has been shown and proved by experience."* (Venice Charter, International Charter for the Conservation and Restoration of Monuments and Sites)

Investigation should continue in both directions (both traditional carpentry efficiency and innovative materials and techniques), because the amount of solutions and possibilities available for the designer will increase with the knowledge coming from each, and consequently, so will historical structural heritage.

One important fact to notice is the sad lack of specialized workers available at the present times. Carpenter knowledge and experience can be of great value in conservation and measures should be taken for the revival and teaching of the traditional techniques developed over long years of improvement through experience which used the materials in the most structurally correct way. At the same time, investigation on the effectiveness and structural behaviour of those techniques will allow its resurrection in future conservation works.

3. WOOD PROPERTIES

Naturally, in order to successfully design a restoration intervention on a timber structure, it is necessary to deeply understand the material we are dealing with. Being an organic material, wood possesses unique characteristics deriving from its nature that offer it a high level of complexity. It is an extremely versatile material with a wide range of physical and mechanical properties among its many species. Therefore, in this chapter has been done a brief review of its structure and properties.

3.1. WOOD STRUCTURE

3.1.1. MICROSTRUCTURE

The primary blocks of wood are the fibre cells. These multilayered closed-end tubes with four distinct cell wall layers (Figure 5), disposed side by side with the central axis parallel the tree trunk, form a strong structure that is responsible for bearing the compressive stresses introduced by the tree self weight and the tensile stresses from bending due to wind actions. This tubular structure with large cell cavities makes wood an excellent building material once the large volume of voids offers it an advantageous strength-to-weight ratio. Each of the cell layers is composed by a combination of three polymers: cellulose and hemicellulose forming respectively long and short unbranched chains that are encrusted by lignin.

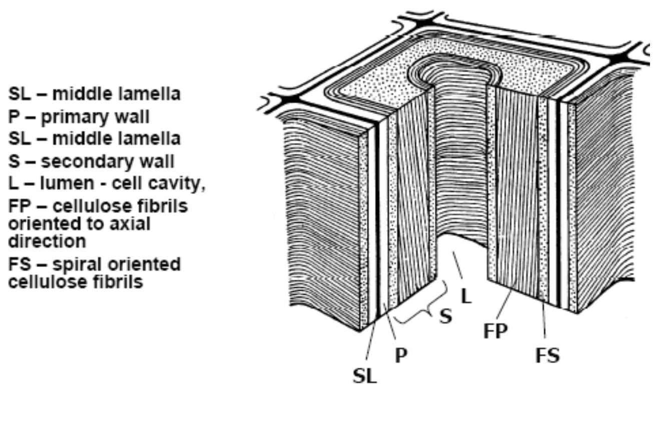


Figure 5 – Ultra Structure of cell wall: anatomical level.

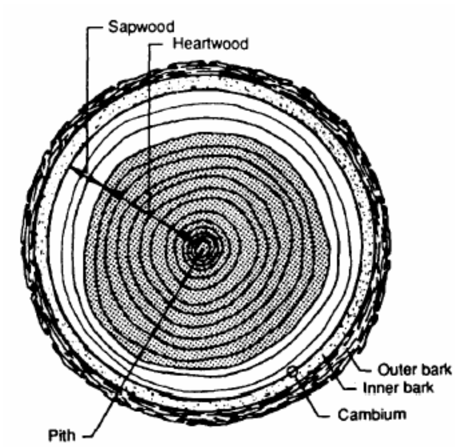


Figure 6 – Wood cross-section.

3.1.2. MACROSTRUCTURE

The cross-section of a tree allows distinguishing three categories, bark, wood and cambium (Figure 6).

Bark is the outer layer and composed of dead outer phloem of dry corky material and a thin inner phloem of living cells having as primary functions, protection and nutrient transport. Its thickness and appearance depend on the tree's age and specie.

Wood is composed of the inner sections of the trunk having the mechanic function of bearing the tree as well nutrient conduction and storage. Wood is divided into two general classes: sapwood and heartwood. Sapwood is located next to the cambium being responsible for the nutrient storage and the transport of sap and its radial thickness may vary form 35 to 150mm depending on the species. Heartwood consists of an inner core of wood cells that have changed, both chemically and physically, from the cells of the outer sapwood. Its cell cavities may contain deposits of various materials that frequently give heartwood a much darker colour. Extractive deposits formed during the conversion of living sapwood to dead heartwood often make the heartwood of some species more durable in conditions that may induce decay.

The cambium is a continuous ring of reproductive tissue located between the sapwood and the inner layer of layer of the bark being usually, depending on the season, 1 to 10 cells wide. All wood and bark cells are aligned radially because each cell in a radial line had its origin on the same cambial cell.

Growth in trees is both affected by the soil and environmental conditions. The new cells formed in the cambium, by cell division, are pushed either to the inside and the outside, being some of them retained to account for the increasing cambial circumference. Earlywood cells have large cavities and thin walls while latewood cells have smaller cavities and thicker walls and therefore a higher density and hardness.

Growth rings are formed due to the different growth conditions along the year. During the hot seasons the production is higher than on could seasons (growth may stop on winter) and cells produced during spring have larger dimensions and thinner walls while in autumn the cells are smaller with thick walls. These differences explain the colour pattern that can be seen on the cross sections of wood, and obviously relating it to the tree's age. It is important to notice that in species from regions where these climatic changes don't occur during the year (i.e. tropical climates) the growths rings won't be formed.

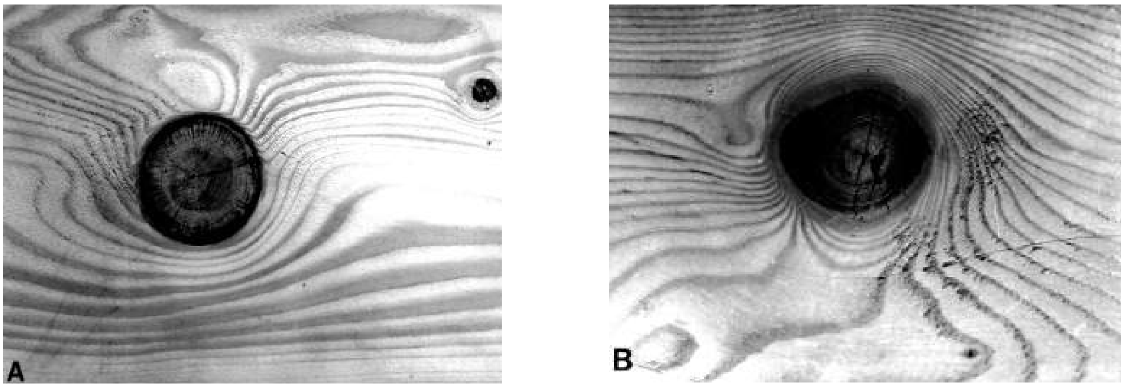


Figure 7 – A, encased knot. B, Intergrown knot.

As a tree grows, branches develop laterally from the trunk resulting in knots when the log is sawn into lumber or timber. Knots are classified on two categories: intergrown knots and encased or loose knots. Intergrown knots are formed by living branches. These branches produce gross deviations in the grain of the trunk which, adding to the loss of resistant cross section that is introduced by the knots themselves, decisively undermines the strength of the cross sections once straight-grained wood is approximately 10 to 20 times stronger parallel to the grain.

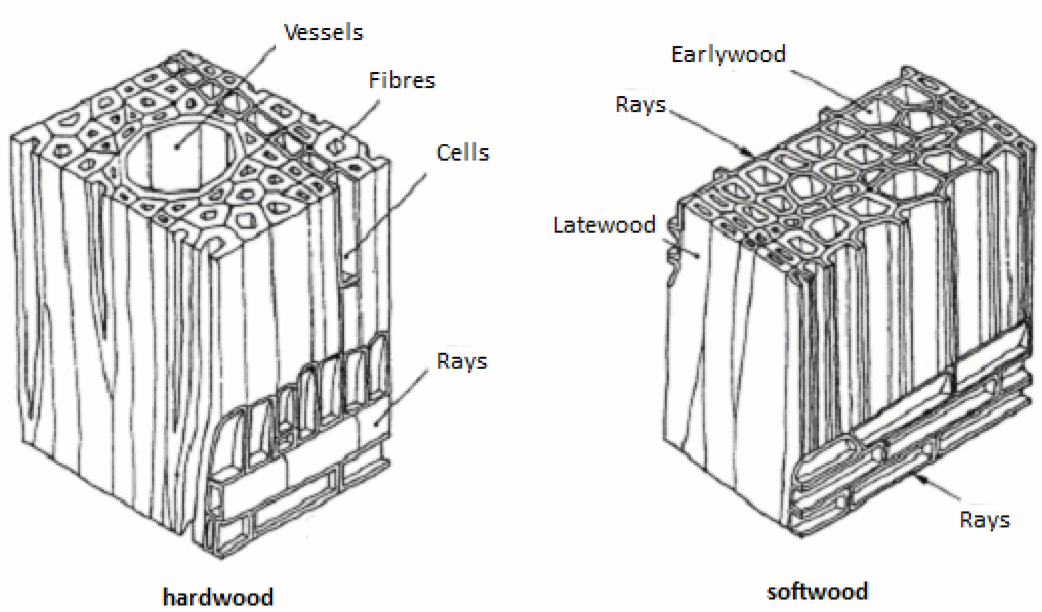


Figure 8 – Structure of softwood and hardwood.

3.2. PHYSICAL PROPERTIES

Wood physical properties directly influence the structural timber performance; therefore the most relevant aspects are here presented in a brief way. These include the directional properties, density, dimensional stability, moisture content, thermal properties and decay resistance.

3.2.1. DIRECTIONAL PROPERTIES

By understanding its biologic nature and growth characteristics it becomes clear why wood is an anisotropic and orthotropic material. Because of the orientation of the wood fibbers and the way in which the tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial and tangential (Figure 10).

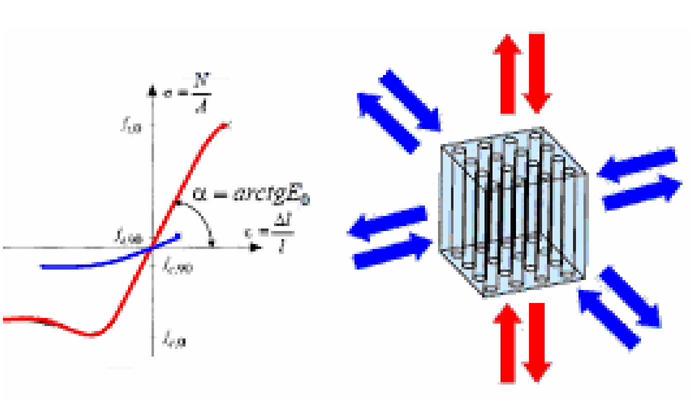


Figure 9 – Wood anisotropy.

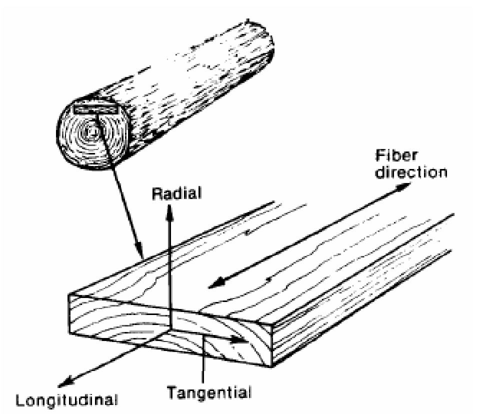
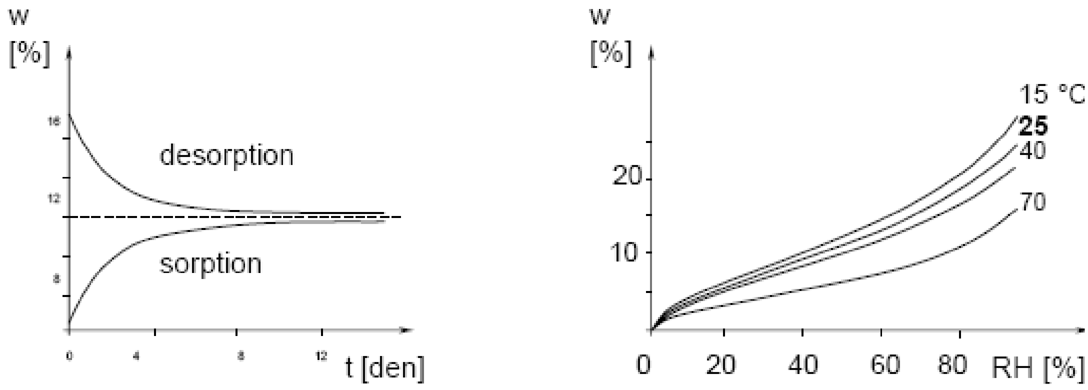


Figure 10 – Three principal axes of wood with respect to grain direction and growth rings.

The longitudinal axis is parallel to the grain direction, the radial axis perpendicular is normal to the growth rings and the tangential axis is perpendicular to the grain direction and tangent to the growth rings. Although most wood properties differ in each of these three axis directions, differences between the radial and tangential axis are relatively minor when compared to differences between the radial or tangential axis and the longitudinal axis.

3.2.2. MOISTURE CONTENT

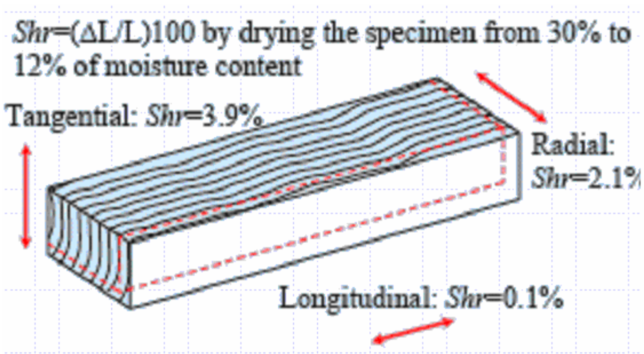
In living trees, moisture content may range from approximately 25% to more than 250% being usually higher on sapwood then on heartwood. Water exists in wood either as bound water, in the cell wall), or free water, in the cell cavity (Figure 11). When wood dies, free water separates at a faster rate than bound water due to accessibility and absence of secondary bonding.



(a) (b)

Figure 11 – (a) Equilibrium moisture content during sorption and desorption, (b) equilibrium moisture content at different temperatures.

The moisture content at which the cell walls are still saturated but virtually no water exists in the cell cavities is called the fibber saturation point ranging between 21% and 28%. The equilibrium moisture content of wood is a function of atmospheric conditions and depends on the relative humidity and temperature of the surrounding air (Figure 11). Because the variations in the percentage of bounded water result in shrinkage and swelling it leads to tension formation into wood distorting the shape of wood pieces. These changes in dimension can only occur when the moisture content fluctuates under the fibber saturation point once above this value only the amount free water is affected and therefore not the wood structure itself.



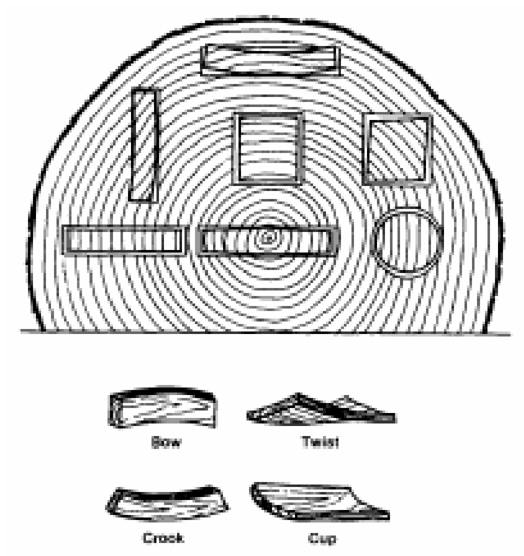


Figure 12 – Shrinkage and swelling in the 3 orthogonal directions.

Figure 13 – Characteristic shrinkage effects of variously shaped wood cutouts according to their location in the cross section.

Because distortions are explained by the different radial and tangential shrinkage**,** usually wood that has the same value for both is preferred. These changes in shape and dimension, may affect the structures through stresses introduced on connections, loss of solidarity between connected elements and cracks originated during the drying process affecting the strength and vulnerability to biological attack.

The wood density is the ratio between its weight and volume for specific moisture content, usually 12%. Most mechanical properties of timber are positively correlated to density. Structural wood should have low density, together with high strength and elasticity modulus. Having a porous structure, wood is a permeable material and therefore can absorb substances that can affect its properties in a negative way, although its natural resistance to chemicals can be considered superior to other building materials. This porous nature is also used to improve its natural properties by impregnation with preservatives that greatly enhance its performance.

3.3. MECHANICAL PROPERTIES

Trees are usually well prepared to resist bending caused by wind loads but not so much to compression coming from its self weight. Due to the defects (knots) present on sawn timber, generally the great ability of timber to resist tensile stresses is dramatically affected and therefore failures in bending are usually on the tension zone. Strength varies significantly depending on species (Table 1), loading conditions, load duration, and a number of assorted material and environmental factors. Also, as referred before, mechanical properties are completely different between the different axis.

Table 1 – Average coefficients of variation for some mechanical properties of clear wood.

Property	Coefficient of variation[a] (%)
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending	25
Compression parallel to grain	18
Compression perpendicular to grain	28
Shear parallel to grain, maximum shearing strength	14
Tension parallel to grain	25
Side hardness	20
Toughness	34
Specific gravity	10

[a]Values based on results of tests of green wood from approximately 50 species. Values for wood adjusted to 12% moisture content may be assumed to be approximately of the same magnitude.

3.3.1. ELASTIC PROPERTIES

Twelve constants (nine are independent) are needed to describe the elastic behaviour of wood: three elasticity modulus ***E***, three rigidity modulus ***G***, and six Poisson's ratios μ. The elastic constants themselves, as well as the elastic ratios between the orthogonal directions vary within and between species (Table 1) and with moisture content and specific gravity. Average values are shown in the Table 2 for the strength classes.

Table 2 – Strength classes of timber and characteristic values (R. Rodrigues 2005).

		Espécie Coniferas									Espécie Folhosas					
		C14	C16	C18	C22	C24	C27	C30	C35	C40	D30	D35	D40	D50	D60	D70
Propriedades resistentes em N/mm^2 (MPa)																
Flexão	$f_{m,k}$	14	16	18	22	24	27	30	35	40	30	35	40	50	60	70
Tracção //	$f_{t,0,k}$	8	10	11	13	14	16	18	21	24	18	21	24	30	36	42
Tracção ⊥	$f_{t,90,k}$	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.7	0.9
Compressão //	$f_{c,0,k}$	16	17	18	20	21	22	23	25	26	23	25	26	29	32	34
Compressão ⊥	$f_{c,90,k}$	4.3	4.6	4.8	5.1	5.3	5.6	5.7	6.0	6.3	8.0	8.4	8.8	9.7	10.5	13.5
Corte	$f_{v,k}$	1.7	1.8	2.0	2.4	2.5	2.8	3.0	3.4	3.8	3.0	3.4	3.8	4.6	5.3	6.0
Propriedades de rigidez em KN/mm^2 (GPa)																
Modulo Elasticidade //	$E_{0,mean}$	7	8	9	10	11	12	12	13	14	10	10	11	14	17	20
Modulo Elasticidade // (5°percentil)	$E_{0,k}$	4.7	5.4	6.0	6.7	7.4	8.0	8.0	8.7	9.4	8.0	8.7	9.4	11.8	14.3	16.8
Modulo E. ⊥	$E_{90,mean}$	0.23	0.27	0.30	0.33	0.37	0.40	0.40	0.43	0.47	0.64	0.69	0.75	0.93	1.13	1.33
Módulo de distorção	G	0.44	0.50	0.56	0.63	0.69	0.75	0.75	0.81	0.88	0.60	0.65	0.70	0.88	1.06	1.25
Densidade em Kg/m^3																
Densidade	P_k	290	310	320	340	350	370	380	400	420	530	560	590	650	700	900
Densidade média	P_{mean}	350	370	380	410	420	450	460	480	500	640	670	700	780	840	1080

3.3.2. STRENGTH PROPERTIES

Compression parallel to the grain deforms wood cells along their axis and failure occurs when cell walls start to suffer from instability. When the loads are applied perpendicular to grain, the cells deform easily due to the cavities in its interior. Once the cavities have collapsed wood becomes quite strong because voids no longer exist. Due to the high deformations caused by this mechanism of collapse, in practice, the strength perpendicular to grain is limited to 4% of its limit value. Members failing from compression stresses usually show slip surfaces along planes that have an angle of 40º to 60º to the tangential plane or with relative slip by separation of planes parallel to the grain.

