ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

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ASSESSMENT AND REHABILITATION OF THE TIMBER ROOF STRUCTURE OF THE "ASSUMPTION OF THE VIRGIN" CHURCH IN KUSTENDIL

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Keywords: *timber structure, degrading factors, strengthening, wood, traditional materials*

ABSTRACT

Timber is one of the most used materials in the roofs and floors of monumental constructions in Bulgaria. Complex timber structures, such as those belonging to the roofs of large monuments, are often not easy to understand in an expeditious way. Load bearing timber structures are exposed during their life to some degradation factors which lead, in the absence of appropriate maintenance interventions, to the loss of their structural integrity and serviceability. The objective of this paper is to present some experience in this field, regarding the case studies of timber roof structures of the "Assumption of the Virgin" church in Kustendil. Based on detailed visual inspection results, the scope and general methods of works construction ensuring adequate rigidity and load capacity of the structure are determined.

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1. Introduction

In Bulgaria, wood constructions have a vast occurrence, and an old tradition in the civil and industrial domains (Fig. 1*a,b,c*).

***a*)**  ***b*)**  ***c*)** 

Figure 1*a,b,c*. Wood in roof construction in the civil: *a*), *c*) and industrial domains: *b*)

Most of the buildings built till the beginning of the XX century in Bulgaria are made of masonry, mainly stone (exterior and some interior walls), and timber elements (floors, roofs, ceilings, interior and some exterior walls) as is abroad [1 – 5, 7, 9, 14, 16, 22, 23 and 29]. According to [4, 6, 11,12, 13, 28], if these elements are properly connected, they promote a good global behaviour: the masonry walls support the floor beams and roof trusses which, on the other hand, act as horizontal braces, inducing a more uniform distribution of stiffness and loading throughout the structure. Thus, if properly designed and in good conditions, these systems constitute efficient structures. This type of construction is disseminated all over the country and represents most of our built heritage, justifying the increasing interest on its preservation as memory of culture and identity (Figure 1*a,b,c*). Unfortunately, *most of them are degraded and abandoned,* demanding urgent intervention [19]. In general, direct intervention on the elements, avoiding substitutions, not only results in heritage preservation, but also in the minimization of the necessary actions and their impact. In this field, and particularly for old timber structures, NCREP's option [19] (Nucleus for the Conservation and Rehabilitation of Building and Built Heritage), respecting the International charts and ICOMOS [30], has been mostly oriented to techniques using traditional materials, like wood and steel. These techniques, consisting in the addition of timber elements and steel plates, have been applied in the rehabilitation of old buildings with very good results [28, 30]. One example with old timber roof construction, namely the "Assumption of the Virgin" church, will be analysed in this paper. It was built at end of 1816 [20] (Fig. 1*d,e*).

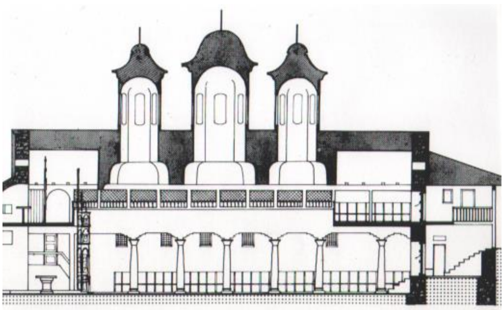
***d*)**  ***e*)** 

Figure 1*d,e*. Longitudinal section and inside view of the Church

According to [25] the success of the wood as a first class construction material has been proven since the time of the first villages; its applications were varied and intense due to its wide spreading, workability, high strength, and low specific weight. Among the meaningful accomplishments in our country, the churches and monasteries represent a real value for the cultural heritage and conserving them is an important step in our evolution. The preservation of original timber parts makes it possible for them to fulfil design restrictions, reducing the structure alterations to a minimum in a rapid and efficient manner. Considering the fact that the strengthening is applied to buildings with a remarkable cultural value, their aesthetic characteristics must be preserved and emphasized. This can be easily done by using traditional materials. Materials like metal, wood or concrete have been used in strengthening systems worldwide and do not disregard the aesthetic aspect. Nowadays, the modern age brings up in front the easily tailored, thin, high-strength and light-weight traditional materials, whose advantages especially in this domain are impressive. Steel and wood elements do not only bring an increase in the strength of the members they work with, but also reduce their size and self-weight and increase their ductility and fatigue performance. The necessity of using such materials is therefore reflected in the need of more subtle yet higher quality strengthening works [24].

