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An Overview of Historical Traditional Wooden Structure Conservation Techniques

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Abstract

Historical wooden building architecture is a cultural value that should be conserved considering its authentic wooden material and architectural details. Accordingly, the actions to be taken against the distortions that may emerge in the wooden building architecture are as important as the relevant building itself. Historical wooden buildings are faced with wrong intervention methods implemented within the modern restoration efforts. Consequently, authentic details of the traditional wooden architecture as well as the unique assembly methods and wooden materials disappear in time. Another result of these wrong intervention methods is that historical wooden buildings continue existing with their authentic values decreasing due to unqualified extensions and further wrong techniques. The correct action methods to be implemented on wooden building elements was presented through this study considering the concepts of architecture, aesthetic, practicality and economic dimension. Previous studies have generally reviewed the topic through a single method, and only a limited number of studies that have been conducted in a more comprehensive and detailed manner have collectively mentioned the traditional and modern repairing and reinforcement methods. The structure and anatomic characteristics of wooden material were investigated through the relevant literature in the present study. Then, common distortion issues seen on wooden building material were presented. The repairing and reinforcement methods employed on wooden building material were explained through theoretical and practical approaches while considering the information achieved from the literature. Moreover, various technical drawing and practical photographs were utilized. This study aimed to serve as a guide for the repairing and strengthening interventions for historical wooden buildings. The results indicated that traditional methods were preferred more than the modern ones in the field activities within the wooden structure restoration procedures conducted in Türkiye and that traditional methods being known more and considered as more economical played a key role in this context.

1. INTRODUCTION

The historical buildings that still reflect the social, cultural, economic and theological structure, construction methods and materials of previous civilizations should be conserved at the highest degree possible and passed down to the next generations. These historical findings also have a documentation value as they will continue being valuable and important from various aspects in future. The conveyance of this value in its original form depends on the consistency of modern conservation approaches. The conservation approach that is theoretically comprehensive and detailed cannot be displayed in a consistent manner due to several reasons such as different interests regarding practices, economic capabilities - incapabilities, lack of education / opinion of the relevant discipline, and preference of easy methods regarding the material and details. These factors result in the extinction of details regarding building culture, construction technology and material that have been conserved thus far without sufficient documentation.

The traditional construction culture suggests that one of the most commonly used construction material is wooden, which has been in relation to the architectural possibilities. The ability to obtain from the

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immediate vicinity by making insignificant amount of efforts, being considered as reliable, solid and durable and the trait of allowing detailed solutions through easy and smart practices are among the important criteria for the selection of wood. Wood as a construction material has been used as a single material or in combination with other materials within various construction systems. Therefore, there are many historical buildings which were constructed using wooden material. Some of these buildings totally lost their original material and details due to wrong conservation approaches, while some lost their original assemblies, ornamentation and structure due to non-original alterations and/or partial repairs. These buildings are cultural examples that reflect the material, knowledge, technology and engineering knowledge as well as carpentry skills of the relevant time. However, the tradition of wooden building craftsmanship shrank in time, resulting in this culture being partially forgotten.

In addition to the ability to find wood easily and generation the desired details easily, replacement being the most economical and easiest manner to solve the distortions in wooden material causes people to make the decision of replacing wooden pieces in distortion-related scenarios. Replacement of original wooden material and details instead of conserving them constitutes a significant problem that results in the loss of both significant and original details. The original wooden material that is removed from the relevant building is generally replaced with a different type of wooden material that does not architecturally and aesthetically suit the original material, or with concrete or steel elements. As a result, original combination methods regarding wooden material disappear, or original wooden material does not suit the newly added material and get distorted in time.

With its material and details lost as a result of the wrong repairing approaches and interventions, the traditional wooden architecture method disappears before it is documented. The efforts to raise awareness of importance regarding the traditional historical wooden architecture and awareness of the idea of conserving this architecture are therefore significant. The theoretical and practical studies regarding this topic are generally limited with the material distortions in traditional wooden construction method or traditional wooden assembly details. The theoretical studies related to repairing and reinforcement include "Repair and Reinforcement of Timber Columns and Shear Walls-A review" by Chang with the definitions of repair and reinforcement for wooden columns and shear walls [1]; "Self-Tapping Screws and Threaded Rods as Reinforcement for Structural Timber Elements- A-State-of-the-Art-Report" by Dietsch and Brandner examining reinforcement methods with self-tapping screw and threaded rods in wooden building elements [2]. "State of the Art Technology on Conservation of Ancient Roofs with Timber Structures" by Tampone and Ruggieri examining the current technological approaches related to the repair of historical wooden roofs [3] and "Historical scarf and splice carpentry joints: state of the art" by Karolak et al. reviewing the traditional carpentry and assembly details in historical buildings [4]. Nevertheless, no comprehensive practical study regarding the repairing and reinforcement methods for wooden building restorations was found.