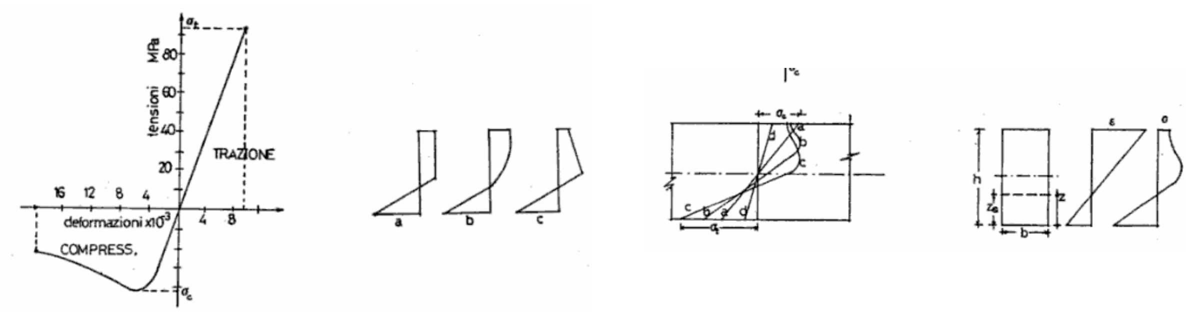


Figure 14 – Wood constitutive model and behaviour in bending.

Parallel to its grain, wood is very strong in tension. Failure occurs by a combination of cell-to-cell slippage and cell wall failure. In contrast, perpendicular to grain, wood is very weak. Stresses in this direction produce splitting or cleavage along the grain which can have a significant effect on structural integrity and should be carefully taken into account when details are designed (Figure 15).

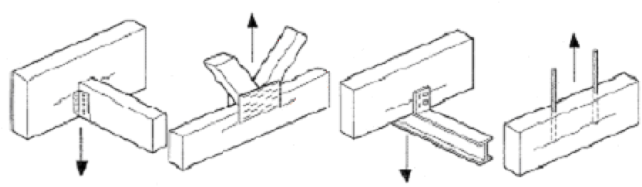


Figure 15 – Cracks originated by tension parallel to the grain.

The good mechanical properties of wood are easily recognizable by comparison with other construction materials.

Table 3 – Comparison of wood with other materials (Binda, 2007).

Materials	Elasticity modulus/Density	Tensile strength/Density	Compressive Strength/Density
Wood	20 – 30	120 – 170	60 – 90
Mild Steel	26	30	30
Aluminium	25	180	130
Concrete	15	3	30

3.4. FACTORES AFFECTING WOOD PROPERTIES

The focus here is on the environmental factors affecting wood properties. Mechanical properties are affected by changes in moisture content below fibber saturation point. Most of them increase with decreasing moisture content (Figure 16). It is also relevant to note that high moisture content, above fibre saturation point, makes timber less resistant to biological attack.

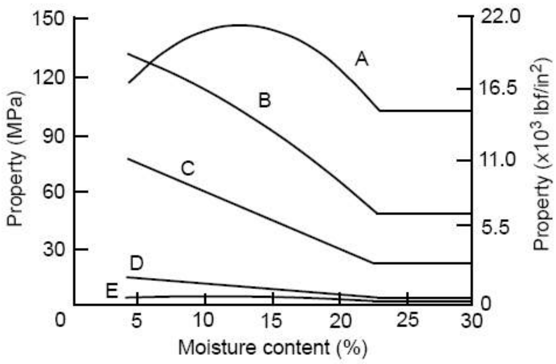


Figure 16 – Effect of moisture content on wood strength properties. A, tension parallel to grain; B, Bending; C, Compression parallel to grain; D, compression perpendicular to grain; E, tension perpendicular to grain.

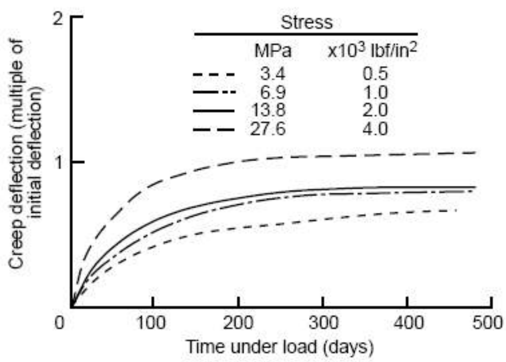


Figure 17 – Influence of four levels of stress on creep.

Given its viscous nature, wood members have an additional time-dependent deformation after the initial instantaneous elastic deformation (Figure 17). At typical design levels and use environments, after several years the additional deformation caused by creep may approximately equal the initial.

Temperature that usually influences wood's mechanical properties negatively when it gets higher (generally above 150ºC), causes creep to increase. An increase of about 28ºC in temperature can cause a two to threefold increase in creep. Also variations in humidity directly influence the viscous behaviour of wood. Elastic deformations are immediate and complete after the unloading of a member and creep deformations can be recovered to approximately half its value. Obviously, the viscosity of wood is also reflected on its relaxation, which is affected, like creep, by the environmental factors of temperature and humidity.

Like other fibrous materials, wood is quite resistant to cyclic loads (fatigue) and when compared to metals is usually several times higher.

As noted before, wood has a high chemical resistance. The loss of properties is usually related to the capacity of a substance to provoke wood swelling (Water and alcohol). Substances that decompose the wood by hydrolysis or oxidation have a permanent effect on strength. and more on sapwood than heartwood given its lower permeability.

Wood weathering is caused by the alternation of sun (drying plus ultra violet) and water on the surface. Even if the checks or weather are not important to the structural performance they might damage surface protection (if applied), create ways to insects post their eggs or perforate into timber and/or create favourable places for fungus to develop when moisture is available. Ultra-violet rays alone have the power to degrade wood in shallow deepness, mostly in an aesthetic way.

NOTE: References for the sub-chapters 3.1. to 3.4.: (Green, Winandy, and Kretschmann, 1999; Winandy, 1994; Irena Kucerová 2007)

3.5. BIOLOGICAL DECAY

3.5.1. DECAY CAUSED BY INSECTS

Many insect species are able to use wood as a food source. They can cause serious damage to timber by tunnelling into standing trees, freshly felled logs or wet decaying timber. Some species of beetles are also able to attack timber in relatively dry conditions found in buildings being the ones responsible for the damage observed in timber structures. They all have similar life cycles but there is a wide temporal variation in each stage in the life cycle, the type of wood attacked, and the extent and type of damage caused. Adults lay their eggs either on timber surfaces or small cracks in the timber. The eggs hatch to release very small *larvae* which bore into the wood, feeding on cellulose, lignin and other wood components, creating a network of tunnels. The *larvae* of most wood-boring insects fill the tunnels with excreted wood pellets known as bore dust or frass. The signs of their activity like the size and cross section of the tunnels, and the characteristics of the bore dust give clues for the identification of the species. *Larvae* continue feeding for periods of one year or more until they undergo a metamorphosis, passing through a pupal stage before reaching the adult form when they emerge, leaving woodworm exit holes in the timber surface. As adults, beetles stop being a threat, but after mating, females often, but not necessarily, re-infest with eggs wood near the place where they have emerged. Damp conditions generally encourage infestation by most insects, and, in particular, deathwatch beetle and common furniture beetle.

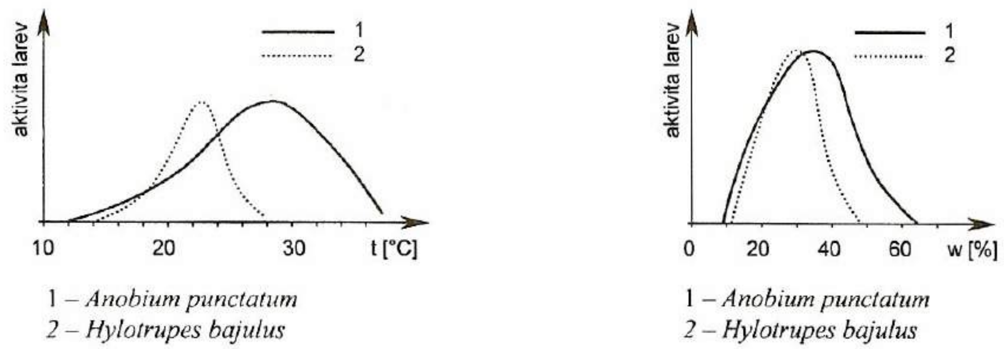


Figure 18 – Influence the environmental conditions, temperature and relative humidity on the activity of wood destructive worms.

<u>Common furniture beetle (*Anobium Punctatum*)</u>

Usually referred to as woodworm, it can attack sapwood of all softwood and European hardwood timbers such as oak and in the case of spruce, since the difference between heartwood and softwood is small, it may spread across the entire cross-section. A severe infestation by this insect can only occur in cases were the moisture content of wood is high. Structural weakening is usually restricted to small-section timbers in severe damp conditions. The grub is white, 2 to 4 mm long and remains in the wood for two years. The bore dust produced is cream-coloured or the colour of freshly cut wood. The exit holes have up to 2 mm in diameter.

Figure 19 – Common furniture beetle.

Figure 20 – Common furniture beetle bore holes.

House longhorn beetle (*Hylotrupes bajalus*)

It is found in roof structures where it attacks sapwood of softwood timbers, often resulting in structural weakening. It is a serious pest in many European countries. It has a lifecycle of 10 years and the frass produced by these insects contains very typical pellets that resemble truncated cylinders when examined with pocket lens. The tunnels and holes are elliptical of 5 to 10 mm in diameter. The ideal conditions for infestation are moisture contents close to 20% in timbers with resin and rests of bark.

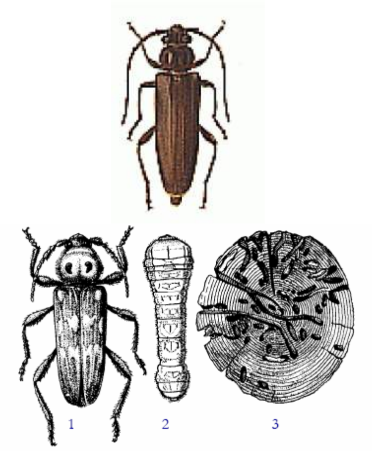


Figure 21 – House longhorn beetle. 1, beetle; 2, larvae; 3,cavities in wood

Figure 22 – House longhorn beetle bore holes

Deathwatch beetle (*Xestobium rufovillosum*)

Attacks hardwoods, but may spread to adjacent softwoods, especially damp, unheated buildings since the *larvae* need a relatively high moisture content and some level of decay to thrive. Grubs are white, 4 to 6 mm long and may remain feeding on the wood between 4 to 10 years. Holes and tunnels are circular, 3 to 4 mm in diameter, spreading in the direction of the wood grain, producing a cream coloured, disc-shaped pellets (bore dust).

Termites

Termites are a threat in tropic and subtropic regions. There two groups: sub-terrain terrain and dry-wood termites. They live inside the timber, often hollowing timber with large cross-sections, but leaving a thin shell for protection that can make it hard to recognize the attack in advance.

3.5.2. DECAY CAUSED BY FUNGI

Decay fungi are spread by microscopic airborne spores that settle on the surface of damp timber with a moisture content of more than about 22%, value below which they cannot survive. After germination they develop fine thread-like filaments – hyphae – which penetrate the wood. These release chemicals – enzymes – into the surrounding wood, dissolving it in order to allow the absorption by the fungal hyphae. As the growth extends through the wood, a fine network of threads is formed, known as mycelium. Behind the advancing front of the actively growing mycelium, the hyphae may fuse to form strands which conduct food and water. The lifecycle ends with the production of a spore-bearing fruit-body on the surface of the decayed timber. Colour, size and appearance of the mycelium, the strands and the fruit-body can help on the identification of the fungal species causing the decay.

Wet rot

Wet rot is a term used to cover the vast majority of fungal species responsible for timber decay. Those that can attack the cellulose but not the lignin are called brown rots. These fungi species leave the wood cross-cracked in cube-like shapes with a characteristic brown colouration. Wet rot that is capable of attacking both cellulose and lignin are called white rots and leave the affected wood fibrous and pale in colour.

Figure 23 – Wet rot on extremities of beams, in contact with masonry.

Dry rot

A particular species of brown rot, *Serpula Lacrymans*, is the only so-called dry rot fungus. The cube-like shapes on damaged wood are usually larger in size than those of other brown rots, being typically 4 to 7 cm long. A skin-like mycelium is formed, white at first and then turning grey, being easily peeled of the wood. Having a high resistance to alkaline conditions it can also form a strand mycelium that easily penetrates mortar joints in masonry walls. The growth is very fast and may reach 10mm in only one day.

Figure 24 – Dry rot.

Fungi seriously reduce strength by metabolizing the cellulose fraction of wood. Decay has the greatest effect on toughness and impact bending as opposed to the lightest effects on shear and hardness. In fact, mechanical properties are affected during the beginning stage of wood decay, despite wood hardness does not appear to have any changes. Density decrease is a quantitative indicator of its damage degree but before the attack is visible or any loss of weight is detected the mechanical properties of wood can be already reduced by a 10% and when the weight loss reaches 10%, wood's mechanical properties can already be affected by its 80%.

Figure 25 – Typical cube-like shapes of brown rot.

NOTE: References for the sub-chapter: (Drdácký, 2007; Eaton, 1993; Ridout 2000).

3.6. MECHANICAL DECAY

The survey of degradation originated by mechanical actions is of fundamental importance. Failures may comprehend deformations, disconnections, displacements, ruptures, splitting, cracking, etc, which may imply general or localised loss of stability.

Visible failures should then be connected with the possible reasons for their presence. For example, the type and shape of cracks, which are originated when strains have reached the material limit, have distinct characteristics according to the stresses that are present; compression, tension, bending, shear, or torsion, and naturally, the presence of biological deterioration. They are frayed, irregular and progressive if the wood tissues are sound, on the contrary sharp, straight and instantaneous (sudden) if the tissues are affected by biotic decay. The most dangerous are the transversal ones caused by tension; being the last stage of a severe failure, they precede collapse. Compressive cracks are characterized by a plastic consistence and bulging of the tissues affected with the presence of small longitudinal cracks (Tampone, 2001).

Figure 26 – Reliquary Room of Santa Cruz, Coimbra. Excessive deformation of member.

Figure 27 – Church of Mirteto, Italy. Break of the rafter of a truss caused by the instability of the strut.

Malfunctioning of connections by loosening, twisting or breaking can progressively affect the rest of the hierarchic organization, being the causes for these failures either mechanical (excessive or anomalous stresses), biotic decay, the environmental actions which can cause important changes in dimensions and corrosion of metallic elements or an original inaccurate design of the joint. These failures are more frequent than the cracking of members due to excessive stresses and are extremely serious in many cases, taking to changes in the configuration and correct hierarchic dependence of members, being common causes of collapse (Tampone, 2001).

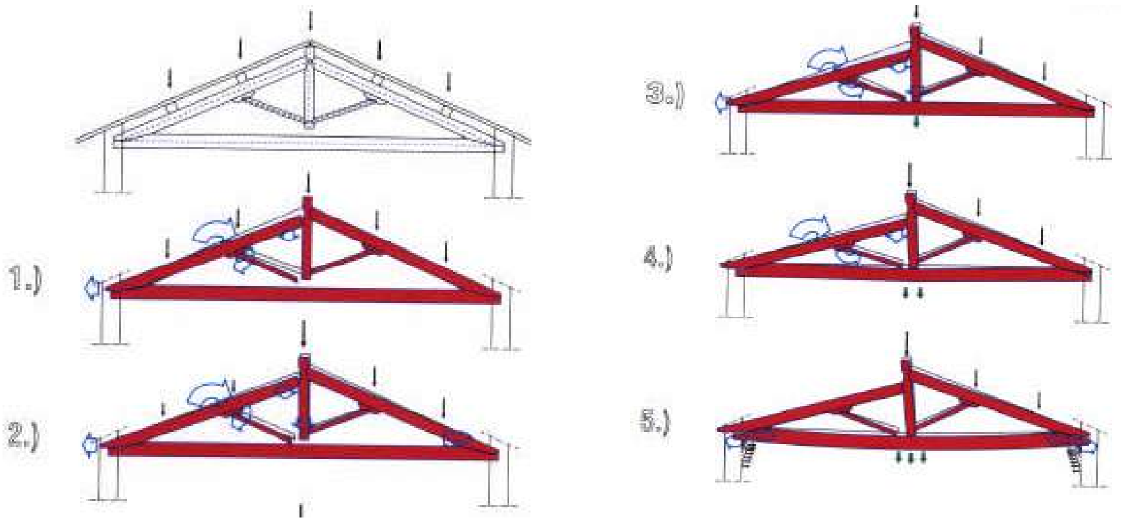


Figure 28 – Schematic progressive failure of king post truss due faulty connection between rafter and tie beam.

4. INVESTIGATION AND DIAGNOSIS

Investigation and diagnosis are probably the crucial steps in conservation. No intervention is possible without proper recollection of information about the structure in cause and the value, accurateness, and appropriateness of any action is definitively linked to the quality of this investigation, its interpretation and correct diagnosis. The ICOMOS committee, in several communications, raises attention to this fact by giving a great amount of recommendations about the subject:

> *"1.6 - The peculiarity of heritage structures, with their complex history, requires the organisation of studies and proposals in precise steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the searches for significant data and information, individuation of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions. In order to achieve cost effectiveness and minimal impact on architectural heritage using funds available in a rational way; it is usually necessary that the study repeats these steps in an iterative process."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

> *"2.3 - A full understanding of the structural and material characteristics is required in conservation practice. Information is essential on the structure in its original and earlier states, on the techniques that were used in the construction, on the alterations and their effects, on the phenomena that have occurred, and, finally, on its present state."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

> *"2.5 Diagnosis is based on historical, qualitative and quantitative approaches; the qualitative approach being mainly based on direct observation of the structural damage and material decay as well as historical and archaeological research, and the quantitative approach mainly on material and structural tests, monitoring and structural analysis."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

> *"2.6 Before making a decision on structural intervention it is indispensable to determine first the causes of damage and decay, and then to evaluate the safety level of the structure."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

> *"2.7 The safety evaluation, which is the last step in the diagnosis, where the need for treatment measures is determined, should reconcile qualitative with quantitative analysis: direct observation, historical research, structural analysis and, if it is the case, experiments and tests."* (Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

> *"1 - The condition of the structure and its components should be carefully recorded before any intervention, as well as all materials used in treatments (…). All pertinent*

> *documentation, including characteristic samples of redundant materials or members removed from the structure, and information about relevant traditional skills and technologies, should be collected, catalogued, securely stored and made accessible as appropriate. The documentation should also include the specific reasons given for choice of materials and methods in the preservation work.* (Principles for Restoration of Timber Structures, 1999)
>
> *"2 - A thorough and accurate diagnosis of the condition and the causes of decay and structural failure of the timber structure should precede any intervention. The diagnosis should be based on documentary evidence, physical inspection and analysis, and, if necessary, measurements of physical conditions and non-destructive testing methods. This should not prevent necessary minor interventions and emergency measures."* (Principles for Restoration of Timber Structures, 1999)

Preceding the design of any intervention, a throughout investigation of the structure is essential. Its objectives are the historical and architectonic characterization, the state of conservation of all parts and elements and determination of its structural behaviour.

Usually the historical context and architectonic characterization can give the fundamental information on the type of construction, materials used, typologies and hierarchy of elements, connections and construction techniques as well as distinctive stylistic features and examples of skilled craftsmanship. All this information has an important role, both on the definition of the next steps of investigation and the design of any intervention.

Material characterization and state of conservation as well the definition of all the degradation phenomena affecting it give the essential data to the analysis of the overall structure performance and state of stress of its elements which allows the evaluation of the necessity of any direct action of conservation and its appropriated design.

When the structure is in poor conditions further analysis must detect if causes of decay and failures are still active, the period in which they occurred and the processes that have given origin to the observed damage.