2. Wood Deteriorating Factors

According to [25] the main goal for the civil engineer is to improve the load bearing capacity of specific elements. Before strengthening structural wood elements, one must firstly understand the reasons for which these elements are deteriorating. There are a number of factors determining the durability of structural wood and they will be shortly presented hereinafter. Timber is a natural building *material* which ages and deteriorates in time, even without the influence of external factors. Its properties depend on the specific wood species, the geographical location where the wood has grown and, furthermore, on the local growing conditions of every single part of a tree. All natural imperfections and irregularities are points of weakness in sustaining loads or resisting to other deteriorating factors [24, 25]. Moisture is probably the single most detrimental factor affecting wood structural members. Moisture-related deterioration of wood typically begins to occur when the moisture content of the wood exceeds 20%. This level of moisture which provides sufficient resources for wood-attacking fungal hyphae (rot) to stay active and cause wood-cell material destruction can be achieved by leakage or by repeated wetting and drying in service. *Moisture* (Fig. 2.1*a,b,c*) is the most important factor of influence for all the physical-mechanical properties of wood and it creates favourable growing conditions for agents responsible for wood degradations. Below the fiber saturation point, the wood will shrink when losing moisture and swallow when absorbing moisture [25]. When exposing wood to temperatures higher than 150 °C, its strength will be affected.

***a*)**  ***b*)**  ***c*)** 

Figure 2.1*a,b,c*. Moisture in purlins in axis B and D

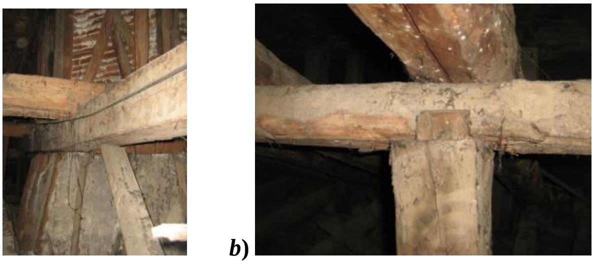
From the *biological agents'* point of view, wood is highly susceptible to the attack of fungi and insects or, in some cases, of some marine borers [21, 24] (Fig. 2.2*a,b,c*).

Figure 2.2*a,b,c*. Massive timber roof elements with different stages of wood destruction

When analysing this aspect, it is important to realize that, if fungi attack is linked to the moisture content of the wood, insects can attack in any conditions [25]. In optimum service conditions wood can last without noticeable deteriorations. Special protective measures and chemical treatments are used when the working conditions are not suitable for the timber elements. Protection against fire, fungi, or insects includes chemical treatments which must consider the nature and severity of the risk, the wood type, the eventual previous treatments, and the possible secondary effects of the chemical products [25]. Usually, ends of timber elements (e.g. roof trusses) bearing in pockets in masonry walls are typically the most vulnerable to the effects of moisture absorbed by the masonry. To compound the issue, bearing ends of the roof-structure timbers are typically in the vicinity of the roof gutters; any associated leakage or masonry saturation could further contribute to deterioration of the roof-structure timbers. Wood is generally a very ductile material that behaves well under loading. However, decay significantly affects the cell structure of the wood, which causes a loss in strength and ductility. Significant deterioration can cause timbers to fail suddenly, in a brittle manner, without undergoing large displacements or giving early warning before the ensuing collapse. Also, because of the lack of redundancy in timber trusses and roof framing, failure of even one member can have catastrophic consequences, including partial or full collapse of the roof structure.