This study compared the repairing and reinforcement methods that could be implemented on the historical wooden building architecture through the relevant examples after assessing them from the perspective of the concepts of aesthetic value, practicability, practicality and cost. The methods were detailed in a manner to contain both traditional and modern repairing and reinforcement methods, and reviewer later. The aim was to create a practical proposal guide that would contain assembly details for repairing and reinforcement approaches suitable for the historical wooden building architecture. This study also aimed to assess the possibilities regarding the original assembly details and to conserve the wooden material before it is replaced. Conservation of original material and details and passing down these materials and details to the next generations in a documentary form was also targeted.

2. BASIC PROPERTIES OF WOOD

As wood is a natural material, the internal living organism within the wood is directly related to the physical and mechanical traits of the wood. Kocataşkın [5] noted that the main cellular structure chemically consisted of cellulose and that wood was developed as many cellulose molecules were connected to one another. Kocataşkın [5] also added that the molecular ties regarding the height direction of wood were stronger, with the molecular ties on the lateral direction being relatively poorer. Due to the tubular cellular structure of wood, traits of wood differ in terms of directions, which excluded the wooden material from the isotropic material features. Accordingly, the pressure applied on the wooden element in a straight direction and the resistance arising from the wood crushing the cellular walls is much lower compared to the direction paralleling the fibers. Similarly, if parallel to the fibers, a much higher resistance is achieved as the tubular cells work like a column. Regarding the tensile force, the parallel direction of fibers results in rupture. When the same force is applied on the fibers in a straight direction, the rupture occurs in the gel between the fibers. Therefore, a lower tensile force in a straight direction to the fibers is achieved. The knots and cracks present on the body of the wood as well as the tilt angle of fibers etc. affect the mechanical structure of the wood [5].

Another factor affecting the structure of wood is moisture. The wood is always in interaction with the environmental moisture. Due to the physical effects, cracks may emerge in the woods; these cracks are in the tangential direction the most and in the axial direction the least. Eriç [6] claimed that broad-leaved trees would have more cracks than coniferous trees due to the moisture transfer of the wood [6]. Regarding the moisture transfer of the wood, Reinprecht [7] noted that a certain amount of moisture increase boosted the strength of wood. However, the strength increase arising from the moisture would be fixed after the moisture level of wood increase to 30%, and no change would occur in pressure, bending and tensile strength values [7]. Factors affecting the structure and strength values of wood include knots and cracks present on the body of the wood as well as the tilt angle of fibers. Due to the aforementioned knots and cracks, severe strength losses occur in relevant areas of wood. These natural faults within the structure of wood reduce the strength of wood significantly [5].

3. COMMON PROBLEMS OF WOODEN BUILDINGS

The distortions seen in wood can be assessed in two groups as human-triggered and natural, with the former being associated with various criteria and factors and the latter occurring after the wood is harmed by different biological and non-biological factors throughout its term of service. These distortions may occur solely or with the combination of many factors, or they may arise from biological or atmospheric factors. The biological distortions, on the other hand, arise from fungi, insects, bacteria and sea organisms.

3.1. Biological Distortions

3.1.1. Fungus

Wood can be invaded by fungi soon as it contacts humidity. Fungi spores reproduce on the wood under convenient conditions, causing it to decay, soften and even lose its strength. Therefore, certain actions can be taken against the fungi invasions in the wooden building construction method. Kocataşkın [5] noted that wooden elements should be detailed in a manner to not contact moisture for protecting against the fungi impact. The same author also suggested that certain materials such as sand or cinder should be dried properly and used in the gaps of wooden floors within traditional buildings. It was also reported that the contact between wooden element and air should not be cut in the wooden building details and that air should flow through a single point, suggesting the importance of ventilation [5].

Fungi can be examined in two groups considering the damage they cause on wooden elements. One of these groups consists of the fungi weakening the structure and strength of wood, and the other covers the fungus species damaging only the wooden surface (Table 1).