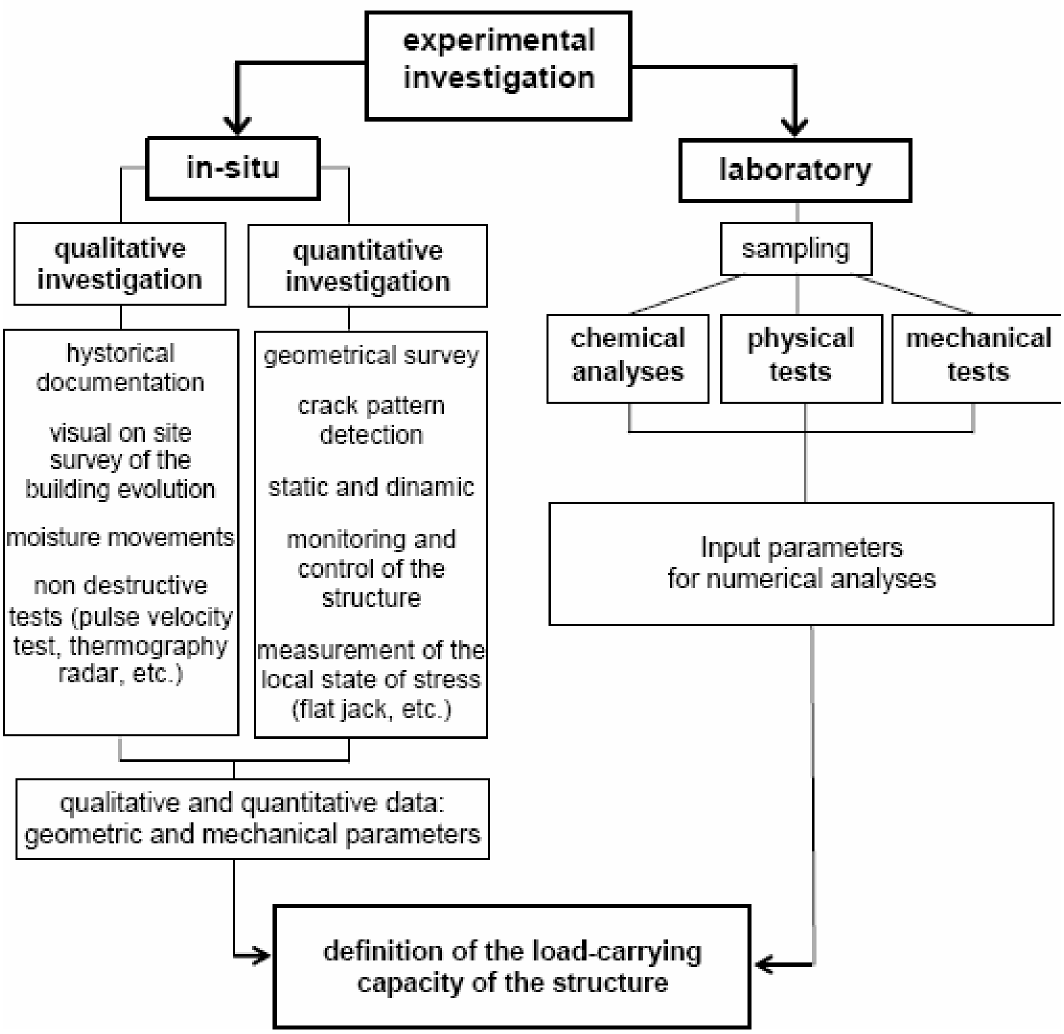


Figure 29 – Experimental survey procedure for structural analysis.

4.1. TECHNOLOGY OF CONSTRUCTION

4.1.1. TRADITIONAL CARPENTRY

The research of the techniques and technology of construction is part of the essential investigations for the analysis of monumental timber structures. Ancient carpentry was a master's craft that used a deep knowledge of the material, its nature, its best use and limitations. Because chemical protection and other materials to suppress its physical and mechanical limitations weren't available, carpentry craftsmanship had to develop use practices that would take the best advantages of the material, avoid incorrect uses and in this way, enhance its durability. These techniques have nearly disappeared in modern times and therefore only by analysing and testing the traces left in historical constructions is possible to revive the ancient techniques, introducing them in today's scientific knowledge. (Larsen, 2004; Drdácký, Mlázovský and Ruzicka, 2006).

Figure 30 – Carpentry techniques on medieval book illustrations.

The research and study of these techniques will allow its reintroduction by application into conservation practice in the cases in which the historical value of the monuments justify their usage for strengthening, repairing or substituting parts and members.

4.1.2. HISTORICAL TYPOLOGIES

> *"Configuration of a structural unit (frame, truss, floor) as part of a structural system is an abstract concept related to the geometry of the mechanical device and of its components (as span, bay, height; number, shape and position in the space, normally the plane, of the members, dimensions and ratio between them), the connections of various nature between the members which determine the relations between the elements and any other structural system connected. The configuration is devised to bear a given system of forces and withstand the foreseen actions thus ensuring strength, equilibrium, stability to the architectural organism."* (Tampone, 2001)

The study of the typologies and its interpretation gives essential clues for the definition of the hierarchic organization of the structural elements and its particular role in the overall structural behaviour (Tampone, 2001). It allows the understanding of the role and importance of each element, the presence of previous interventions (integration, replacement, stiffening, propping…), changes in the static system or incorrect structural performance. The understanding and respect for the placement and function of each element is essential on an intervention that respects the authenticity of a structure, being the study of historic configurations and typologies essential to correct interpretation of the structural behaviour.

In the last years, investigation work has been done with objectives of classification and documentation of common typologies throughout Europe, and of course, given the great diversity even in a single region or country this task reveals itself immense (Szabó, 2005).

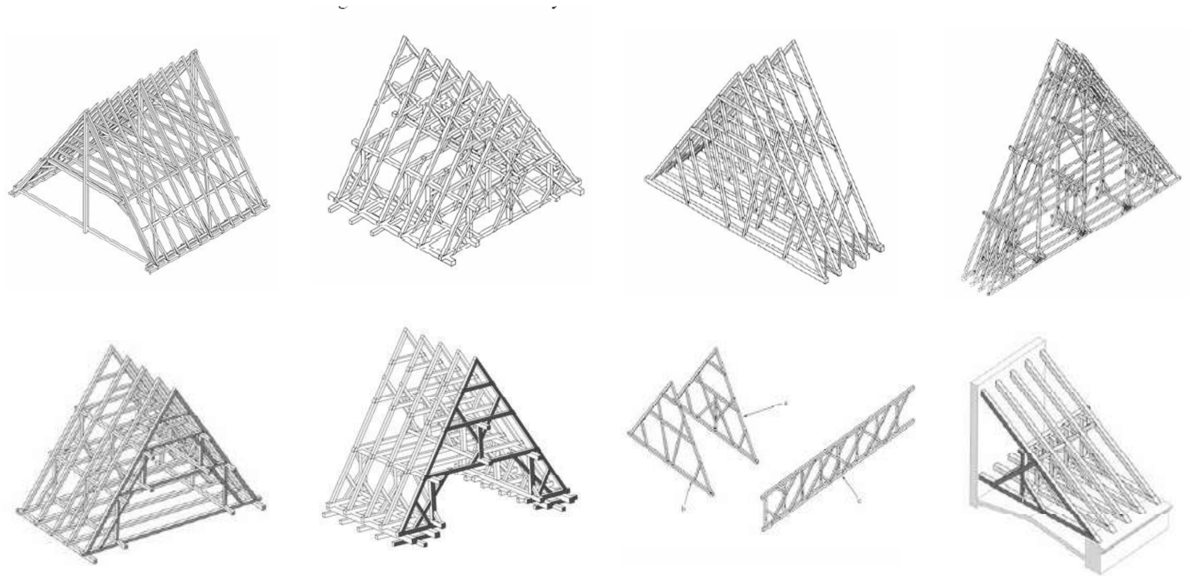


Figure 31 – Roof trusses from central Europe.

Commonly referred as trusses, historical timber roofs usually don't behave as real trusses, but have taken suitable framing configurations that allow them to perform their function as load-bearing structures, able to resist either vertical or horizontal actions. Common rafter and tie beams are probably the most usual configuration throughout Europe, but this simple concept hides a great variety of sub-typologies (Szabó, 2005).

The common rafter roof with tie beam gave origin to a variety of configurations that developed on central and southern Europe with the necessity of reducing the span of the rafters and the tie-beams. Other elements and combination of elements were added, resulting in increasing complexity. Collars, struts, purlins, king posts, queen posts, crow-posts have been combined to achieve more stable and efficient structures with longer spans.

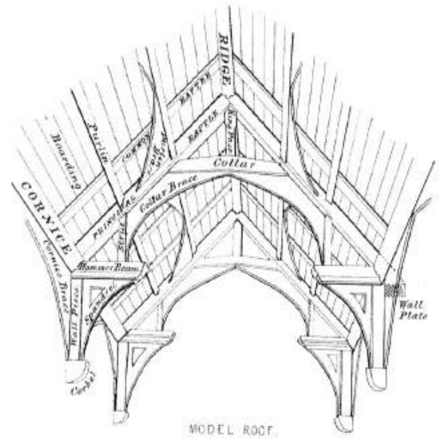


Figure 32 – Hammerbeam truss, typical from England.

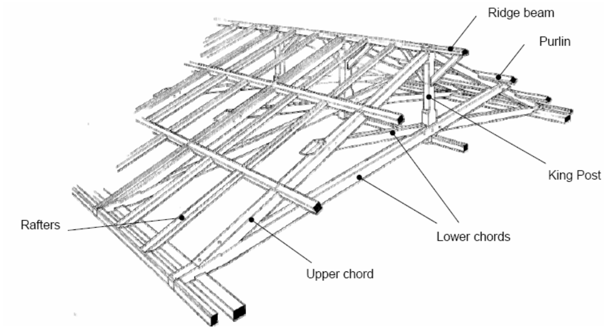


Figure 33 – Scissor truss.

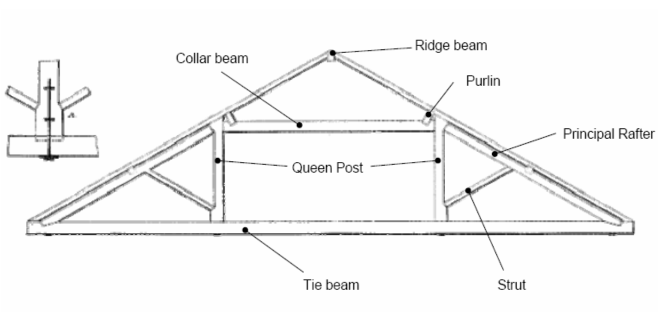


Figure 34 – Queen post truss.

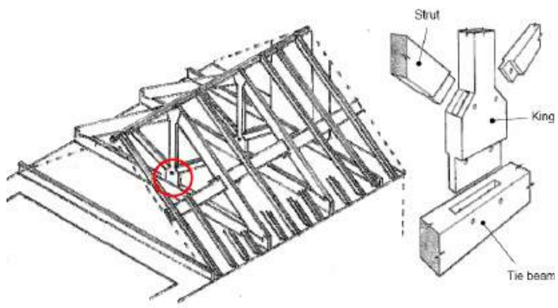


Figure 35 – King post truss.

4.1.3. HISTORICAL CONNECTIONS

"The timber construction technique was mainly centred on the bond, i. e. the art of connecting the member extremities in the best way according to the chosen configuration. Up to the beginning of the XIX c., when many industrial processes were invented for the production of cylindrical nails and these became available and cheap, mortise by means of hollow and tenon or, at least, conjugated shapes of the parts to be faced, were the normal kind of connections, sometimes with the aid of iron fittings such as nails, collar ties, clamps etc. Joints really fixed, anyway, were not available with this kind of connections because of the characteristics of the wood tissues, so the use of struts became necessary to ensure stiffness. In a similar way, struts were used to avoid point loading in the slender members." (Tampone, 2001)

Historic evolution of timber joints starts when the primitive joints by lashing and tongue and fork give place to the more sophisticated joints used in timber framing, the laped, halved, mortise and tenon, housing and birdsmouth joints. Later, extra components are added in order to improve the connection stiffness and shear stress resistance. Dowels, nails and other metallic elements are added to achieve those goals.

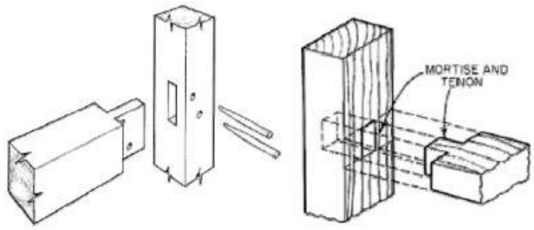


Figure 36 – Mortise and Tenon joint.

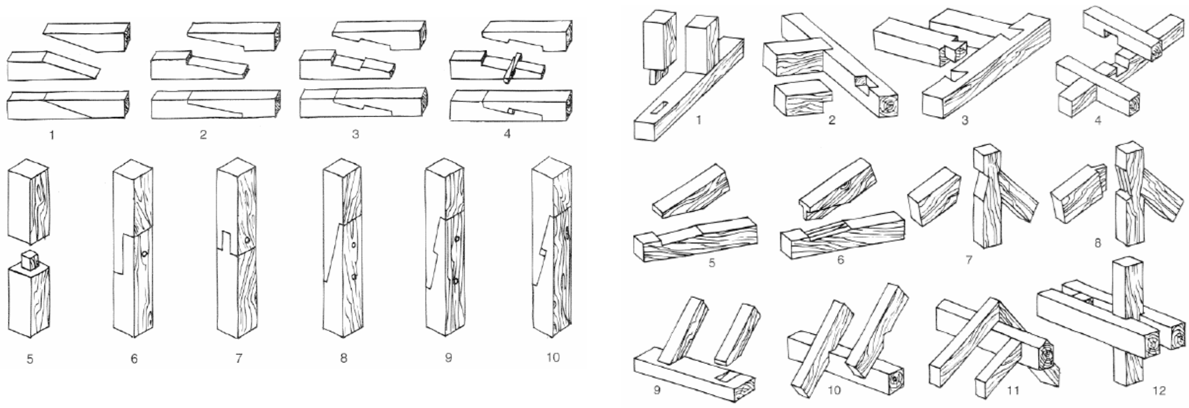


Figure 37 – Roman carpenter joints.

Roman carpentry achieved great innovations giving efficiency and versatility to joints, allowing timber construction to meet more exigent requirements with more rational and sophisticated use of the materials. The diversity of roman carpenter joints can be seen on the Figure XX. The joints kept being used and perfected until the industrial revolution, which introduced a widespread use of metallic elements on timber joinery.

Figure 38 – Detail of halved joints with dowels in a timber roof a connection using metallic elements**.**

4.2. INVESTIGATION AND TESTING METHODS

A wide variety of instruments and techniques of investigation is available at the moment. The increasing interest for application of non-destructive techniques of investigation to cultural heritage buildings contributed to the development of new techniques that are meeting a widespread use in practical cases, which allow assessing the characteristics and condition of the structures while respecting and preserving its fabric.

Traditional visual, point prospecting, hammer percussion and coring are still fundamental but modern methods allow complementing and taking the recognition to a higher level of precision, provided that reliable interpretation of data is made.

Given its interest, a short review of these modern non-destructive and slight destructive techniques of investigation and monitoring is presented. Their objectives are:

- To characterize the building materials;
- To identify decay and damage;
- To determine whether or not phenomena have stabilised;
- To access possible risks and urgent measures to be undertaken;
- To identify any ongoing environmental effects on the building.

Several non-direct methods of evaluating the mechanical properties of wood through correlation with the results obtained from minor destructive techniques have been proposed after recent investigation campaigns. These are essentially based in correlating measured density, superficial hardness and resistance to penetration with wood's mechanical properties. They are not presented in this document, given the intention of just giving a light introduction to the available NDT methods but an interest reading on the subject can be recommended: see Calderoni, Giubileo and Mazzolani 2006; Dardacky 2006; Feio 2005 and Minster, Micka, Václavík 2006)

Controlled drilling

Given that drilling any material requires energy, depending the amount on the integrity of the material, special drilling equipment was developed to record the energy needed to drill wood or the resistance to the drilling. Sound wood requires more energy to be drilled that decayed wood, while voids require no energy at all. The controlled drilling has a constant drilling speed recording the drilling deepness along with the resistance or energy. The result is a map of the drill line in which decayed wood can be identified drops of resistance are recorded (Figure 40).

Figure 39 – Resistograph application.

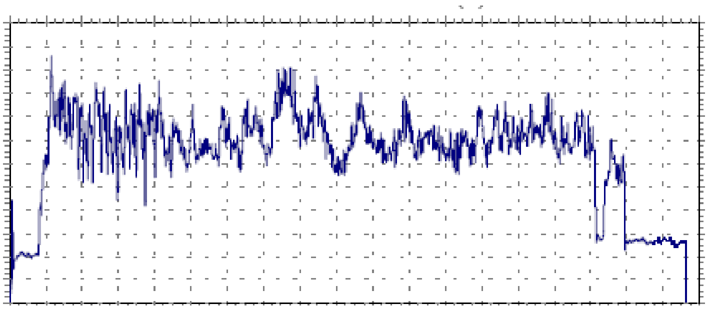


Figure 40 – Resistograph map of drilling.

Pylodin

The pylodin is a simple instrument that drives a pin into timber with fixed impact energy. The depth to which the pin penetrates is indicated on the instrument and is inversely proportional to the wood density. It is a simple instrument that easily allows detecting drops of wood density connected to timber decay.

Figure 41 – Pylodin application.

Figure 42 – Pylodin.

Sound waves or stress waves timing

The travel speed of sound or stress waves is higher on materials with higher elasticity modulus and when meeting voids in the material they contour them taking more time to reach the reception point. By applying a sound wave or stress wave in one point and by controlling the time they take to reach a reception point it is possible to detect, by comparison, sound or decayed wood and internal voids originated by biological attack.

Figure 43 – Sound waves application.

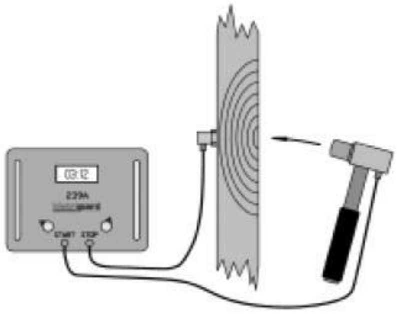


Figure 44 – Sound waves device.

Acoustic detection

It consists on the detection of the activity of insects, namely termites, by capture and amplification the sound waves produced in their activity. By the nature and volume of the detected sound signal it is possible to estimate the intensity of the attack (Botelho 2006).

X-rays

X-rays are high-density rays of photons that transpose materials depending on its density. X-ray density can be registered by appropriated sensors or photographic films. Logically, sound wood offers higher resistance to X-rays and thus the photographic sensibilization differences allow recognizing portions of decayed wood. Also, X-ray tomography may be used to create three-dimensional images of wood details which has a special interest in the case of timber joints.

Figure 45 – X-Ray equipment.

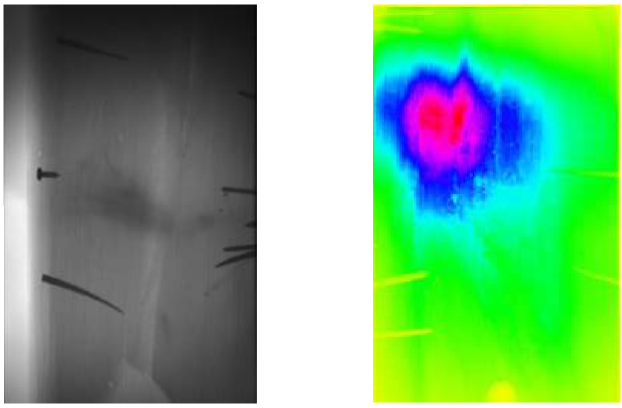


Figure 46 – Detection of metallic elements and hollow sections by X-Ray investigation.

Thermography

Temperature of wood surface along a timber member varies depending on the difference of diffusivity, heat conductivity and density. Knots, cracks, internal cavities and other defects locally change the physical properties of timber and decayed wood has a loss of density, thus these will origin local changes of temperature. A highly sensitive thermo-camera can detect these temperature differences which can be associated with the referred phenomena.

NOTE: References for the sub-chapter: (Telles and Vale 2001).

4.3. STRUCTURAL ANALYSIS

The correct assessment of the need for strengthening and its accurate design requires a reliable evaluation of the structure static behaviour, retrieving real stresses and deformations for the imposed loads. Numerical analysis is naturally an adequate tool to accomplish this purpose although the task of correctly modelling the behaviour of an ancient and decayed timber structure can become extremely demanding. Its results allow understanding the behaviour of each structural element in terms of strength and deformation capabilities, evidencing the weaknesses of the examined wooden structure. Consequently, on the basis of the acquired knowledge, the appropriate restoration intervention can be proposed.

The problem can be synthesised in the correct evaluation of the structure geometry, material properties, structural model (including boundary conditions) and the actions to which it is subjected.

The difficulties start on the material itself. Due to its nature, wood presents several defects (nodes, shakes, shrinkage slits, shape imperfections, fibre deviations, etc.) and structural anomalies (cracking, deformations induced by long duration loads, connection degradation, etc.), moreover it suffers from biological deterioration, closely connected to the external environmental conditions (Marzo, Faggiano and Mazzolani 2006). Consequently preliminary structural diagnosis inspections must collect the information to correctly define the geometry (including deviations and anomalies) and the materials properties. The assessment of the strength of the materials, although in a statistic and probabilistic way, is one of the most difficult tasks because it is not possible to deduce one or more members from an ancient structure for direct testing on structural scale samples. The common procedure is to determine the medium stock's properties (grading) (Tampone, 2001).

The definition of the actions to which the structure is subjected requires the assessment for the present and future conditions has well as investigations on past. Actions should be characterized in terms of entity, duration, application areas and variations. Non-mechanical actions must also be carefully evaluated; frequently, environmental factors can reveal themselves crucial. If permanent, variable and accidental loads are precisely determined for each specific situation the safety coefficients can be justifiably reduced.

Concerning the definition of an adequate structural model many uncertainties arise, which, if not correctly evaluated can strongly affect the accuracy and reliability of the results. The problems involve (Bamonte, Ceraldi, Ermolli):

<u>Interpretation of external constraints behaviour</u>

The presence and relation with other structural systems, such as the masonry supports, are often hard to determine requiring specific investigation on the matter.