3. Mechanical Failure of the Structural System of the Roof

According to [28] the stability of the existing roof timber structures of the church is commonly studied with the general methodology of the Structural Mechanics, the Theory of Timber Construction, the Theory of Materials applied to the wood, the Technology of the Timber Constructions (see for instance the European Codes). The most common causes of failure of the our timber structural systems are inadequacy of configuration (geometry of the structure, sizing of the members, kind of connection of the members, bracing, etc.) in relation to the actions, both static and dynamic loading; besides slenderness, instability, defects of the wood laid in place, severe biotic damages, accidental factors. No doubt, that the decay of the wood caused by beetles and fungi is a major problem both for members and structures. In fact, mechanical failures can also be caused by biotic factors that reduce the strength of the material. The failures can hit the structure at any hierarchic level, i.e. that of the members, the units, the whole structural system and the connections. The widespread habit of replacement of the damaged parts of the ancient structures or their total demolition and rebuilding is, unfortunately, extended up to the present days though only by a restricted number of culturally unacquainted operators who rely on a supposed tradition [21]. This habit has the effectual alternative, required by the contemporary cultural instances, of the repair and strengthening with minimum disturbance of the ancient complex. This new vision demands for an updated scientific and technical approach [26]. If repair and strengthening must be planned in order to recover the lost efficacy of the system and, at the same time, avoid modifications or at least minimize them, in any case without significantly altering the general concept of the same system, the mechanical failures as well as the causes of their presence must be known and interpreted; a general evaluation of the efficiency and of the safety of the system will then be possible [32]. Planning the strengthening will subsequently follow in a natural way as the activity meant to take the right measures and put in place only those remedies judged adequate to counteract the recorded effects of each failure, avoiding the assumption of the generic remedies featured and recommended in the handbooks and in the *dépliants* of companies without a specific reference to the real nature of the damage, and cancel or at least neutralize the causes that are responsible for the problem. A quite specific failure mode is to be considered the longitudinal break of the extremity of a member where a pin or nail is inserted in order to apply the tension. The wood divides along the fibres (*in other words it splits*) and the holding device slides along the borders of the split thus allowing the tension to release (Fig. 3.1*a,b*).



***a*)** ***b*)**

Figure 3.1*a,b*. Wood divides along the fibres

The missing of the tie in a three-hinge frame will be leading in the future to the catastrophe consequences for the whole behaviour of the wood construction (Fig. 3.2). This fact leads to the displacement in the connection between column and horizontal beam in place of the missing tie in a three-hinge framework.

Figure 3.2. Reversal in the connection between column and horizontal beam

The most considered *stresses* in the design of wood elements are the bending moment, tensile, compressive and shear forces. Nevertheless, there are other strength properties that are less important but that can also be used, like the torsion, creep or fatigue resistance, cracks in the horizontal elements [25] (Fig. 3.3*a,b,c*).

a) ***b***) ***c***)

Figure 3.3*a,b,c*. Torsion of beam, horizontal displacement in the top of columns: *a*), vertical displacement of beam – caused the creep: *b*), and cracks in the beam: *c*)