Table 1. *Fungi causing structural and superficial damage to wood, table re-interpreted [8].*

	FUNGUS	APPEARANCE AND CHARACTERISTIC FEATURES	EXAMPLE
FUNGI CAUSING STRUCTURAL DAMAGE TO WOOD	**Dry rot fungus**	They are seen on the points where wet concrete or brick walls contact with the wooden elements. They may also be seen in poorly ventilated spaces. They consume and damage the cellulosic parts of the wood, therefore leaving a brown layer on the surface. They particularly and mostly invade softwood.	 The wood decayed by Serpula lacrymans [9]
	Wet rot fungus	They consume both cellulose and lignin. They generally invade the softwood species. They are mostly present in the wood submerged in water and result in cross cracks on the wooden surface.	 Phanerochaete chrysosporium damage [9]
	Soft rot fungus	They attack the wood that is wet at the same level. As a result of its damage, they cause a longitudinal crack on the wooden surface and form a soft surface. It is possible to see invasions in all sorts of wood.	 Phanerochaetaceae damage [9]
FUNGI THAT CAUSE SUPERFICIAL DAMAGE TO WOOD	**Spot fungus (blue spot fungus)**	They leave a dark blue layer on the wooden surface due to their invasion. Furthermore, semi-transparent or transparent surface may also occur below the invaded surface.	 Blue coloration on solid wood [9].
	Mold fungus	It grows on the solid part of the wood. It may leave a black, brown, green or orange trace on the wooden surface. It is a highly dangerous species as it can even affect the wooden element coated with a preservative.	 Fungus damage on timber [9]

3.1.2. Bacteria

Bacteria: Bacteria are the smallest organisms that are visible under a light microscope, and their main organisms consist of a wall, cytoplasm and nuclei. They generally do not have chlorophyll and plastids. Bacteria are generally divided into two as aerob and anaerob based on the environment they are developed in. Aerobic bacteria need oxygen to survive and receive cellulose through hydrolytic way. However, anaerobic bacteria can survive even when oxygen is absent, and they particularly invade the water-logged wood [9].

3.1.3. Insects

Insects affecting wooden elements: Coleoptera and Isoptera (termites) (Table 2). From a general perspective, insects exist at four different stages: egg, larva, pupa and mature. Larva duration may vary from one to ten years, depending on the type of insect and environmental conditions. Insects create cavities on the wooden element in the larva stage and start to get in these cavities to find food. However, while transiting from the larva to the pupa form, insects become mature. At this stage, insects begin to form flying holes that are close to the wooden surface and continue through the surface (Figure 1a). Wood dust start to emerge around the flying holes in the wooden element [8]. Insects may invade the wooden elements in buildings when suitable humidity, temperature and relevant values are present. Only a limited number of insect species have the capability of attacking the wooden elements as timbers assembled as dried wooden construction elements. Specifically, three insect species that attack the dry wooden elements cause significant economic losses. The first two of these insects are ptinidae and common furniture beetle from Anobiidae family. The third is hylotrupes from Cerambycidae family [10].

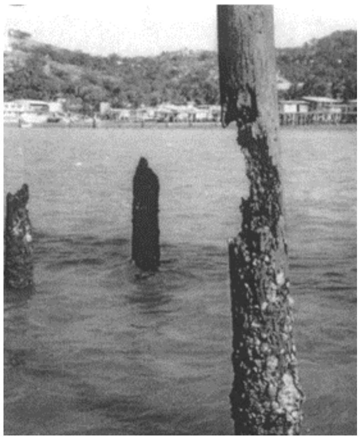
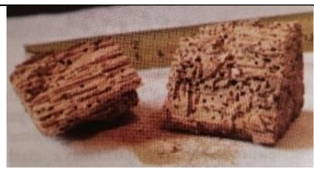


Figure 1. *(a) Flight holes created by insects at the wooden beam; (b) Port Moresby, Papua New Guinea: CCA-treated hoop pine pilings destroyed by infestation in the intertidal zone by Sphaeroma triste [11].*

Table 2. *Coleoptera and Isoptera (termite) type of insects' name, invasion type, appearance and example, table reinterpreted [8].*

	INSECT	FORM OF INVASION	APPEARANCE	EXAMPLE
COLEOPTERA SPECIES	**Powder Post Beetle**	They solely damage the solid parts of hardwood. As a result of the damage caused by them, a great gap is formed on these solid parts.	Moreover, they create flying holes of 1.6 mm and leave dirt resembling to flour.	 Damage from powder post beetles [12].
	Anobiid borers	They can attack all sorts of trees and are mostly seen on wet wooden elements. They are dangerous species as they are difficult to stop once their invasion begins.	Their flying holes reach as much as 2 mm in size, and their waste can be seen around these holes.	 Tunnels opened by Anobium punctatum [9]