<u>Interpretation of internal constraints behaviour</u>

Schematisation of joints made of timber or with metal strengthening requires a correct interpretation of the type of joint and corresponding restraints implied to the connected members. Usually, joints are considered to be articulations or semi-articulations, being in the second case extremely hard to determine the corresponding rotational, axial and shear stiffness. This evaluation might be of crucial importance once the definition of a model with semi-articulated joints can sufficiently change the results of the analysis in a way that no need for intervention is concluded. The determination involves the usual factors of geometric configuration, mechanical properties of the material, deformation mechanism and eventual connectors (Piazza 2004). EC5 (ENV 1995-1-1) indicates that joints should be considered as articulated in ultimate limit state and semi-articulated in service conditions. Taking in account the high displacements reached for the ULS it seams reasonable to believe that there are great advantages in considering also semi-articulations for the ULS, as long as appropriately evaluated.

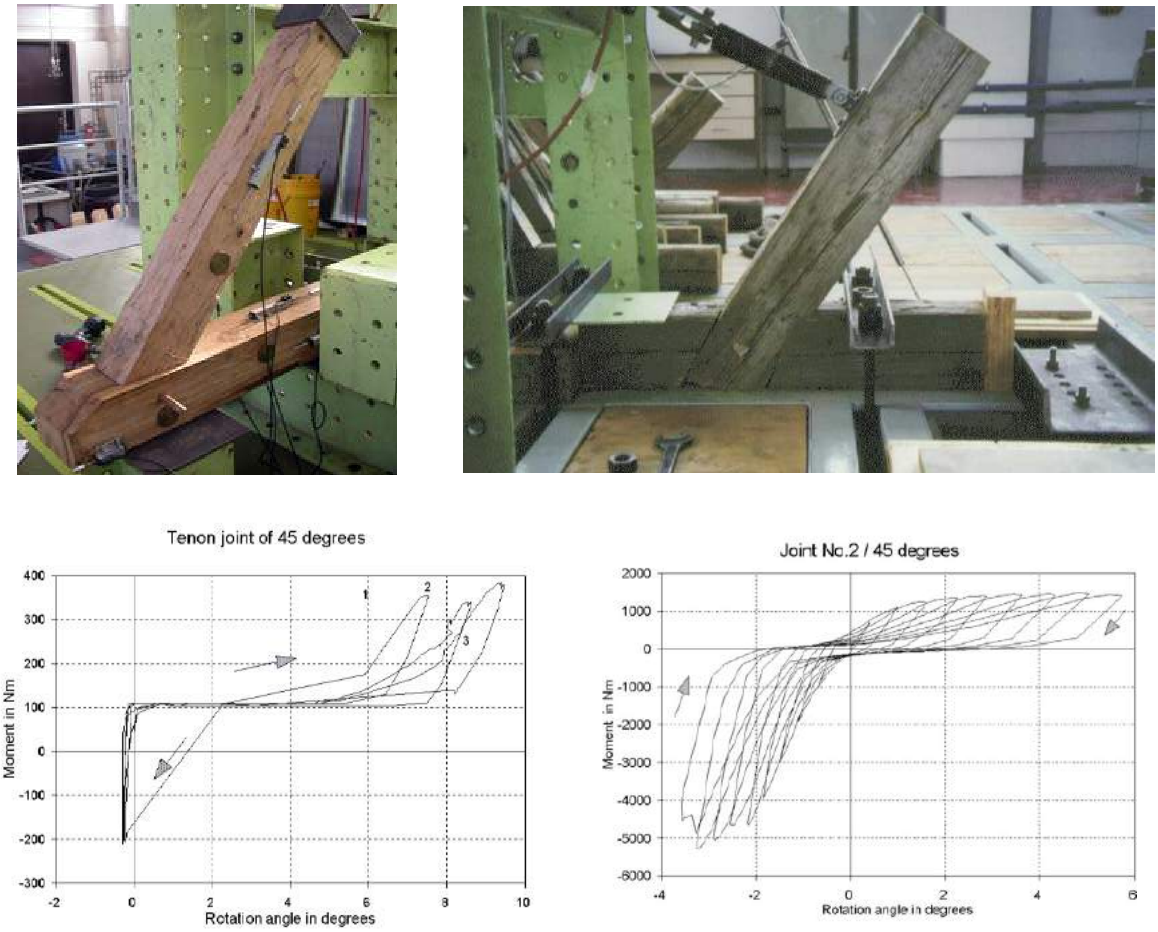


Figure 47 – Stiffness tests on tenon and halved joints (ITAM, Prague).

Tests performed on historic samples collected from demolished structures and on replicas of joints made from several hundred years old timber (Figure 47) have shown that although historical timber connections frequently show a good quality, the rigidity of historical frames reduces the influence of the connection's bending stiffness making the consideration of pined joints suitable in most practical cases. The always present slip in connections is more dominant and can significantly influence the response of historical frames (Drdácký, Mlázovský, Ruzicka 2006). Testing the stiffness of carpentry joints is especially interesting to calibrate FEM models.

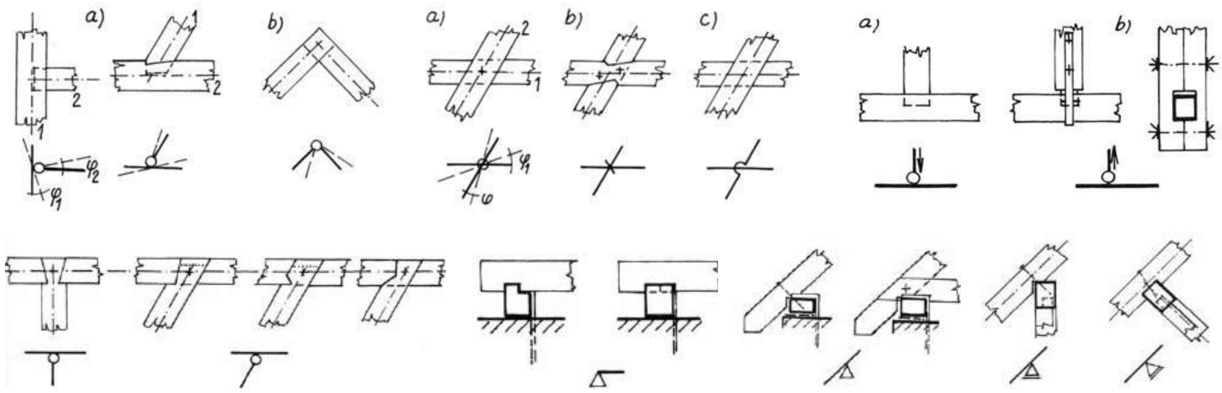


Figure 48 – Models of connections.

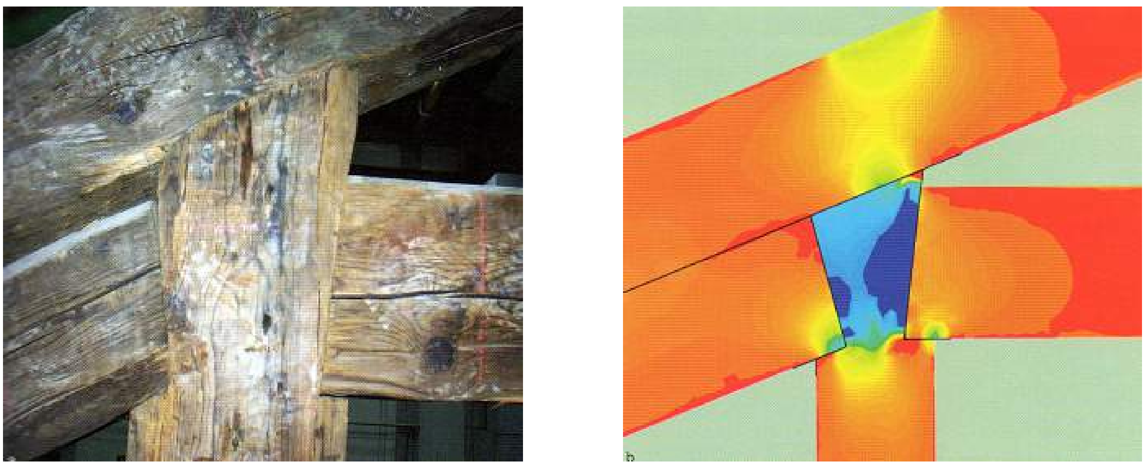


Figure 49 – FEM models of details are particularly suitable to evaluate the concentration of stresses in joints. In this case it can be seen an excessive stress perpendicular to the grain.

Evaluation of efficiency in the distribution of stresses on contact elements

In trusses it is common to find elements in contact, sometimes strapped, resisting together as a composite system. It is extremely hard to model this contact, as the distribution of stresses is influenced by several variables such as the friction between the members, their boundary conditions and the stiffness of the straps. This was the case in Naples Royal Palace trusses (Figure 50).

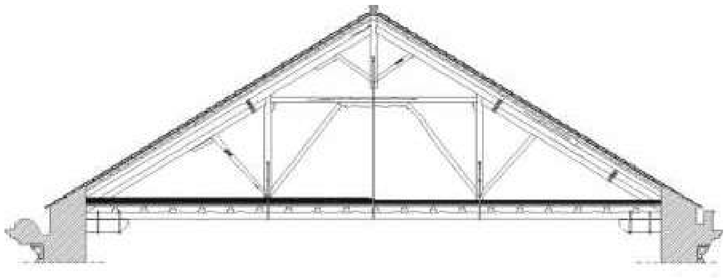


Figure 50 – Naples Royal Palace studied truss.

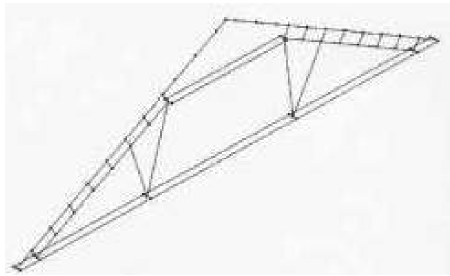
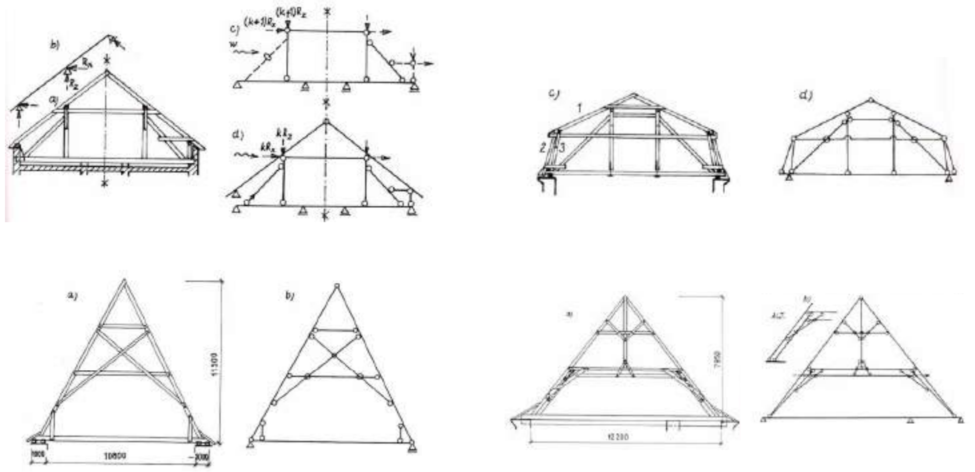


Figure 51 – Numerical model of prototype.

The evaluation of the distribution of stresses between principal and jack rafters was accomplished by calibrating a model that simulated the contact by introducing elements clamped to both the members, being adjusted their stiffness in order to approximate the results to those obtained in the truss model test performed on laboratory. Finally, the calibrated numerical model is applied to the analysis of the palace's trusses (Bamonte, Ceraldi and Ermolli 2001).

<u>Complexity of structures and numerous sources of errors</u>

The number of elements and the variety of structural functions that they assume can immensely complicate the elaboration of numerical models accurately reflecting the real structural behaviour. Secondary elements, which are present to increase local stiffness of joints and great number of external and internal constraints, might cause a sum of small errors that take final results to be far from reality (Figure 52).



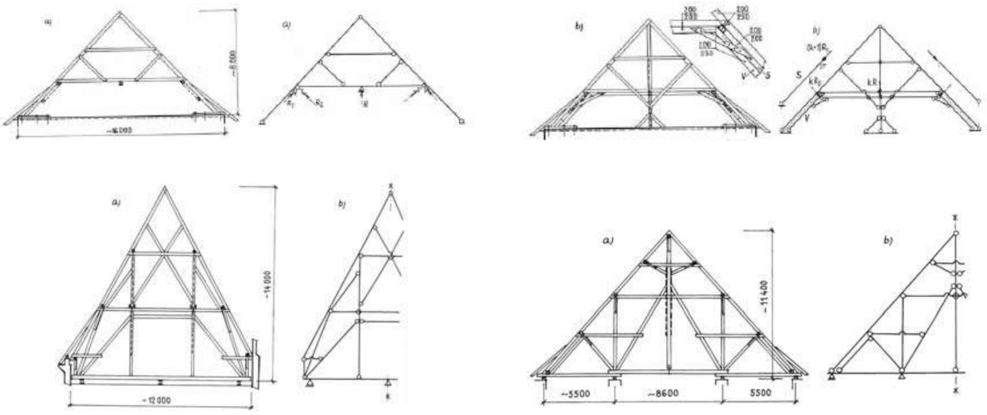


Figure 52 – Some models for timber trusses.

It is generally advisable to study several possible situations, assuming different internal and external boundary conditions and make judgements based on a variety of situations (Figure 53), (Ceraldi and Russo, 2006). New campaigns of inspections might be needed to confirm the results coming from the numerical analysis.

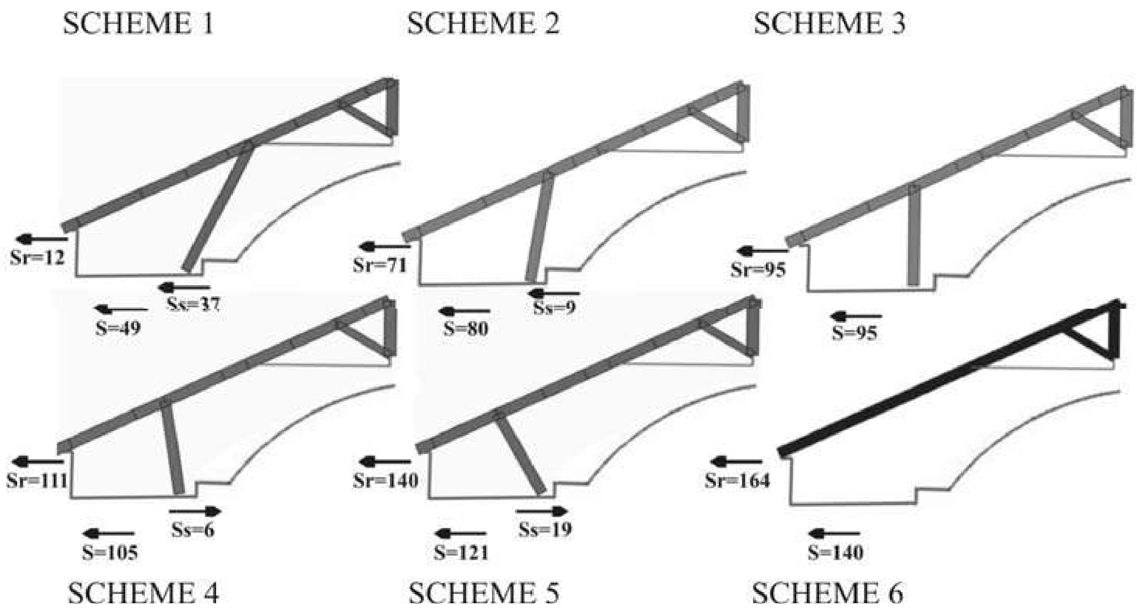


Figure 53 – Analysis of the timber coverings of the Palatine Chapel in the Caserta Royal Palace where different calculated schemes returned very distinct values of the horizontal thrusts.

5. REPAIR AND STRENGTHNING METHODS

The diversity of failures, decay phenomena and needs for upgrading the bearing capacity of structures has forced the development and application of a never ending variety of solutions to repair and strengthen timber structures. It is then presented a collection of techniques with an organization based on the materials and objectives to accomplish. It is essential to notice, that the design of interventions of conservation is not a simple "pick from catalogue" task; it requires knowledge and imagination from the designer in order to outstand the difficulties of each particular case. The designer must not limit himself to the use of preconceived so catalogued solutions, but to assume a critic, imaginative and open mind attitude, being able to approach the variety with design options that assure safe, effective and durable interventions.

5.1. CHOICE OF INTERVENTION TECHNIQUE

The decision on the selection of the type of repair or strengthening, being of central importance in any intervention, must take in account a diversity of factors, making it extremely complex. Engineering and design criteria, economic aspects and compliance with conservation principles are the general problems in decision making.

In particular, the following pure engineering aspects should be carefully studied (CNR-DT 200/2004):

- The geometry and materials, both of the original structure and the strengthening as well as the structural behaviour, before and after the intervention;
- The visibility of the strengthening, the material compatibility and the possible environmental conditions affecting the strengthening, such as the thermo-hygrometric conditions and other chemical or physical factors to which it can be exposed;
- The evaluation of the interventions durability. Historical structures have prevailed until our times and the central objective of conservation is to give them the capacity to continue resisting for a long time. It is therefore crucial to design repair and strengthening interventions that are able "survive" undamaged by mechanical and environmental actions. Material durability and compatibility is an essential aspect to be evaluated in order to assure this objective. Objectives that can be accomplished

with reliable materials and techniques that have passed long years of testing and have proven to be effective must prevail over innovative but not sufficiently tested actions.

- Economic aspects such the cost of the intervention and the availability of specialized staff can also be determining on the selection of strengthening type.
- As referred before, regard to the structural authenticity and aesthetical values should be a constant factor in decision making, playing the modern principles of conservation the role of a guide to assure respectful interventions.

5.2. DURABILITY REQUIREMENTS

Interventions frequently give origin to composite systems of high complexity by creating sections of different materials put together by some kind of connection system, either chemical, mechanical or both.

The judgment on the durability of each strengthening must take into account the durability of each material to environmental factors (humidity, temperature) and extraordinary actions like fire. As to their mechanical performance, both the individual materials performance and the composite system created should be carefully evaluated as well as the influence of each material and its decay on the behaviour of the global system. The difference between the strain properties of each material can create complex situations to analyse. As an example, an excessive stiffness of an adhesive, with subsequent inability to sustain the timber strains, especially those due to hygrometric variation, can seriously increase the existing cracking state and even provoke new cracks as a new stress state is originated due to the constraints imposed by the different material behaviour under temperature variations (CNR-DT 201/2005). The physical and mechanical properties of all materials and designed systems should then be carefully evaluated during the design phase, with possible previous testing and posterior monitoring.

A few general recommendations can be (CNR-DT 201/2005):

- The correct design of the connection between materials, giving priority to the realization of the connections, taking into account the constitutive behaviour of the materials used.

- The limitation of stresses in service conditions ensuring admissible stress states for all the materials involved, taking in account temperature and humidity variations.
- Insurance of the effectiveness of the strengthening by adopting construction details that allow an easy protection of the materials against the environmental and accidental factors avoiding the need to use additional protections materials.
- Special care on the construction phase must be given, once if a single phase is not carried properly the all system can be compromised.
- Controlling the environmental conditions is crucial on ensuring a long life both to the structure and reinforcement. The interventions must allow timber to exchange humidity with the external environment, avoiding water deposits on the interfaces. Assuring a proper ventilation of the structure, mainly on beams supported on external walls and on the upper parts of beams avoiding stagnation and condensation of water.

5.3. INTERVENTION MATERIALS

13. Contemporary materials, such as epoxy resins, and techniques, such as structural steel reinforcement, should be chosen and used with the greatest caution, and only in cases where the durability and structural behaviour of the materials and construction techniques have been satisfactorily proven over a sufficiently long period of time.(…) (ICOMOS Principles for Restoration of Timber Structures, 1999)

3.10 The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term impacts, so that undesirable side-effects are avoided. (ICOMOS Principles for the analysis, conservation and structural restoration of architectural heritage, 2003)

As the citations show, the choice of the appropriate material is often a hard decision. There are several factors that should be taken in account for a successful choice; the pros and cons of each material and its compatibility with the original ones, the environmental conditions, the type of intervention desired, principles like reversibility and minimum invasivity are some of them. It’s a complex decision that requires, before anything else, a deep understanding of the materials alone, its composite behaviour and its long term performance.

Various techniques with the aim of increasing the strength and stiffness of timber structures have been used through conservation history. These include the use of elements made from timber, iron, steel, aluminium, concrete and the more recent laminated timber, epoxy resins and fibber reinforced polymers.

In this sub-chapter a brief review of the materials presently available for the conservation interventions is done.