4. Strengthening Methods Implying Traditional Materials

According to [4, 8, 11] the need for the intervention on timber structures is usually related to the existence of damages or alterations of use with load increase. Among the most common damages, one can refer to the natural ones (knots, splits, etc.) and those resulting from biotic attacks (insects and fungi) and from incorrect constructive details or structural interventions. These causes not always originate the collapse of the structural elements or structures, but are often associated with their deficient behaviour, with high levels of vibrations and deformations. Consequently, in order to ensure the safety and, at the same time, the proper performance of the structures, it is necessary to intervene in the damaged structural elements through rehabilitation actions. The decision about the type of intervention should be taken only after a rigorous and careful survey of the structure [9, 14, 15]. According to the results obtained in the survey and to the circumstances of each situation, the intervention on a particular element or structure can take two different ways: Rehabilitation or Substitution. Rehabilitation can be seen as the natural solution that allows the maintenance of the element or the structure. This option may involve a strengthening action, particularly when the original structures are improperly designed or when changes of use (with higher loads) are expected, demanding a higher strength. In a limit situation, the intervention can consist in the *Substitution* of the element or structure, a solution that should be carefully analysed taking into account the percentage and intensity of the damage [12]. The rehabilitation of timber structures can be done using different techniques, with pros and cons concerning effectiveness, compatibility, intrusiveness, etc. when choosing the techniques and materials to use. There are, among others, two criteria linked to heritage protection that should be respected: Compatibility and Reversibility [12]. Compatibility is linked to the physical and chemical interaction between the existing structure and the intervention solution. In particular, the elements, materials and (or) techniques implemented should not react with those of the existing structure or introduce higher stiffness in localized structural areas. This criterion avoids the introduction of new damage in the structure through the intervention. A good example of that are the glued or very rigid connections in timber elements that may induce concentration of stresses in the interface area, i.e. the occurrence of new damage. Reversibility is linked to the will that the interventions be substitutable so that they can give place to more efficient and (or) protective interventions in the future. Generally speaking, the less intrusive solutions are often the more reversible ones [11]. There are many different ways of using traditional rehabilitation techniques in old timber structures, namely: – the fixation of timber pieces or thin steel plates, with varied configurations, to the sides of the element; – the introduction of thin steel plates in the interior of the element; – the installation of steel belts around the element; – the installation of new structural elements (timber or steel) parallel to the existents, among others [12]. To increase knowledge on the efficiency of these techniques in order to give useful information to designers and constructors about the suitability of each technique to solve specific situations, in Prague [8] and NCREP [19] a laboratorial testing campaign is being developed. As a matter of fact, the information related to research on rehabilitation techniques on old timber structures using traditional materials is quite limited. In the case of traditional carpentry joints, despite of being widely used, the number of studies on their mechanical performance and on possible strengthening techniques is scarce. With few exceptions, research on timber joints has been oriented towards new engineering configurations. Simultaneously, only few studies were developed in elements subjected mainly to bending; some authors performed bending tests in beams reinforced with steel elements, but reaching contradictory results. The majority of the studies were done in elements with high axial or shear forces. Strengthening techniques on floors to improve the diaphragm behaviour have also been analysed, proving experimentally its efficiency, but advising that further refinement is still needed for the technology to be applied in the construction practice. Concerning the connections between timber structures (roof, walls and floors) and masonry walls, although it is usually appointed as a key element to the overall behaviour of a building [12], in particular under seismic events, no significant efforts have been spent on their study.

5. Interventions with Timber and Steel Elements

The use of timber elements in the rehabilitation of old timber structures is a very common solution. However, in these interventions it is important to have timber elements of the same wood species and with similar characteristics: density, strength and stiffness, to those of the original structure. [18] refers to the convenience of using old timber elements, with the drying process completed, and the importance of having compatible moisture contents between new and old elements to avoid physical incompatibilities. When it is not possible to obtain similar wood, timber elements retrieved from the demolition of old buildings can be used or, as alternative, the new elements, already dry, can be previously placed in the constructions where they will be installed to acquire a moisture content in equilibrium with the construction environment. On the other hand, solutions with steel elements are commonly used in interventions on old timber structures, particularly on timber floors, leading to an increase of strength and stiffness. Nevertheless, when using these elements, two questions should be analyzed: the compatibility with the timber elements (the behavior of wood and steel is considerably different) and the fire resistance of the metallic elements. In fact, timber structures support temperatures for which steel structures would have already failed. Therefore, to avoid the steel elements to become the weakest point of the strengthened structure it is important to improve their fire resistance, which can be done through physical barriers or fire retardant products. Simultaneously, steel elements should be protected against corrosion [18]. Strengthening wood structures involves various methods and techniques depending on the final purpose for the intervention, the elements and materials involved, and the importance of the work. Explicit objectives must be set, such as the intention of keeping the original material and structural concept, the conservation by maintaining the aspect of the elements and structural solution, the modification, restoration or improvement of the bearing capacity, rigidity and other characteristics of the elements and structure [25]. No matter what method of strengthening is chosen, the works must be compatible with the existing structure, so that the coherent assemble can be easily performed. The repairs can be made on the whole length of the element or on certain degraded parts. Due to environmental factors and biological agents, surface degradations like holes and cracks can appear. Therefore, the repair techniques must imply the injection of wood with resins that fill up these openings and thus restoring the wood mechanical characteristics. Timber structures, more than those made of other materials, show a very complicated deformational behavior, mainly because of the property of the viscoelasticity that wood possesses, in an accentuated way, if compared to other materials, due to the nature of the tissues and the longitudinal position of the fibers. Therefore, often it is difficult to assess the cause, the kind and the entity of the stresses which are responsible for the deformations detected [10, 18, 25]. In the case of eccentric *compressive* loads, when the elements become subjected to both compression and bending, the supplementary efforts that appear are extremely dangerous, compromising the integrity of the entire element. Different strengthening methods have been developed to partially reduce the deformations and enhance the rigidity of the member but, for all of them, the considered elements must be discharged. For elements subjected to *bending,* the considered degradations are either *cracks* situated especially in the middle span area or excessive deformations caused by the change of loads or by long lasting loads. *In these cases the local interventions are meant to stop crack propagation or to enclose it.* One solution includes the utilization of metallic elements that induce compression perpendicular to the crack and stop its propagation [25]. Two holes are drilled at both ends of the crack and two metallic plates are disposed on parallel sides of the element, bonded with bolts, as shown in Fig. 5.1*a,b,c*.

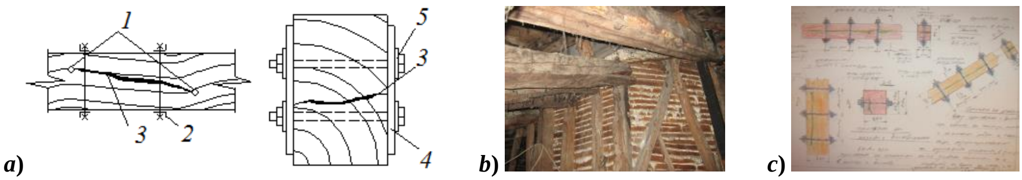


Figure 5.1*a,b,c*. Local strengthening of beams: longitudinal cracks [3]:
***1* – drilled holes, *2* – clamp, *3* – crack, *4* – plate, *5* – bolts**

Total strengthening of beams can be made with or without increasing its transversal dimensions. To change the cross-section, new elements of wood, metal or concrete are added above, below or lateral to the existing members [25]. For instance, placing new wooden elements under the existing beams does not influence the secondary elements or the floor; they are linked with metallic anchorages, (Fig. 5.2*a*). The same type of anchorages is used for the laterally added elements (Fig. 5.2*b*).

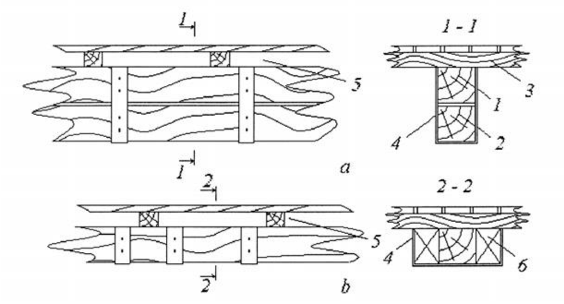


Fig. 5.2. Beam strengthening using wood and steel elements [14]:
***1* – existing beam, *2* – new beam, *3* – secondary beam, *4* – metallic anchorage,**
***5* – air, *6* – lateral beams**

When keeping the initial beam dimensions, the strengthening involves the insertion of metallic profiles, which have a lower height than the actual beam. The metallic elements must be proofed with epoxy resins. A first layer of resin is poured after the longitudinal pockets for the metallic elements are made. Then, the metallic elements are inserted into the pocket (for the metallic profiles case, bolts can be used) and filled up with resin [25].

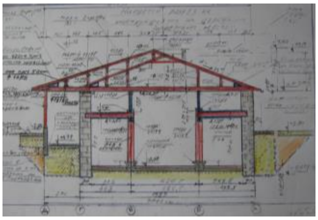
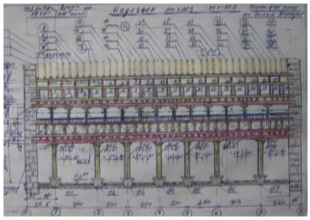
a)  ***b***)  ***c***) 

Figure 5.3*a,b,c*. Structures will be strengthened using steel profiles

When the damage of the beam consists in the rotting of its ends, usually caused by water absorption through the joints or from meteorological water, the degraded material can be removed and replaced with a new one or it can be strengthened using epoxy resins (Fig. 5.3*a,b,c*). This second procedure involves only a partial removal of the material at the ends [15]. The rehabilitation of the timber beams supports was performed through the fixation with steel triangle and steel bolts. Additional connection between roof rafters and horizontal floor beams *using steel triangle* guarantee the global behavior of the building and their correct connection to the stone masonry wall (Fig.5.4*a,b,c*). The extremities of the beams were treated against biotic attacks.