5.3.1. TIMBER

Naturally, since we are addressing timber structures, timber itself was the most largely used material for the repair and strengthening since ancient times, being common to find past timber interventions in historical structures. The use of timber in conservation has the advantage of avoiding material incompatibilities and degradation due to different physical behaviour of materials to environmental actions, assuring in this way the maximum durability to interventions. Among the possible materials available to the designer, timber is the most reliable if used in a correct way. Traditional and modern knowledge on connections carpentry allows using all timber solutions (or close) in a diversity of situations which is always preferable to other techniques. The advantage of traditional materials and techniques is that they have been used and tested during centuries offering in this way complete reliability. Modern materials are frequently used for lifetimes of a few decades (experience frequently proves less) but historical timber structures can reach several centuries of age. It is easy to understand that interventions should aim at lasting in the same order of greatness, or at least, to cause reduced damage to historical fabric and allow its future substitution if it is required by their short durability.

Figure 54 – Examples of timber prosthesisation using traditional timber carpentry techniques (Japan).

Timber used in conservation of heritage buildings must be carefully selected. Second-hand timber is not generally recommended but might be used in special cases if it sound and perfectly free from decay, with the right scantling. New timber is preferred and should be selected in a way that approximately matches natural characteristics of the original material, avoiding incompatibilities between new and historical parts. Should be from the same species and have similar quality. Moisture content and other physical properties should be close to the existing structure. It is essential to assure timber used in restoration to be aged properly and preferably to be hewn in the case of extremely valuable historical buildings (Drdácký, 2007).

5.3.2. STEEL

Metals have been traditionally used in timber structures, either as original material or in conservation interventions. Since the XIX century the physical and mechanical properties of metals are used to overcome inefficiencies of timber elements or to easily achieve connections that otherwise needed difficult carpentry details, being widely applied in the form of nails, bolts, straps and ties (Figure 55). The connection of timber members was either designed from the beginning with the help of metal elements, or improved with metallic insertions when some malfunctioning was detected, which would substitute or collaborate with the timber elements in its structural role.

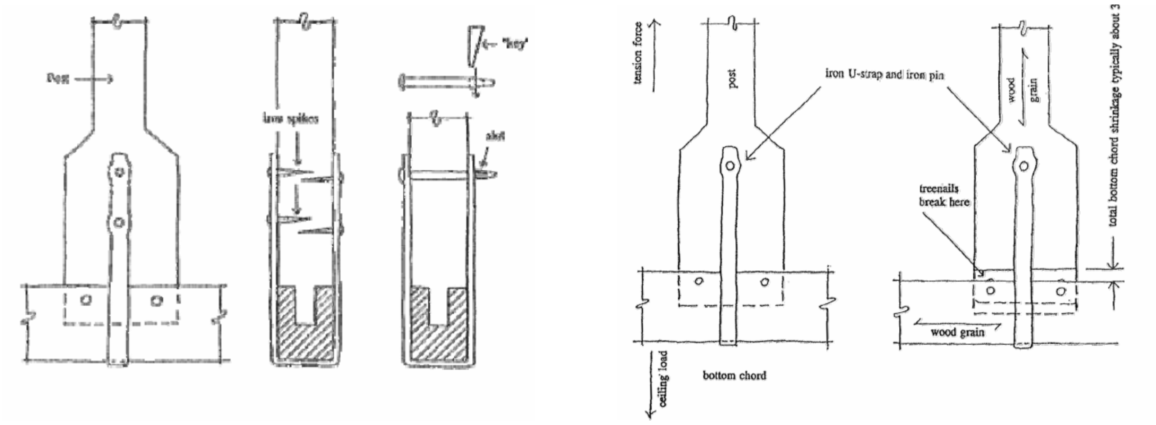


Figure 55 – Metallic U-straps in joints.

Figure 56 – Metallic straps and locking bolts.

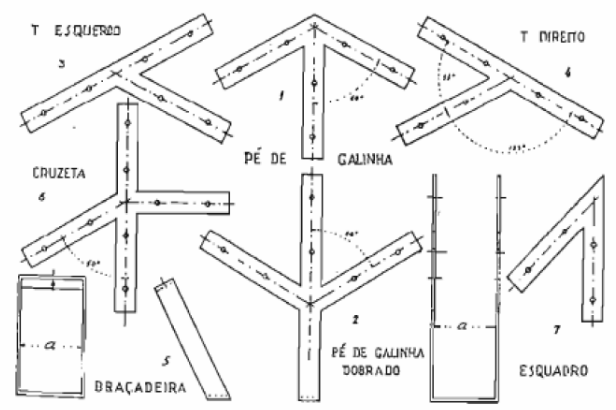


Figure 57 – Metallic straps in timber joints of lattice trusses.

Some of these techniques are still an option for nowadays interventions, once many have been perfected through long years of experience, but its blind application may take to useless interventions once not all traditional techniques have proven to be effective and some can only be used in very specific conditions. It is therefore essential to check the suitability of solutions for every specific situation even if they have been widely used before.

As an example, an experimental campaign aiming at the mechanical evaluation of some traditional techniques to strengthen birdsmouth connections used in Portugal (Figure 58) has obtained interesting results.

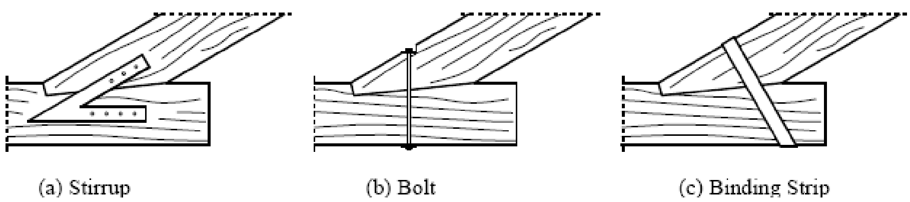


Figure 58 – Traditional strengthening techniques evaluated.

The results have shown that the systems significantly increase joints stiffness, resistance, ductility and response to cyclic loadings which once again demonstrates the suitability and interest of traditional techniques in modern conservation (Branco, Piazza, Varum 2006).

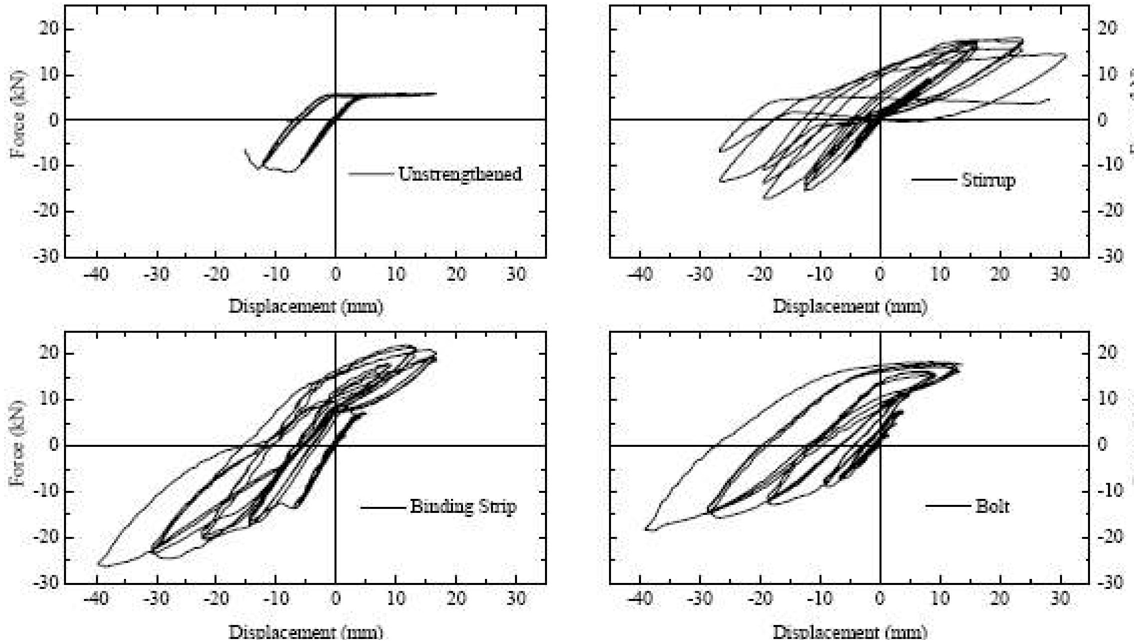


Figure 59 – Test results. Force-displacement diagrams.

Steel ideal mechanical behaviour makes it especially suitable for interventions but attention should be given to its response to environmental factors. The possible condensation on the interfaces of steel and timber elements takes to the degradation of the surrounding wood and at the same time undermining the effectiveness of connections. Some techniques which hide the steel elements can be a worst solution once they also hide its possible degradation, and by not allowing its inspection may take to dangerous states of decay. The best solution to avoid corrosion problems is the use of stainless steel which has the only problem of being a more expensive option.

Other drawback on the use of steel is its resistance to fire. Once wood is far more effective under high temperatures, steel elements suffer from a quicker loss of mechanical properties. This can be of great danger once steel is often used in key structural roles, such as connections and import improvements of bearing capacity, originating the failure of the structure due to the early failure of the steel elements.

Overall, if these weaknesses are taken in account and are correctly prevented, steel is a very effective and versatile material for conservation purposes, mainly stainless steel once it surpasses the usual corrosion problems of steel interventions.

5.3.3. CONCRETE

Interventions using concrete are restricted to the cast of concrete slabs over timber floors. By assuring a proper connection between concrete and timber beams a composite system is created, taking the best profit from both materials. The concrete slab is stressed to compression while the timber beams work in tension. The system has been used has a way of stiffening timber floors to in-plane actions, allowing the distribution of loads along the masonry bearing walls.

The old recommendation of Athens Charter in 1931 which stated that interventions using Portland cement were respectful, solid and durable, being approved the judicious use of all the resources at the disposal of modern techniques and more especially reinforced concrete, is now completely out of date once experience has shown otherwise. In a large number of situations concrete has generated significant deterioration due to incompatibility (mechanical, chemical, rheological, thermal) with original materials requiring much repair and re-restoration works. Moreover, the exaggerated stiffening and increase of dead loads coming from the extra weight of concrete slabs has been the cause of a series of failures during earthquakes which have shown the inappropriateness of the technique (Figure 60).

Figure 60 – Out-of-plane collapse of a masonry walls due to “hammering” of concrete floor and roof.

The Venice Carter states that interventions must be carried in away that future actions are not made impossible which is precisely what happens in the case on concrete interventions. The technique is completely in regard to the principles of low invasiveness and reversibility and moreover the authenticity of the traditional timber floors is completely disrespected.

The fact that there are presently a number of techniques that achieve interesting structural objectives while being respectful to the historical monument make the present interest of concrete-timber interventions, disinteresting and not recommended.

5.3.4. FIBRE REINFORCED POLYMERS

Fibre reinforced polymers are composite, heterogeneous and anisotropic materials with a prevalent linear behaviour until failure. An FRP-reinforcement consists of connecting parts (stripes, plates or rods of high strength fibres embedded in a polymer matrix) and a bonding agent (glue, mortar or casting compound) (CNR-DT 200/2005). Fibre-reinforced composite materials offer several advantages that make them very attractive when used for timber repair and strengthening. They are easily applicable and offer extremely versatile design options being suitable for strengthening of timber elements under bending, connections between different elements or between original elements and prosthesis, local bridging where defects are present, confine local rupture or prevent crack opening. Plates, sheets and bars can be applied giving to the strengthened element a better performance in terms of strength, deformability and ductility. Joints can be upgraded to a better performance under cyclic loading, to improve their capacity to resist tensile stresses perpendicular to the fibres and generally to improve their capacity to transmit axial, bending and shear forces. Also, the strengthening of structures subjected to in-plane actions, such as the stiffening of timber floors giving them the capability of transmission of horizontal in-plane forces by connecting to the wood planking rows of FRP plates laid orthogonally to each other (CNR-DT 201/2005).

The most common fibres used in composites are glass, carbon and aramid. The following table summarizes their properties, together with the polymeric resin and steel for comparison.

Table 4 – Comparison between properties of fibres, resin and steel (typical values) (CNR-DT 201/2005).

	Young's modulus E	Tensile strength σ_r	Strain at failure ε_r	Coefficient of thermal expansion α	Density ρ
	[GPa]	[MPa]	[%]	$[10^{-6}\ °C^{-1}]$	$[g/cm^3]$
E-glass	70 – 80	2000 – 3500	3.5 – 4.5	5 – 5.4	2.5 – 2.6
S-glass	85 – 90	3500 – 4800	4.5 – 5.5	1.6 – 2.9	2.46 – 2.49
Carbon (high modulus)	390 – 760	2400 – 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon (high strength)	240 – 280	4100 – 5100	1.6 – 1.73	-0.6 – -0.9	1.75
Aramid	62 – 180	3600 – 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 – 3.6	40 – 82	1.4 – 5.2	30 – 54	1.10 – 1.25
Steel	206	250 – 400 (yield) 350 – 600 (failure)	20 – 30	10.4	7.8

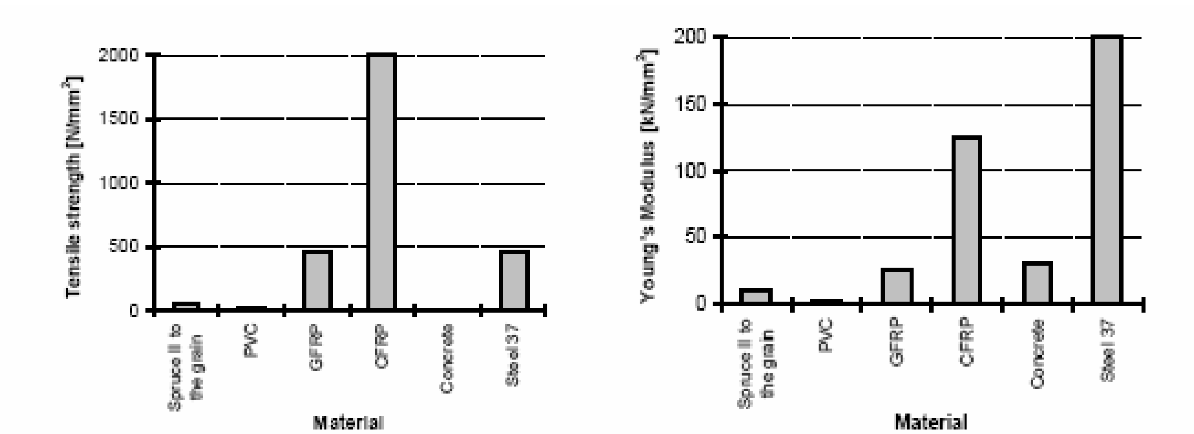


Figure 61 – Mechanical properties (tensile strength / Young's modulus) for FPRs, steel and concrete.

One of the main characteristic of FRP composites is their elastic behaviour until failure (Figure 62). This should be carefully taken in account when designing the strengthening because although timber presents an elasto-plastic behaviour, generally timber members have brittle failures, once the collapse is triggered where natural defects, such as knots or excessive fibre inclination are located. In members subjected to bending the brittle failure can be avoided by locating the strengthening in the tension zone, being mobilized sufficient strains in the compression zone and thus forcing the plasticization of this zone before the tensile region fails (CNR-DT 201/2005).

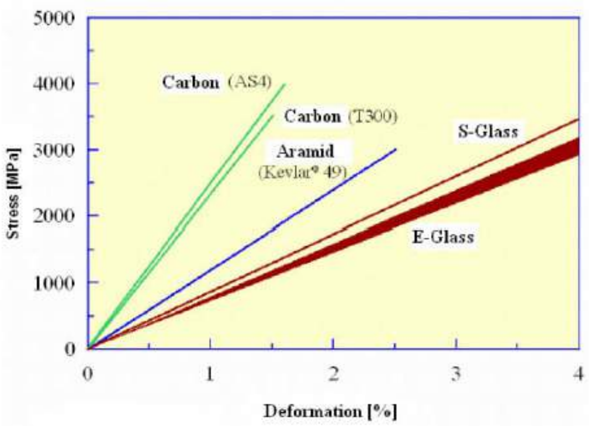


Figure 62 – Constitutive models of fibre reinforced polymers.

Among the several types of fibres of these composites there is a significant variety of characteristics. Each can be optimal for a specific use and situation (CNR-DT 201/2005):

- Carbon fibres are less sensitive to environmental conditions and creep phenomena;
- Aramid fibres are more resistant to impulsive loads;
- Glass fibres have a constitutive model that easily adapts to timber strains. They have a low elastic modulus and high ultimate strain, therefore reducing the risk of debounding which can cause a premature collapse.

The connecting parts can be installed either (CNR-DT 201/2005):

- Inside the wood member, which presents a number of difficulties for the realisation, but has important advantages as well: invisible, better fire-proofing, etc;
- Outside, which is the most common case for reinforcement work on existing structures;

The actual bonding of the laminates must be prepared very carefully (Steiger 2007):

- The wood surface must be flat, unweathered and clean, to insure proper anchoring.
- The wood surface must be dry at the time of gluing.
- The gluing interface of the FRP-lamellae must be degreased and clean.
- The application of the lamellae must take place at a reasonable temperature (> 10ºC) and there must not be any stresses on the glue lines during the curing of the bond.

The main advantages of using CFRP-laminates rather than steel plates are their light weight and the corrosion resistance. But a number of flaws makes its use on heritage timber structures very questionable.

FRPs thermal resistance is governed by the resistance of its polymer matrix which starts loosing the mechanical properties at around 100ºC, decisively undermining its resistance in case of fire. But, regardless of this, the adhesive used in bonding of FRPs to timber is even more sensitive to high temperatures as it is described later. Such early loss of strength can be partially avoided by hiding and covering the FRPs inside cut slots on timber but important bearing roles are not advisable if appropriate anti-fire protection is not present (CNR-DT 201/2005).

5.3.5. EPOXY RESINS

Epoxy resins have now more than 40 years of testing on structural functions. Although having a number of drawbacks, they have proven to be effective and useful in a diversity of interventions (Larsen 2004):

- Reparation of extremities of beams;
- Filling of hollow sections due to biotic attack;
- In situ strengthening of floor beams;
- As adhesives for all other materials.

The utilization of epoxy adhesives associated with steel or FRP bars or plates is one of the more promising recent techniques, allowing low invasiveness interventions with minimum substitution of original fabric. As fillers of hollow sections they are mixed with a suitably graded filler with small to large granolometry and casted in situ. Its successful application is only achieved if care is given to a number of factors. They are very sensible to relative dosage of components, service and curing temperatures, humidity (it's not recommended to use them in exterior conditions) and workability, making it essential to be handled by specialized staff or expert supervision. A large number of studies has tried in recent years to establish the influence of construction details such as the geometry of perforations or cuts in timber (number, dimensions, length, inclination and positioning), weight of the glue lines, etc (Cruz and Custódio 2007).

Epoxy adhesives

The suitable adhesives for timber strengthening purposes, as for many other structural uses, are epoxy resins. They are usually a by-component viscous mixture that once hardened, trough a cross-lining chemical reaction, becomes suitable for structural applications (CNR-DT 200/2004).

Adhesion mechanisms (Figure 63) primary consist of interlocking of the adhesive with the surface of the support with formation of chemical bonds between polymer and support.

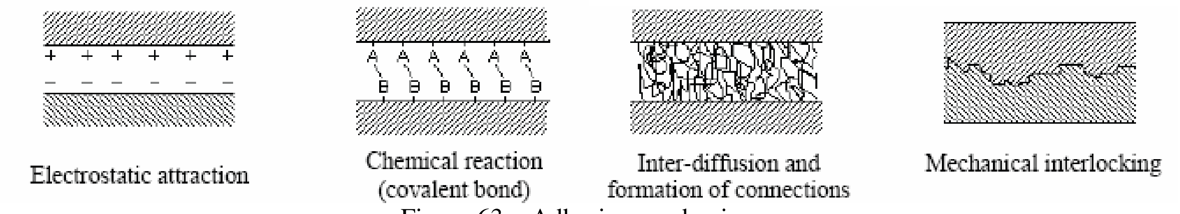


Figure 63 – Adhesive mechanisms.

Obviously, the adhesion effectiveness can be improved by treatments that enhance the chemical compatibility and mechanical interlocking, being critical the appliance of a primer layer and the assurance of an adequate surface roughness. The removal of surface contaminations is of main importance; oxides, foreign particles, oil, laitance, dust, moisture enhances the formation of stronger and more durable bonds.

There are three types of fracture for adhesive bonding. Cohesive fracture is characterized by failure in one of the materials connected, which is the ideal fracture mechanism, indicating that the problem was not on the bond itself but on an incorrect evaluation of the composite system, originating an exaggerated stress concentration on one of the materials. Adhesive fracture takes place between the adhesive and on of the materials connected, indicating that the adhesive strength is lower than of the support which highlights inaccurate applications. Finally, mixed failures may occur.

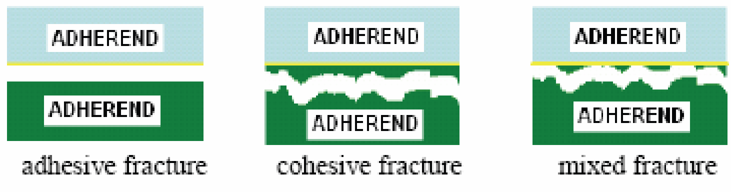


Figure 64 – Comparison between different types of fracture.

The advantages of adhesive bonding compared to mechanical systems is the versatility and easiness of connection between different materials, providing greater stiffness, uniform distribution of loads and consequently uniform stress distribution (CNR-DT 200/2004).

Against it, and making its use not advisable in most uses is its sensitivity to environmental conditions. Their main problem is the effect of temperature in its resistance. Attention should be given to the effect of temperature both on curing and service conditions. Curing at low temperatures, inferior to 15ºC might provoke insufficient hardening (Steiger 2008). In service, for modest temperatures, above 40º degrees, which is a temperature easy to achieve in roof structures (Cruz and Custódio 2008), the glass transition is initiated. This value can be increased by thermal activation (post-curing at 80°C for four hours) with additives used for this purpose, which then allows a higher permissible service temperature (Steiger 2008).

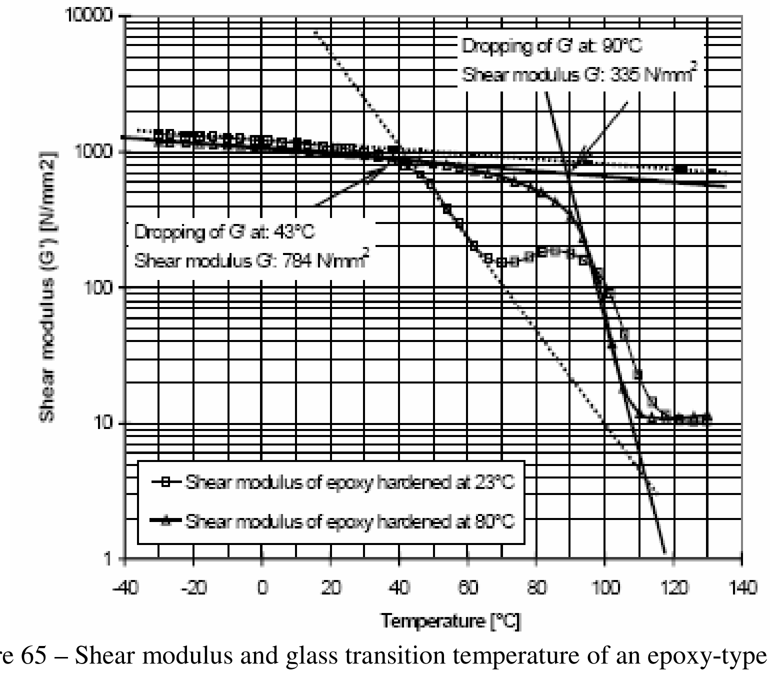


Figure 65 – Shear modulus and glass transition temperature of an epoxy-type adhesive.

Its use for important structural roles is compromised by its fire resistance, even though special constructive details can be adopted, “hiding” the strengthening inside the timber members, inserting it in deep cut slots.

5.4. INTERVENTION TECHNIQUES

5.4.1. REMOVAL

Original members and parts, even if have been put to a secondary role due to some past intervention should not be removed. The care for its value as original part of the structure is the central objective of the conservation intervention and therefore its removal is considered to be a malpractice to conservation principles. In the case of extremely advanced states of decay, when conservation by other means is demonstrated to be impossible or unreasonable its substitution can be considered (see *dismantling and replacement/reassembly*).
The question is placed on the case of imperfections, alterations and past strengthening interventions. It is generally advised to avoid the removal or alteration of any materials or distinctive architectural features, especially in the case when they have become part of the history of the structure as a successful strengthening measure. Even though, in some specific cases, if the safety requirements are demonstrated to be compromised by the inconsistency of these elements their removal might be an acceptable measure.

5.4.2. DISMANTLING AND REASSEMBLY/REPLACEMENT

Similar to the case of removal, dismantling and reassembly or replacement is only advisable in exceptional cases when conservation by other means is demonstrated to be impossible or harmful. The ICOMOS principles advise that repair should be preferred to replacement, whenever it is possible.

If the need is demonstrated, the replacement should preferably be a replica of the original part, respecting the overall relevant historical and aesthetical values. If the original element was not suitable for its function, and that was the cause of its collapse or decay, adequate design criteria to correct the original wrong design should be taken. A list of general criteria can be given (Drdácký 2007):

- To use the same specie of wood with the same or, if demonstrated necessary, better grading than the replaced member.
- Wood with similar natural characteristics, avoiding incompatibilities between new and historical parts. Moisture content and other physical properties should be close to the existing structure.

- If appropriated (proved as the best solution), craftsmanship and construction technology should correspond with those used originally, reproducing original support and connection techniques. The same goes for secondary materials such as nails and straps.
- Although traditional or modern methods may be used to match the colouring of the old and the new, without harming the wood surface, new members or parts should be accepted to be distinguishable from the existing ones. Natural decay and deformation should are not desirable to be copied. The replacement of members is still a conservation measure with a high degree of invasiveness that should, as in other interventions, be kept visible, as long as it doesn't affect the aesthetical value of the structure.
- Finally, it is recommended for new member or parts to be discreetly marked, by carving, by burnt marks or by other methods, so that they can be identified later.

Naturally, the investment on the reproduction and of the original members must be evaluated on a case to case basis. There are fundamental differences of historical and aesthetical value among structures that make it suitable to evaluate the best option for each case. An example of two interventions where replacement of elements was needed but slightly different approaches where taken can be given; both cases in the Czech Republic. The case of the of the Karlštejn Castle near Prague (Figures 66), where the visible ceilings have an high aesthetical value as well as historical documentation of high quality carpentry, a carpentry based restoration was undertaken being respected original materials, technologies and aesthetical values.

Figure 66 – .Carpentry based restoration of Karlštejn Castle timber floors.

In the Buštehrad Castle (Figure 67) a different approach was preferred. Given that the value of this timber structure is mainly functional and the original carpentry is more practical than the highly cared seen on the previous case, the replacement of members is focused on substituting the original on its structural role, not being given the same importance to the detail in carpentry techniques. Even though, joints and prosthesis still respect the original typologies and materials.

Figure 67 – Substitution of elements on Buštehrad Castle timber roof.

5.4.3. ADDITION OF ELEMENTS

The addition of elements can be a solution to several situations, particularly in the case of structures that need to be strengthened due to higher loads coming from a new use. Instead of strengthening its members, new elements may be added, giving the structure the desired bearing capacity. Several advantages of this simple technique can be easily recognized, among them some of the most important principles listed in ICOMOS recommendations:

- The new elements can be totally recognizable;
- No intrusive intervention is done on the original members or materials;
- The intervention is totally reversible.

A simple case in a floor structure would be, for example, the addition of beams parallel to the original (figure 68). A drawback can be considered the need to remove the timber floor above the existing beams in order to perform the intervention, although the same elements may be then replaced.

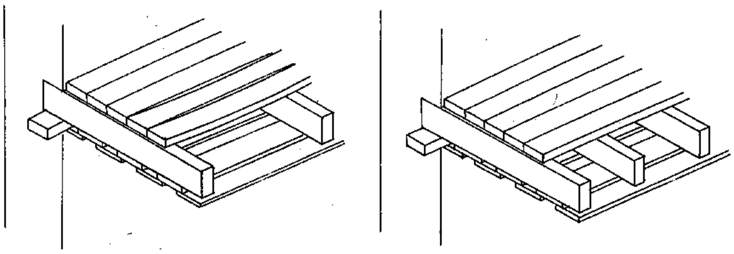


Figure 68 – Addition of beams in a floor system.

The introduction of new bracing elements (Figure 69), struts or cables in roof structures is also very common and although in some cases significantly changes the original system, it still keeps the advantages referred before.

Figure 69 – Addition of timber bracing members (Kutna Hora Cathedral)

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5.4.4. PROSTHESISATION

Prosthesisation is a concept used to name interventions in which a part of a single member is cut out and substituted by an element that substitutes its function, being accomplished the structural continuity throw the use of any connection technique.

Generally, these are interventions on the extremities of elements, close to the supports of floor beams and roof frames, where conditions are met for advanced states of degradation due to biotic attack, taking sections to become vulnerable to the present shear stresses.

The removed parts may be replaced by timber, being the connection between new and original parts done with several available materials: timber, steel, FRPs and epoxy adhesives.

Traditional techniques achieve this objective by connecting new timber parts using all timber connections or steel bolts, studs and straps (Figure 70).

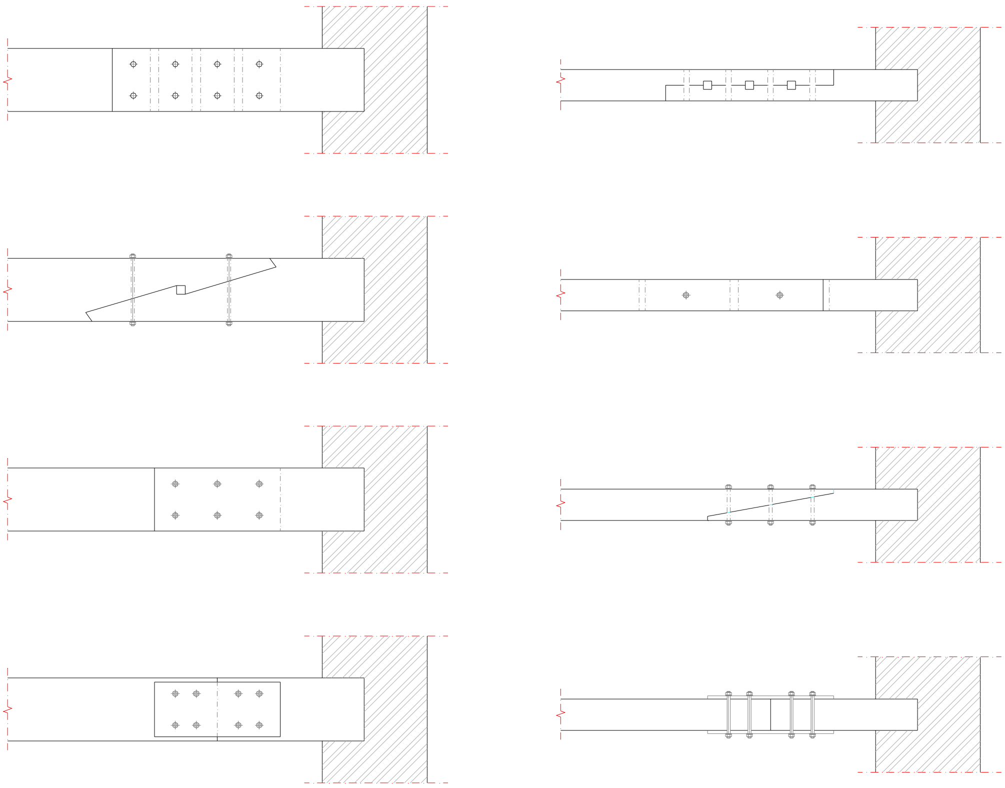


Figure 70 – Prosthesisation using mechanical connections with timber and steel.

Other possibilities are, as in many other situations, to duplicate the decayed timber by adding new timber elements and connected by bored connectors (bolts and dowels) and straps (Figure 71).

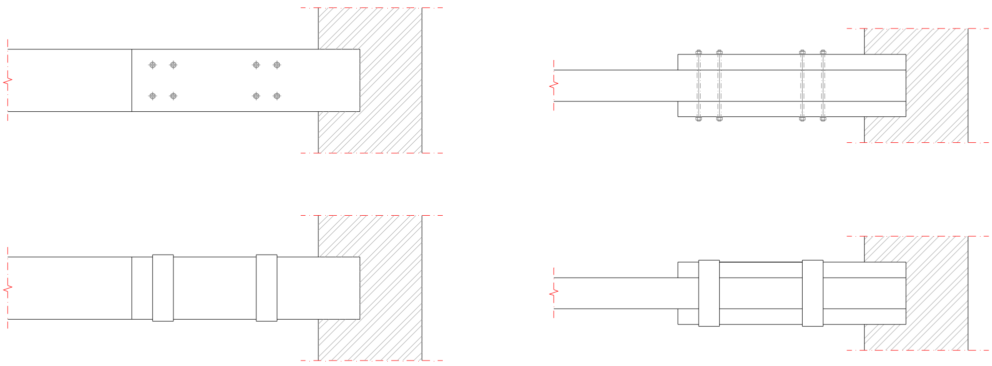


Figure 71 – Strengthening of joist ends by *empalmes*.

Steel allows designing and easily executing joints that are able to bear high stresses, assuring an efficient transmission of forces and a ductile failure mode. Thus, steel mechanical connections allow small displacements avoiding stresses introduced when the materials shrink and swell due to temperature and humidity. This is the reason why steel as been successfully used in timber connections and repairs since it became available.

Figure 72 – Example of prosthesisation with steel bolts as connectors (Buštehrad Castle).

Being an ideal material from the mechanical point of view, its vulnerability to environmental factors is its drawback. If corrosion is easily avoided by using stainless steel, the vulnerability of steel to high temperatures (in case of fire) makes it essential to efficiently adopt protective details that prevent high temperatures of reaching the steel elements.

(a)

(b)

Figure 73 – Examples of prosthesisation by similar methods. In both cases the tension in the tie-beam is transmitted by a mechanism of shear parallel to the timber grain but in on case the mechanism is achieved by steel plates (a) and in other is obtained by carpentry detail (b).

Being far more effective under high temperatures, taking much more time to loose its mechanical properties, timber can be used in connections of prothesis. Prosthetisation using all-timber connections with modern timber carpentry techniques can, and has been successfully used in recent restorations (Figure 74).

Figure 74 – Prosthesisation with all timber connections and modern carpentry techniques. "Butterfly" dowels joining old floor joists with new strengthening flange beams (Building in Prague).

The use of all timber connections has the advantage of avoiding material incompatibilities and degradation due to different physical behaviour of materials to environmental actions. Recent investigations on the behaviour of halved timber joints have shown that their mechanical behaviour is satisfactory, being achieved a connection stiffness equivalent to bolted joints although a smaller ultimate strength (Drdácký 2007). Given the advantages, traditional and modern woodwork joints should, if appropriate and compatible with structural requirements, be used to splice the new and the existing parts.

Figure 75 – Four point bending tests to compare the performance of steel and timber connections (ITAM, Prague).

Interventions replacing timber by epoxy resin have the advantage of avoiding problems of bonding and shrinkage. Decayed timber is removed and replaced by a new timber end or cast in situ epoxy resin, with connection assured by FRP or stainless steel bars and plates bonded by epoxy adhesives (Figure 76).

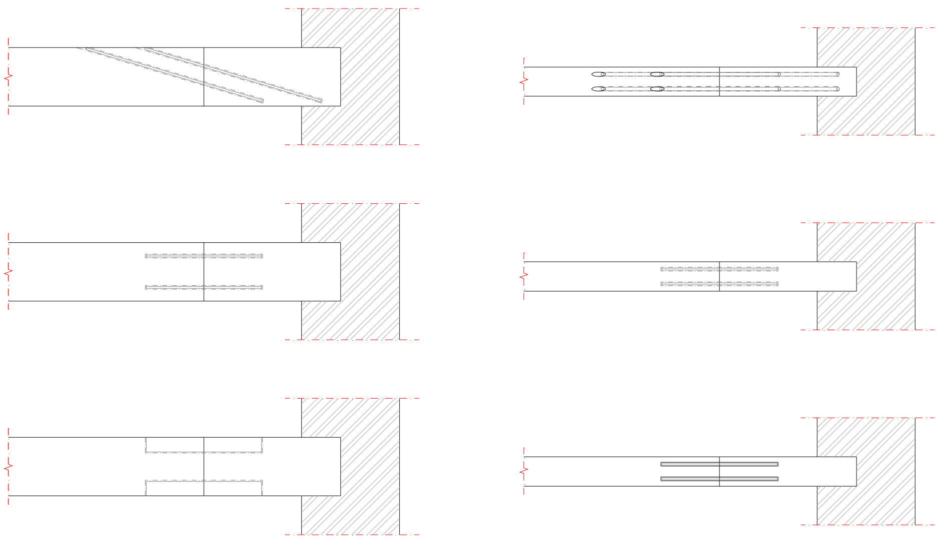


Figure 76 – Prosthesisation using FRP connections.

Recent investigation and experience from practical cases proved that interventions using FRPs can be effective as long as attention is given to a variety of criteria. The quality of the bond and the design of the detail are of main importance. Although the bond between timber and epoxy resin provides no problems, satisfactorily adhesion to FRP laminates is harder to achieve, but can be improved by appliance of a resorcinol primer. The quality of the filling joints depends greatly on the viscosity of the resin that should be adjusted to the type of application, casting or overhead work. The anchorage length should be established assuming that wood is the weak agent both in tension and shear. In order to balance stress distribution avoiding strong stress concentrations; tests retrieved that it is essential to adjust the number of lamellas when timber members are thicker. Have demonstrated has well that the better performance of adhesives and reinforcements of greater stiffness, preferably CFRP (Steiger 2008).

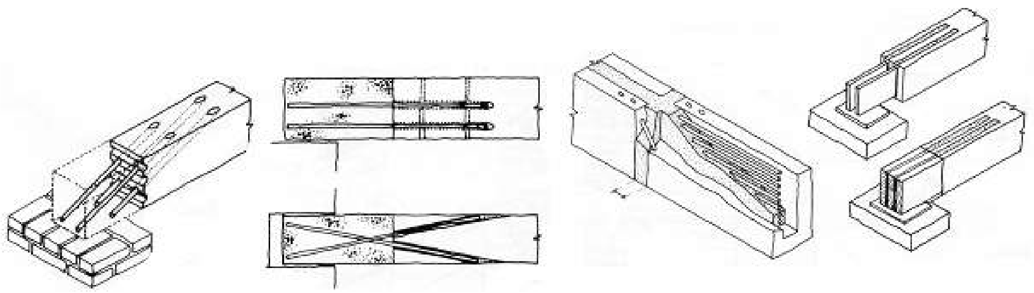


Figure 77 – Prosthesisation using FRP connections. Detail of the placement of bars and lamellas.

Experimental investigations on the performance and comparison of connections using plates, bars, varying angle of the joints, together with glued and unglued surfaces showed that the best results can be obtained using FRP plates in 45º joints and unglued surfaces (Figure) (Cruz, Custódio, Nascimento and Empis 2008).

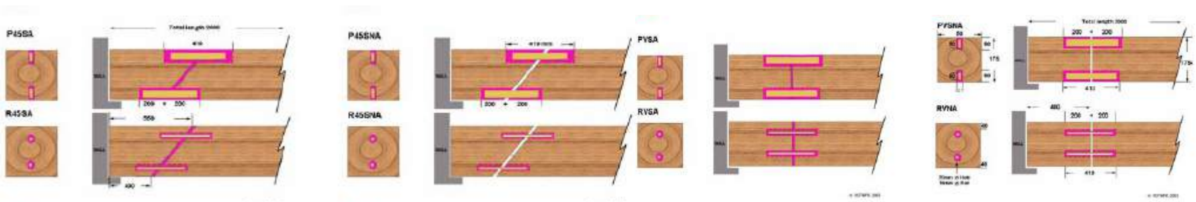


Figure 78 – Schemes for comparison tests between different connections using FRP bars and lamellas (LNEC, Lisbon).

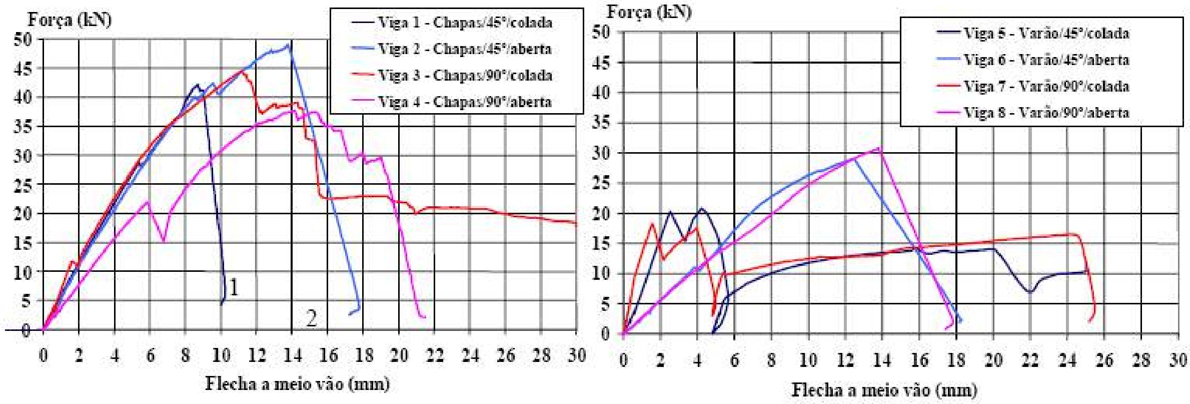


Figure 79 – Performance of the tested connections using FRP bars and lamellas (LNEC, Lisbon)

Figure 80 – Sequence of execution of a prosthesisation using steel bonded bars to achieve structural continuity.