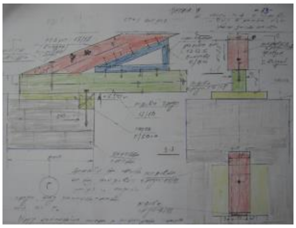
a)  ***b***)  ***c***) 

Figure 5.4*a,b,c,d*. Connection between floor and roof beam using steel triangle

Anchoring of purlins to the outside wall is recommended to be done using the steel lashes and steel bolts (Fig. 5.5*a,b*)

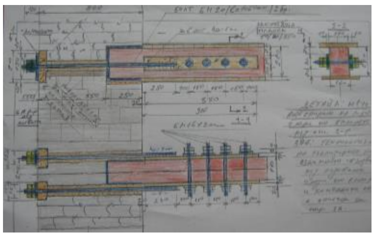
a)  ***b***) 

Figure 5.5*a,b*. Anchoring of purlin to the outside wall by steel lashes

After the rehabilitation of the supports and removal of the heavy load from the roof surface, the existing deflection in the purlins can reduce throughout a system of truss construction (Fig. 5.7*a,b*).

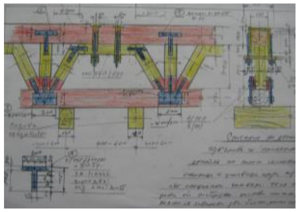
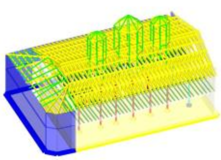
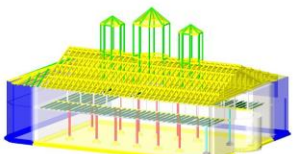
a)  *b*) 

Figure 5.6*a,b*. Support of the purlins throughout truss construction

6. Numerical Analysis of the Timber Roof of the Church

The main purpose of this part of the article is to show the potentials of a three dimensional computer modelling and simulation of a building structure. We would like to show how the science of engineering in particular, and advanced computer modelling including finite element methods (FEM), can be used to increase the understanding of a structure. We intend to show more than simple strength calculations, which is the most common range of application of the finite element method. We will also demonstrate how to apply this method to a historical building structure. This includes a comprehensive study of the structure in mind, which is done not only to be able to reveal the geometry, but even more to learn to understand the structure and its behaviour. This knowledge is necessary to be able to judge the truth of the results. When the static behaviour of the structure is found we will illustrate this in a way that is simple to understand even for the less experienced viewer. A historical wooden framework is very likely to be highly complex and like a time machine. That is why it is very important to be able to study the results of a calculation when dealing with the framework in its entirety. This includes plots of deformations and reaction forces on the complete structure, as well as special examination of smaller sections of the structure. With the computer model needed for the above analysis it is easy to go further and simulate damage to the structure or exposure to special load cases. This can be done either to include realistic or probable damage in the dimensioning when restoring the building or to verify observed damage. This will not be demonstrated explicitly in this work, but the possibility will be obvious. As an additional purpose we will also discuss different methods of analysing building structures, especially old historical wooden structures. With the different tools, computer calculations and hand calculations respectively, used in Bulgaria we will try to investigate how the norms and regulations are used. We are interested in whether the rules must be completely obeyed or whether they may in some cases take advantage of the calculation method in question. Within the structural analysis of the historic timber structure, a model is built [27] (Fig. 6.1*a,b*).

a) *b*)

Figure 6.1*a,b,c*. Ch. "Assumption of the Vigin" – (*a*) View on the roof structures, (*b*) View on the first and second level of the timber structures of the church

Of course, at all times, the structural model is a compromise between a scheme close to reality, but too complex to calculate, and a scheme easy to calculate, but far away from reality.

The better the model is in line with reality, the more reliable the diagnosis will be. Therefore, a step-by-step procedure within the modelling is used. Initially, with the information available from a visual inspection, a first structural model is made often not accounting for detailed information on material degradation, missing structural elements, and the actual deformed shape of the structure. The outcome results of the structural model are compared with the deficiencies identified on site. This initial analysis is fully worth since it better aligns additional research efforts. According to [6, 7] the updated model, therefore, should ideally account for: overall geometry of the timber roof, cross-sections of the structural elements, nodal details, displacements, missing elements, structural interventions, alterations and weakening; actual material properties, taking into account the rate of decay (mechanical and physical-chemical-biological), instead of the material characteristics specified in the original design or provided by codes; the correct nature of connections and boundary conditions, including differential settlements of the supports; the uncertainty associated with the validity and accuracy of the models. In general, the following remarks can be made: the structural analysis software used (Supperstat, Tower) is mainly developed for the design of new timber structures, according to the limit states design principles, using partial safety factors; there is no software available that accounts for the time dependent (creep) behaviour of timber. The general frame analysis software mainly used within practice does not account for the non-isotropic material characteristics of the timber. Within the analysis different types of nodes are encountered. The outcome of the analysis results strongly depend on the nodal stiffness assumed and their actual restrained (Figure 6.2).

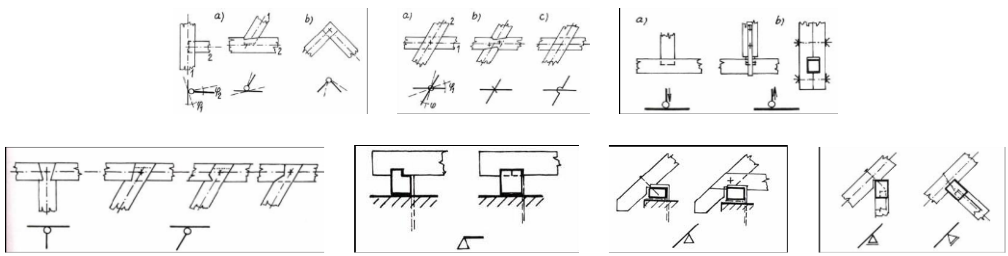


Figure 6.2. Different types of nodes modelled as hinge joints within the structural analysis

7. Conclusion

Trusses and other timber frames have been successfully used to support roof systems in houses of worship for centuries, and, with proper maintenance and repairs, they should continue to serve as reliable and effective roof framing systems for years to come. In the practice, a wide combination of the failure presented in the above mentioned text here can be found. It is demonstrated that the failures of the timber structures are very peculiar, certainly depending on the kind of action, and different from those of the constructions of other materials, besides characterized by a larger number of types. Technicians must be acquainted with them and be able to recognize and interpret them on the spot. They must be able to express an immediate judgement about the level of safety of the construction in the observed condition, take the immediate measures to avoid collapse, delaying to a further accurate survey the full evaluation of the general situation. The full understanding of the failures of an existing structural system can greatly help to interpret its behaviour, inconsistencies, shortening of the level of serviceability. Similarly, the full understanding of an old structural system, reducing the number of unknown factors, allows a direct and appropriate design of the strengthening measures and devices, the cutting down of the extent and quantity of the intervention with evident advantage for the costs but more for the conservation of the authenticity of the ancient surviving specimens. The risk, otherwise, is to make useless or, worst, harmful interventions. To prevent this regrettable situation, the strengthening measures must be designed only by technicians who are familiar with the peculiar way of failing of the timber structures and capable to enter into their conception [16]. In general, the preservation of the structural elements results in benefits, not only in terms of built heritage preservation, but also in minimization of the interventions and their impact. Even though, when this strategy is followed, the implementation of traditional rehabilitation techniques has been commonly passed over by techniques which use modern materials, frequently expensive and with doubtful efficiency. This situation is particularly common in old timber structures, namely roofs and floors, which exist all over the world, in some cases for many centuries. Therefore, an effort should be done to change this situation i.e. to show the community that it is possible to preserve timber structures and at the same time to use traditional materials and techniques, which will lead to more sustained interventions [4, 6, 8, 13, 15, 20, 21, 31 and 32]. Proper understanding of the material behaviour, structural characteristics, and system limitations is needed to enable designers and builders to develop effective remedial or strengthening solutions in historic restoration or renovation projects.

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