5.4.5. SEALING

Sealing consists on the introduction of new wood binding it to the original timber element with epoxy adhesive and reinforcement bars or the simple filling of voids with a prepared putty (e. g. epoxy resin) (Drdácký 2007).

Figure 81 – Sealing.

5.4.6. REPAIR OF CRACKS

Cracks can be repaired using a wide variety of techniques, from traditional to modern, using a several different materials, which naturally result in different approaches. The type of crack is decisive on the selection of the technique since the correct evaluation of the failure can give the answer to the appropriate solution.

Some traditional approaches are the application of *empalmes*, bolts and straps (Figure 92).

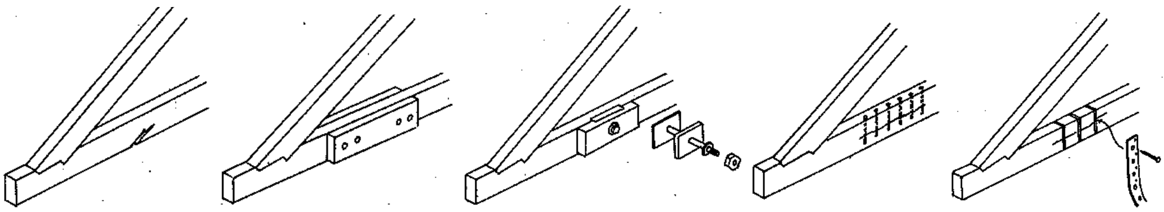


Figure 82 – Different traditional techniques to repair cracks.

Empalmes can be used for the repair of transversal cracks. They consist on the addition of new timber elements on one or both sides of a beam, connecting the new and the original materials with bolts or nails. The careful evaluation of the failure should give information on the longitudinal dimension of the additional members and the correct evaluation of number and spacing of connectors (Reis, Branco and Mascarenhas 2006). Longitudinal cracks can be repaired with bolts or straps. The technique consists on tying and stitching the crack with perpendicular bolts that completely cross the section or straps that tighten and close the cracks (Reis, Branco and Mascarenhas 2006)..

(a) (b)

Figure 83 – Example of application of traditional techniques on the repair of cracks. (a) *Empalme*, (b) Stiching of crack with steel bolts.

Modern techniques can copy the traditional ones substituting the materials used by new materials like FRPs, but the development of new materials and its application on timber conservation opens a new kind of solutions.

Epoxy resins with low viscosity can be injected on cracks conferring to the section a mechanical behaviour identical to the sane situation. The introduction of reinforcement bars of stainless steal or FRPs bonded with epoxy can as well be an appropriate solution for both longitudinal and transversal cracks (Reis, Branco and Mascarenhas 2006), (Figuree 94).

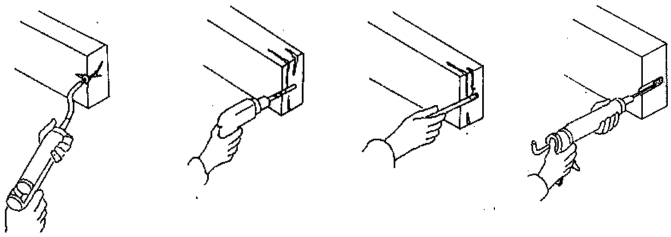


Figure 84 – Repair of cracks by injection of epoxy resin.

In those cases when the damage is not localized but disperse throughout the beam the reinforcement can be distributed along the beam, being obtained in this way a composite beam. The following pictures clearly describe the operation.

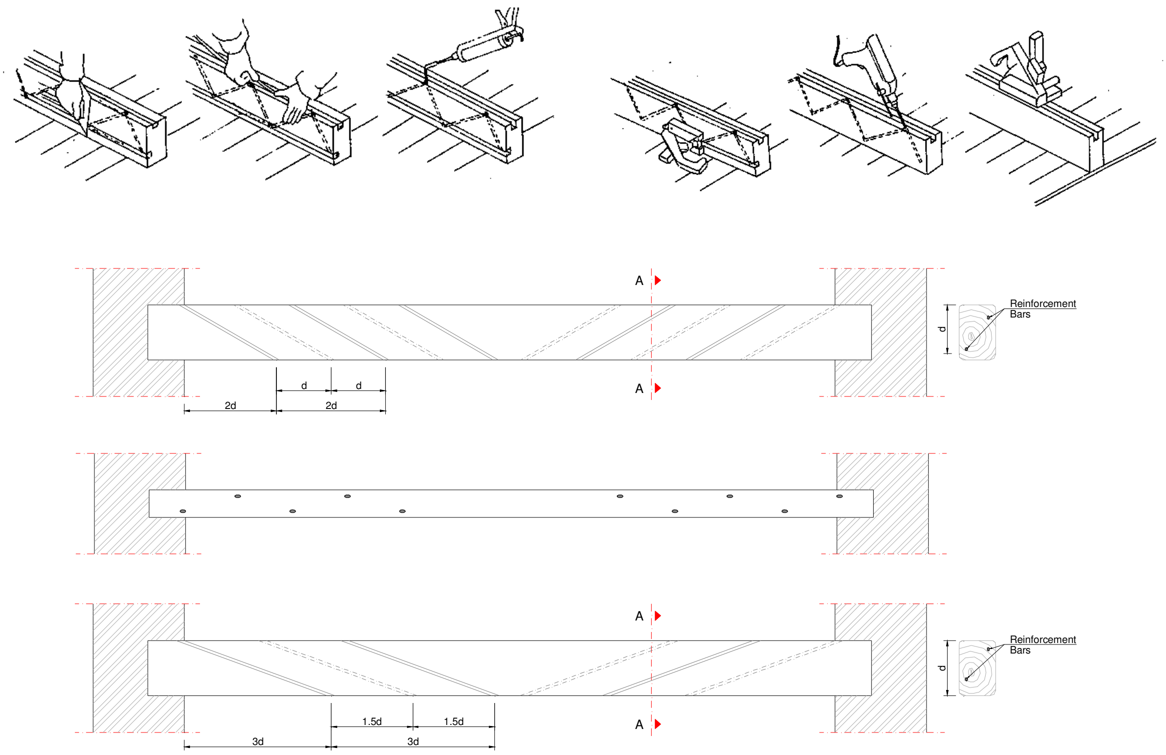


Figure 85 – Strengthening of a diffusely cracked beam.

5.4.7. REPAIR AND STRENGTHENING OF CONNECTIONS

The strengthening of connections of traditional timber structures should be faced with great care. Joints are generally sensible parts of structures, thus cases of degraded joints are common in old structures. Frequently, these failures aren't caused by the bad structural design but, by failures or some malfunctioning on other structural parts, that are later reflected on the structure's joints.

The fact that traditional joints usually allow significant relative displacement of its members should not be regarded as a weakness but as a structural characteristic of these structures that represents a decisive factor on the evolution and development of historic typologies, thus should be respected when conservation is needed. Generally, it is not acceptable to repair joints increasing their stiffness to levels far superior to those of traditional connections, changing in this way the global structural behaviour. The static scheme of the structure should never be changed, unless the scheme in not considered adequate and substantial modification is demonstrated to be necessary. Attention should be given to the fact that an increase of rotational stiffness changes the stress state of the connected members and thus the overall analysis of the structure is required in order to evaluate the consequences of the intervention (CNR-DT 200/2004)

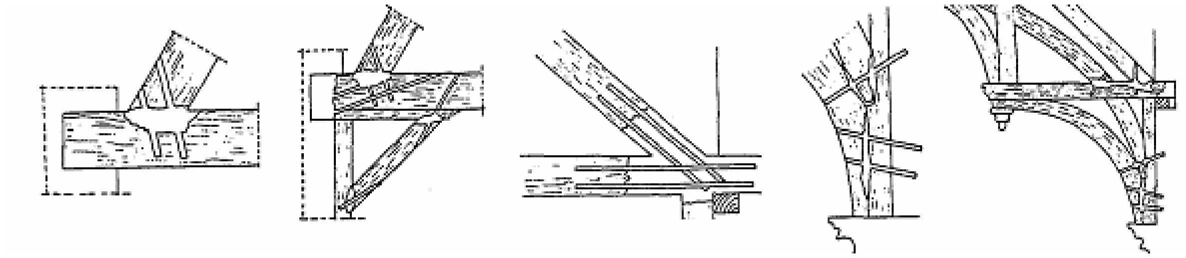


Figure 86 – Strengthening of connections by insertion of steel or FRP bars and epoxy resin filling.

Techniques may aim either at accomplishing the original behaviour or function of a joint that suffered a mechanical failure or material degradation, or if demonstrated to be necessary, the upgrading of its load bearing capacity or dissipative capacity to cyclic loads.

Interventions are very dependent on the type of joint, its geometry and the kind of failure that occurred, requiring many times some imagination by the designer. Some interesting examples can be seen in the Figure 87.

Figure 87 – Repair of connections by moving the location where the tie-beam receives the rafter horizontal thrust.

Generally steel and FRP bars can be used to strengthen a joint by inserting them in drilled holes crossing both members in order to achieve greater stiffness and strength. The diversity of mechanical characteristics (deformability, strength and fatigue behaviour) of steel and FRPs can be used by the designer, evaluating the advantages of each on a case to case basis. As an example, glass fibbers can offer great deformability to the connection while carbon fibbers can be used when stiffness and strength is needed (Borrii and Corradi, 2004). FRPs have other advantages like resistance to aggressive environments, easy workability and low weight. Bars placed perpendicularly to the grain are not recommended once they will oppose to the natural timber swelling and shrinkage (higher in this direction), introducing in this way shear stresses on the adhesive system (Follesa, Lauriola 2004).

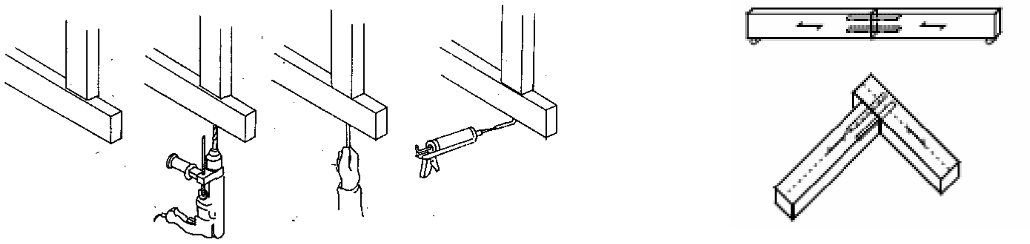
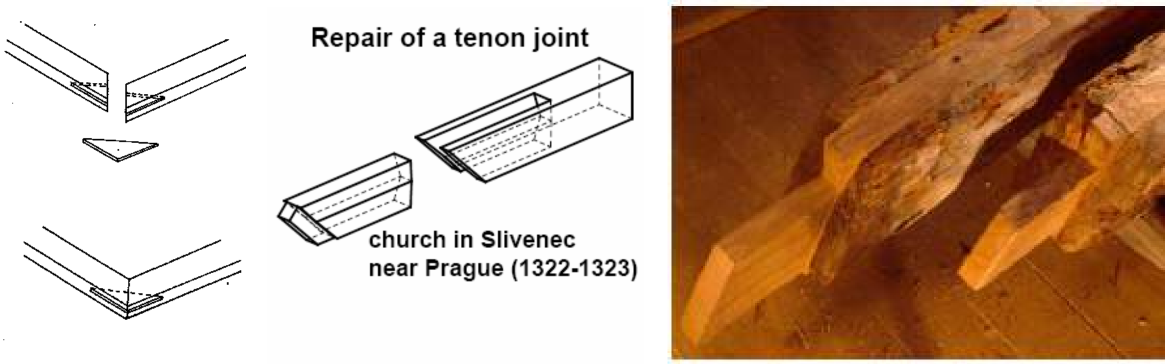


Figure 88 – Schematic strengthening of connections, assuring structural continuity by insertion of FRP or steel bras bonded with epoxy resin.

Naturally recommended are all the possibilities of timber based repairs. When mechanical actions are not the main problem to be dealt with, timber can be used with success. Figure 99 (a) shows the case of a repair by inserting a timber piece on a previously cut part of a simple member connection, and then glued with epoxy resin (can be better done with a mechanical connection by using steel or timber connectors). A more interesting example is the repair of a tenon joint by substituting the tenon, shown in the Figure 89 (b).



(a) (b)

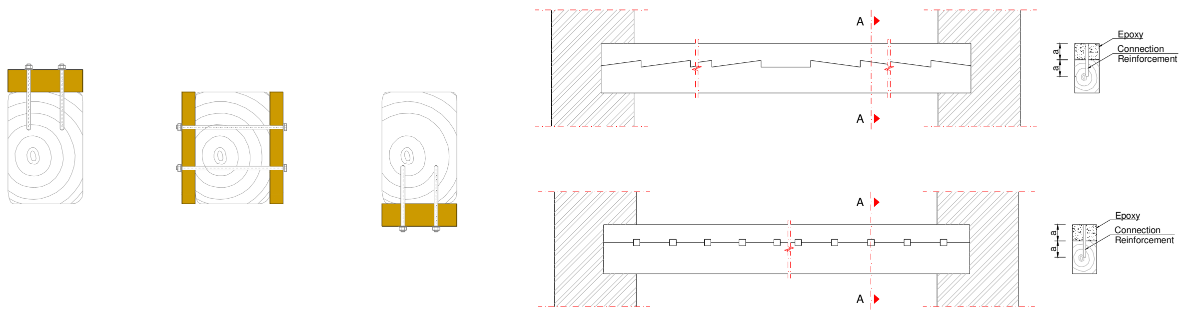
Figure 89 – (a) Repair of connection by insertion of a timber connector (b) Repair of a tenon joint.

As in other types of repair and strengthening, traditional techniques are strongly recommended. Repair and strengthening of connections using timber and steel has shown to be reliable thrown experience and recent investigations (see again Branco, Piazza, Varum 2006) and the structural performance of traditional timber connections has also shown to be reliable (Drdácký 2007) which encourages prosthesisation to original situation in situations of decayed joints.

5.4.8. STRENGHTNING OF SECTIONS

Timber

The strengthening of sections using timber elements is done by adding new timber elements to the original beam, connecting both members using traditional timber carpentry or steel connectors. It obviously the most recommendable option, always that it is possible to apply given all the referred advantages of using timber as strengthening material and mechanical connections to achieve the bond between original strengthening members.



(a) (b)

Figure 90 – Increasing of bending stiffness of beams by connecting new timber elements. (a) Steel connections, (b) traditional timber connections, might be enhanced by straps or bored connectors.

Steel

Steel bars, plates or profiles can be added or inserted in any side of a timber beam in order to increase its carrying capacity. They can be applied to the tension zone, the compression zone, or both. In the case of plates or profiles bonded to the surface of timber element the connection is done with steel bolts, studs or dowels while insertions of bars are bonded with the use of epoxy resin.

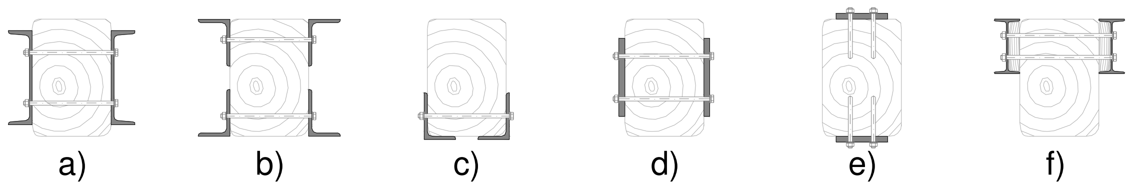


Figure 91 – Strengthening in bending with steel. (a) and (b) profiles applied laterally, (c) profiles applied to the tension zone, (d) plates applied laterally, (e) plates in the tension zone, compression zone or both (top and bottom), (f) profiles in the compression zone (laterally).

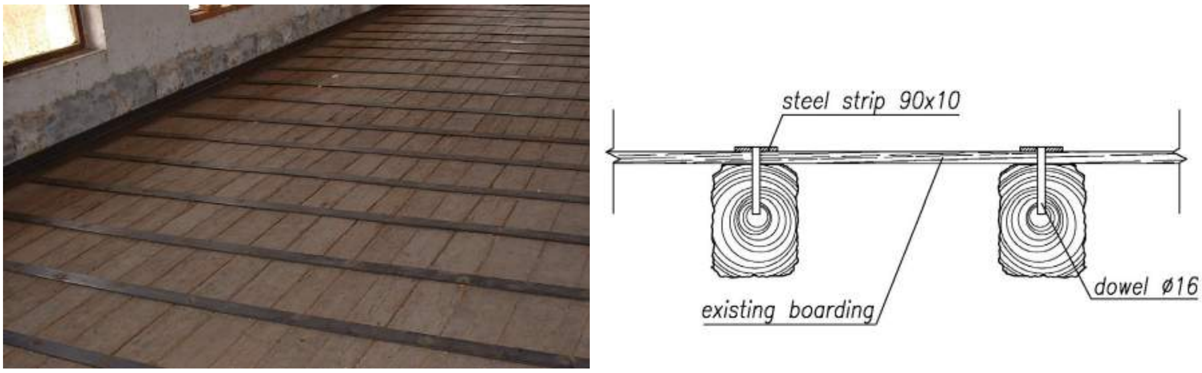


Figure 92 – Example of strengthening in bending of beams, by connecting steel strips to the compression zone.

The Figure 84 details an intervention example aimed at increasing both the bending and in-plane stiffness of a floor system using steel plates. The technique consists in placing, above the existing boarding, a thin steel plate fixed to the joists using steel dowels. The connectors are forced into the beam's drilled holes and welded to the steel plate. This technique has a clear advantage of being completely dry, once there are no cast in situ materials, and totally reversible (Gattesco and Macorini 2006).

The modern philosophy of conservation greatly encourages and raises the interest for "dry" strengthening techniques, which employ planks, timber panels, and steel sheets with thickness compatible with that of the floor.

<u>Fibre Reinforced Polymers</u>

Just like the steel reinforcements, FRPs can be bonded anywhere around or inside cut slots inside beams (Figure 94). While reinforcements working in tension together with timber have a good behaviour bonded externally or internally, as long as the connection is appropriately accomplished, reinforcements subjected to compression are better used inside slots opened in the timber beams in order to avoid the element instability. Hence the bonding surface is doubled in this way.

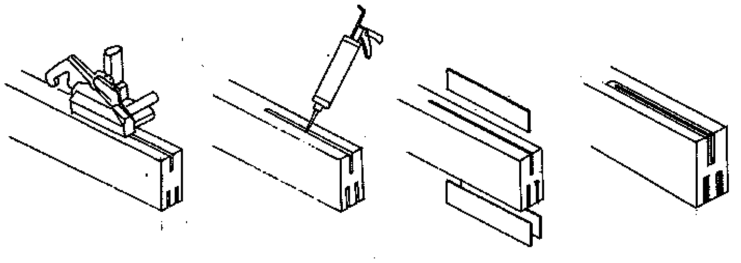


Figure 93 – Insertion of FRP lamellas on beam.

In the case of the internal slots, the reduction of sectional area for the placement of the reinforcement should be taken in account for the calculation of the tangential stresses.

Strengthening externally in the compression zone through the use of profiles, plates or bars must be additionally connected using mechanical devices, like nails or screws (CNR-DT 200/2004).

Other criteria and recommendations on the use of FRPs can be read on the material characteristics and prosthesisation using fibre reinforced polymers.

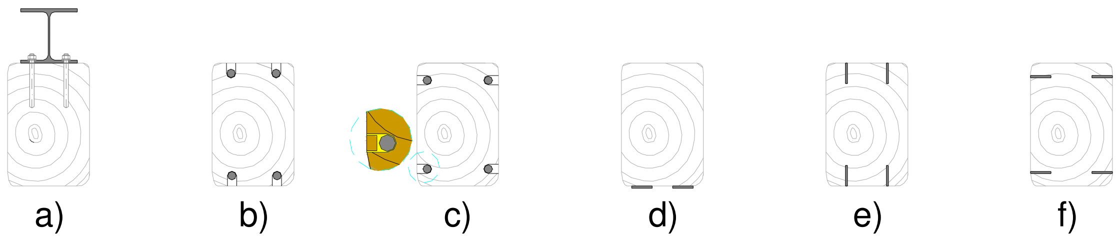


Figure 94 – Strengthening in bending with FRPs. (a) Pultruded profiles in the compression zone connected mechanically, (b) bars on the tension zone, compression zone or both (top and bottom), (c) bars on the tension zone, compression zone or both (laterally) and detail of the bar covering with timber, (d) plates in the tension zone, (e) plates in the tension zone, compression zone or both (top and bottom), (f) plates in the tension zone, compression zone or both (laterally).

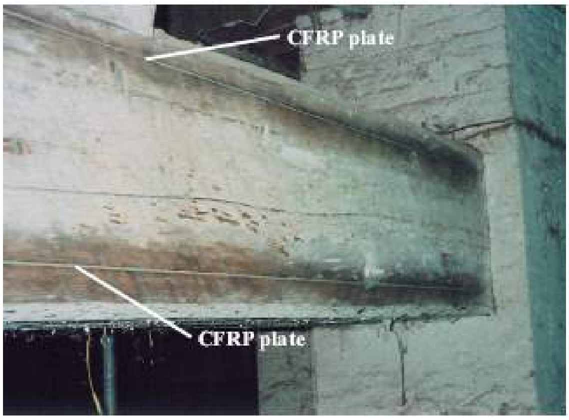


Figure 95 – Strengthening intervention on a beam with lateral insertion and adhesive bonding of CFRP plates.

Figure 96 – Strengthening intervention on a beam with an FRP profile mechanically connected to the compression zone of a beam.

Epoxy

The technique is based on the increasing of the element size by adding epoxy resin and connecting it to the beams with the use of steel or FRP bars as shear connectors (Reis, Branco and Mascarenhas 2006). The composite behaviour achieved in this way can be improved by keyed indentations in the timber beam. Due to the epoxy characteristics its use has the advantage of avoiding problems with shrinkage and bonding, but the described disadvantages of using epoxy resins make it not recommendable to use the technique.

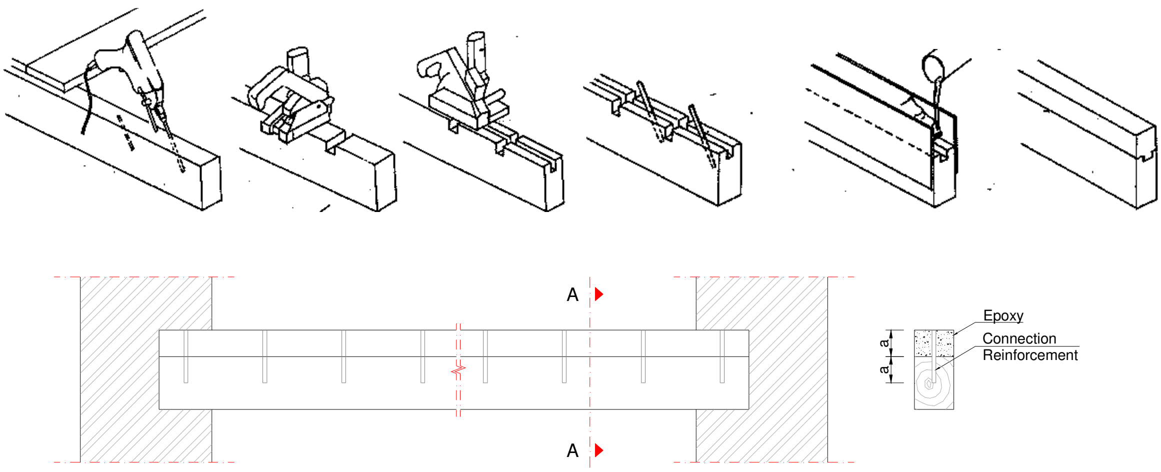


Figure 97 – Strengthening of sections with epoxy resin and connection reinforcement.

<u>Concrete</u>

The cast of a concrete slab on a timber floor while assuring a proper connection between concrete and timber beams creates a composite system (Figure 90) that takes the best profit from both materials. The concrete slab is stressed to compression while the timber beams work in tension.

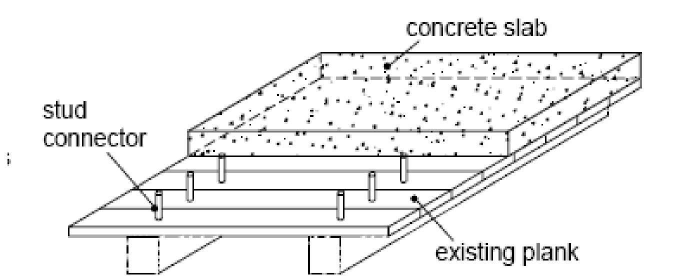


Figure 98 – Scheme of composite timber-concrete slab.

This technique is widely used and was recommended for many years as a way of improving the behaviour of buildings under horizontal actions. Its high invasiveness and low reversibility make it not adequate to use on valuable historical buildings (besides all the disadvantages demonstrated in the sub-chapter dedicated to concrete interventions).

Aside from these facts, in the case of less important buildings, these interventions present great advantages (Ceccotti 2002). They can triple the load bearing capacity and have up to six times the bending stiffness of traditional timber floors, as long as they are well connected. The comfort levels are improved due to the enhanced damping and sound insulation. Finally the fire protection is improved, once the concrete slab represents a barrier to its propagation.

Naturally, the performance of the system is dependent on the connection stiffness. Figure 99 summarizes the most commonly used connection systems. Depending on the type of connectors/glues and treatment of the timber surface the systems will perform accordingly. Those of the group 1 are the less stiff allowing a significant horizontal slip between timber and concrete, while those of group 4 are the stiffest. This variation can go from 50% to 100% in the case of the glued solutions. In this last case design calculations are simplified once, as there is no slip, the section is simply homogenized to one material. In all the other situations the semi-rigid behaviour must be taken in account (Branco and Cruz, 2002).

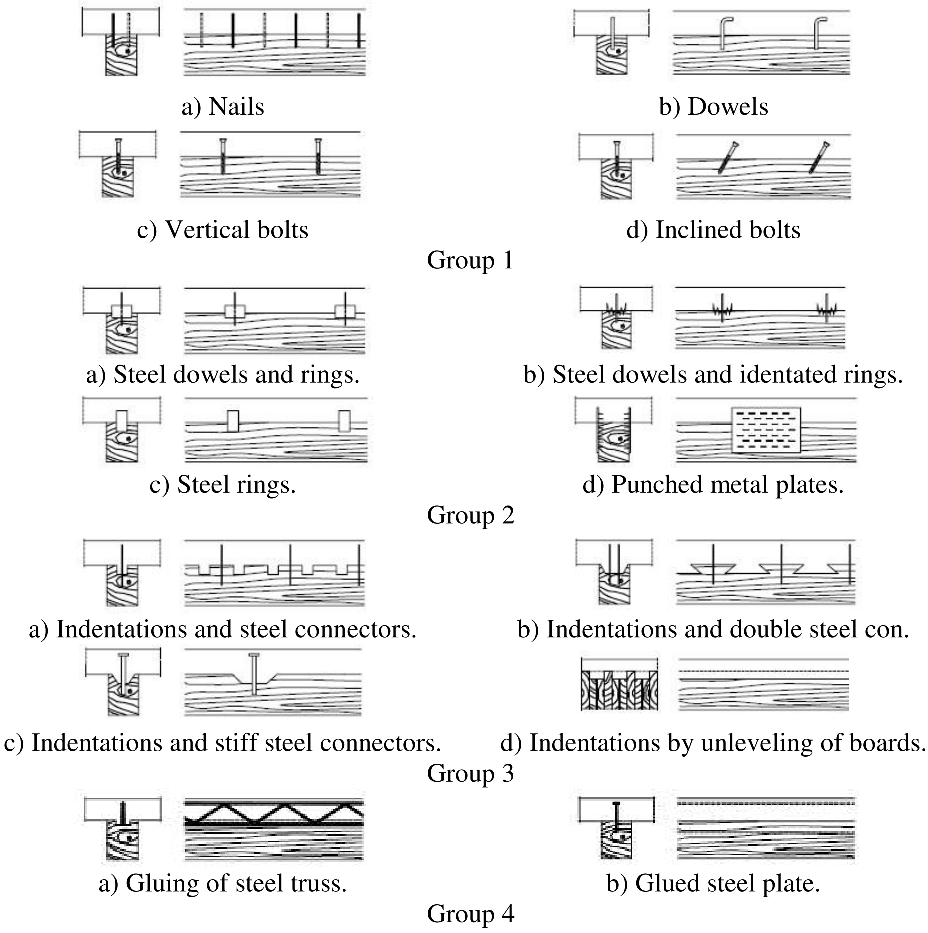


Figure 99 – Possible connection systems between in timber-concrete composite slabs.

Special attention should be given to the collapse mechanism obtained. The ductile behaviour of joist does not necessarily mean the ductile behaviour of the composite beams. If the connection is over-designed non ductile failures will be induced. Also, creep deformations should be taken in account, as depending on the environment they can quadruplicate the instantaneous elastic deformation (Ceccotti 2002).

<u>Recommendations for construction</u>

- Timber should be dry when the intervention is performed;
- Shoring for longer time than usual all-concrete slabs;
- Corrosion free fasteners;
- Reinforce on the concrete slab;
- Protection of timber from moisture using plastic layers when casting the concrete slab;

- Avoidance of timber species that have adverse chemical reaction to cement (high sugar content extracts).

5.4.9. POST-TENSIONING

Post-tensioning based systems are an interesting solution to a diversity of cases, usually where members have a proven lack of bearing capacity in bending. The basic principle of the technique is to strategically position steel cables on the structure, applying forces in a way that helps the structure to resist the external actions.

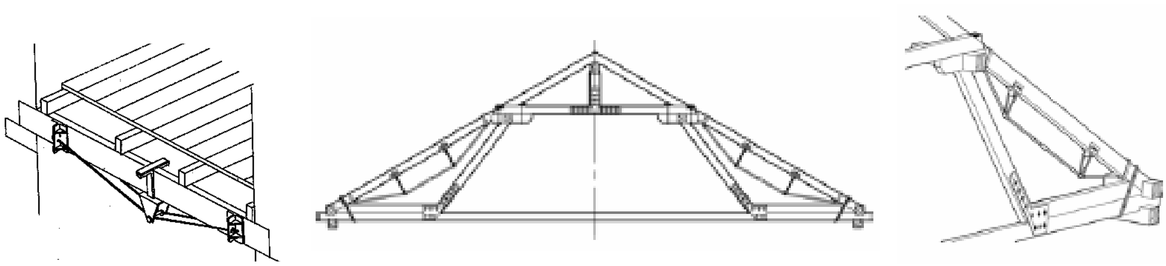


Figure 100 – Post-tensioning systems.

A deep understanding of the structure behaviour and the role of each of its elements, together with the study of the cause of structural deficit can give us clues to imagine systems strategically introducing slight alterations that work together with the structure, helping it on its bearing functions. The forces applied, either actively or passively, when the structure starts to deform under loading, will then help to reduce deformations and improve its overall bearing capacity.

The technique can be applied in a diversity of situations, both on floor and roof structures, but its effectiveness has to be wisely used, evaluating the structural behaviour, both of the original structure and the new system created, as well as the response to environmental factors and accidental actions.

Figure 101 – Post-stressing of a beam.

Figure 102 – Scheme and details of an intervention using post-tensioned steel cables and the addition of a timber member, giving the rafters an extra support and loosening the bending on the tie-beam at the same time.

The alterations introduced change the original structural system of the structure, which is surely invasive from the conservation point of view, depending the level of invasiveness on the amount of changes introduced. Together with introduction of the new materials it can become unacceptable in some cases. As in other situations, the suitability of the technique depends on the comparison with other solutions of intervention. The invasiveness introduced can be completely acceptable if there is a clear advantage of using this technique in confrontation with others. Some advantages, which make it very attractive, are its complete and easy reversibility, the minor destruction of original material and of course its visibility. The technique completely respects original fabric and it is clearly distinguishable from the original members and materials. A disadvantage is the vulnerability of the system to fire.

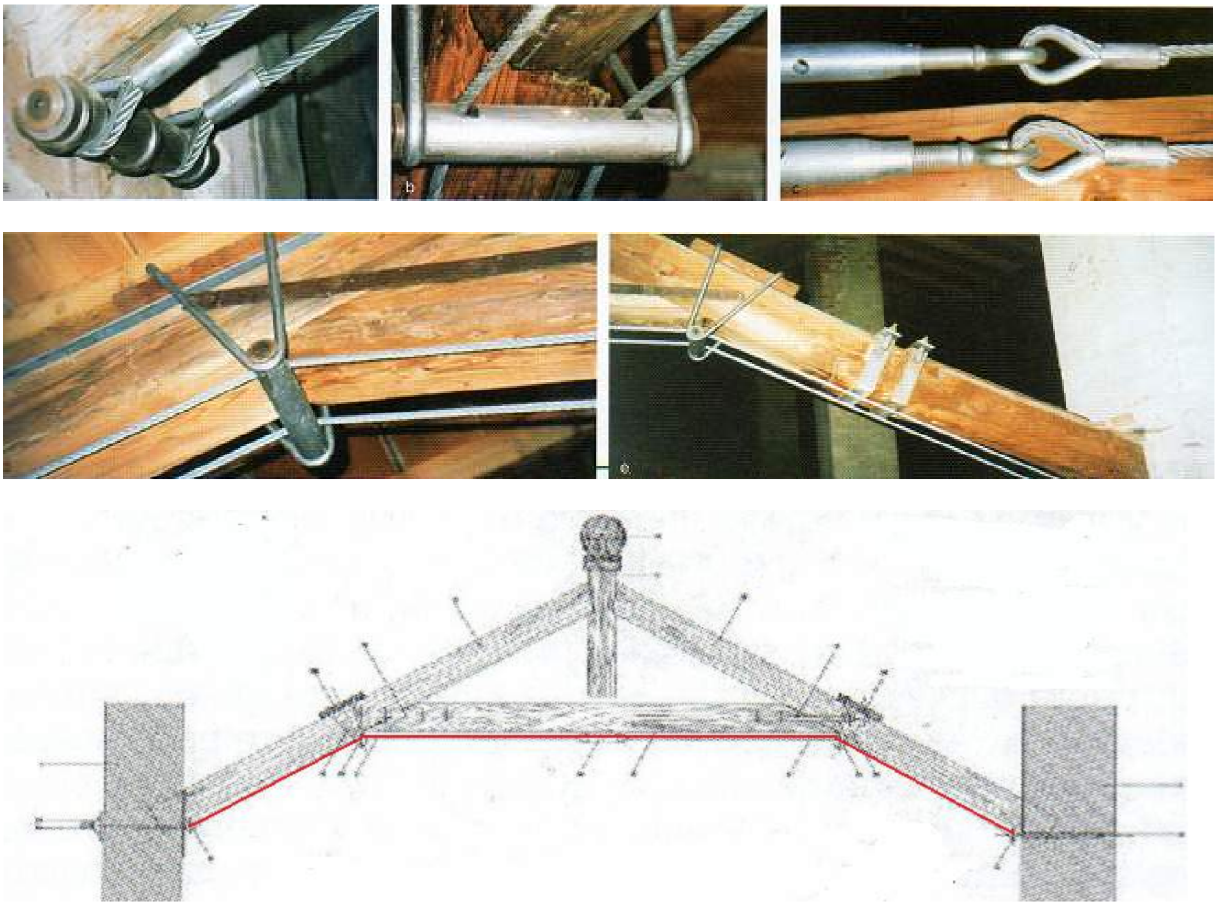


Figure 103 – Scheme and details of an intervention using post-tensioned steel cables that correct the original state of stress by forcing the structure in the opposite way to the one done by the external loads.

5.4.10. STIFFNING TO IN-PLANE ACTIONS

Timber floors and roofs are a structural part of the wider building structure composed not only by these but also by masonry foundations and walls. The interaction between the different individual systems is essential to the stability of the whole structural complex, and must naturally be taken into account when interventions are designed.

When referring to horizontal actions, wind and earthquakes, this interaction becomes of higher relevance. It is important to the global stability of the building that the floor and roof structures work as a diaphragm, efficiently distributing the horizontal actions by the resistant parallel walls. Without some kind of intervention, the original structures are to flexible, not being able to accomplish this objective. It is then essential, to efficiently stiffen timber floors and roofs in areas of strong seismicity.

It is common practice to associate the stiffening to in-plane actions to the increase of the vertical load bearing capacity of the floor systems. The usual systems are:

- Connection of a new layer of timber planks over the existing;
- Cast of a concrete slab over the timber planking;
- Connecting of a layer of diagonally crossing steel strips over the planking;
- The same using fibre reinforced polymers.

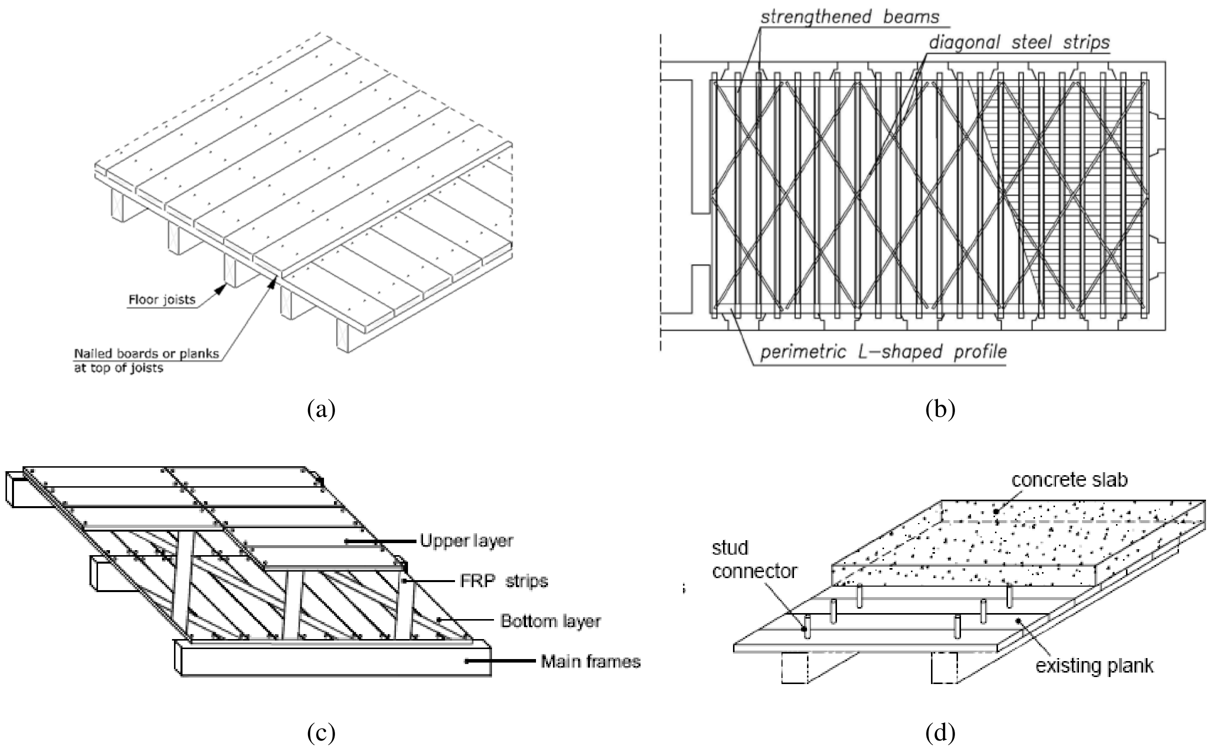


Figure 104 – Stiffening to in-plane actions with, (a) timber, (b) steel, (c) FRP, (d) concrete.

As stated before, the modern philosophy of conservation greatly encourages and raises the interest for dry strengthening techniques, which employ planks, timber panels, and steel sheets with thickness compatible with that of the floor. These techniques have a reduced invasiveness, are reversible and above all, are effective; enough advantages to refuse interventions using reinforced concrete or glued materials.

6. CONCLUSIONS

The presented research allows drawing some general considerations regarding the best way of achieving successful interventions. A good start is to clearly understand which kind of practice and final result must be chased by the intervention designer. It is important to keep in mind that no structural intervention on heritage structures should be taken if enough need is not demonstrated. Having been determined some structural insufficiency that must be adressed, the most durable and reliable, less invasive and preferably reversible should be seek, without forgetting that the minimum intervention possible should be preferred.

Having this always in mind both traditional and modern techniques (as demonstrated) can accomplish the chased goal.

- Prosthesisation is better performed, if mechanical needs are met, with all timber connections. It has the disadvantage of removing large parts of original material, which can be avoidable if other techniques to successfully strengthen the member are found.
- Mechanical connections, among other advantages, are generally easier to accomplish during construction, are more reliable in time and are reversible.
- Epoxy resins should be avoided on connections between members and should not be applied in ways that don't allow timber to naturally swell and shrink. Their vulnerability to high temperatures immensely reduces its range of application.
- Fibre reinforced polymers can be useful in a diversity of situations, but the need for adhesive connections removes part of its interest.
- The stiffening to in-plane actions can be successfully achieved with dry and reversible techniques that don't "over stiff" floors or roofs.
- Proven to be effective traditional techniques, as well as modern and reliable ways of using traditional materials, are welcome in restoration.

- Addition of members and post-tensioning with steel cables have the great advantages of reducing the action over original materials to an almost zero and of being completely reversible.
- No insufficiently tested techniques and materials should be used.

Finally, as it has been demonstrated by some original solutions presented, it should be stressed that structural restoration is a design activity and as so, it requires a combination of knowledge, effort and imagination in each particular situation, in order to be achieved the best results.

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