	Cerambycid borers	They are extremely dangerous species present in certain geographies. They invade the solid wooden parts of softwood.	Their flying holes are generally not visible, but they may become visible once they reach 3-10 mm.	 Cerambycid borers damage [9]
ISOPTERA (TERMITE)	**Subterranean termite**	They emerge when wooden elements contact soil.	As they are active under the moist soil, they can invade the wood after the contact. They attack the inner parts and therefore their damages are not visible outside.	 Latewood layer appearance on the wooden element damaged by subterranean termites [9]
	Dampwood termite	They attack and convey the dampwood, leaving a piece of spoiled drywood behind.	They continue existing as long as the moisture stays.	 Dampwood termite damage [13]
	Drywood termite	They only attack drywood.	They may cause damage without the need for moisture. Tunnels can be found in every direction on the wooden surface.	 Drywood termite damage [9]

3.1.4. Marine Species

The damage caused by marine species on wooden elements has become visible since wood, especially wooden poles, were used on beaches. Although the spoilage of wooden poles can be mitigated using certain preservatives, the problem of spoilage still persists. The wooden element parts under the sea are mostly invaded by marine borers. More specifically, the wooden elements in the mild sea are severely damaged by these marine species [14]. A relevant study by Cragg [11] noted that wood-boring isopoda from the Limnoriidae family constitute a significant threat against the wooden elements in mild waters, while Sphaeromatidae threaten the wooden elements in tropical waters (Figure 1b). According to that study, the dimension of the damage caused by the aforenoted crustaceans and wood-boring crustaceans with double shells (shipworms and Martesia) depends on the environmental conditions. Contrary to shipworms, the attack of these crustaceans can be easily detected even in the early phases [11].

3.2. Distortions Arising from Atmospheric Impacts

Outdoor impacts are the leading atmospheric factors damaging wooden elements. The ultraviolet (UV) rays arising from the solar impact cause distortion in wooden elements. The UV impact of sunlight distort the lignin structure of wood, resulting in a whitened area on the wooden surface. Although this damage occurs in a slow manner, its impact may emerge only as color transformation on the surface after a certain time. Another impact may be observed due to the effect of dust-loaded wind which corrode the wooden surface. However, this corrosion can be particularly seen on the soft, young wooden parts. Rain, dew and other precipitation forms cause wooden elements to shrink and swell in time due to the repeating cycles of getting wet and dried. Moreover, the sizes of wooden elements change, which paves the way for the fungi spores to penetrate into the wooden element and cause structural damage [8].

In addition to the sunlight and precipitation factors, certain chemical may also damage wooden elements. The natural pH value of wood ranged between 2 and 5.5, suggesting natural resistance to weak acids. However, wooden elements are weak against strong acids and alkalis. Due to acidic impact, fibers in wood are ruptured and become visible [8]. In regard to the impact of basic substances on wood, Unger et al. [15] noted that basic substances cause wood to swell first and hemicelluloses and lignin to get separated later, depending on concentration and temperature. They claimed that the mechanical strength of wood significantly decreased due to the impact of basic substances lasting longer than 60 days and due to concentration and temperature. This impact also reduced the durability of the organisms causing biological damage on wooden elements. As a result of these impacts, wooden elements become fragile, meaning they lose their capability of responding to the approaching threats and create a loud sound of breaking [15].

Another atmospheric impact covers the effect of water and moisture. Presence of water and moisture plays a significant role in the distortion of wooden element. The contact between water and wood directly affects the strength and dimensional traits of wood. Moreover, coexistence of water and suitable temperature makes wooden elements a convenient place for certain organisms to survive [8]. The study by Erdin [9] reported in regard to the devastating effect of water that distortions were present on the surfaces of wooden elements extracted from sunken wrecks or the soil even in the oxygen-free environments, adding that these distortions were not in the inner parts of wooden elements. The external sections of the wooden elements extracted from the İstanbul Yenikapı wrecks suffered severe distortions due to the aquatic effect, and the internal part of the elements had a solid section with a solid core (Figure 2) [9].

Figure 2. *Cross sections of water-logged hardwood, Yenikapı Wrecks, İstanbul [9].*

The damage arising from another type of atmospheric impact is related to the thermal effect. The thermal damage seen the most in wooden elements arises from fire. Although the temperature of ignition depends on numerous factors, walls of wooden elements start to get distorted at 200ºC, resulting in methane and carbon monoxide. These gases require a temperature higher than 500ºC to ignite under normal conditions. However, in case of a fire, the ignition may occur above 250 ° C if radiation levels are high ([16]; as cited [10]). The wooden elements that have carbonized have a visible damage which does not resemble to brown-colored decomposition, which may arise from the fact that lignin is the last consumed component in a wooden element. Ridout [10] conducted a study and examined some wooden beams damaged by fire; according to that study, these wooden beams actually appeared mostly intact after the carbonized external layer was removed although these beams initially seemed irreversibly damaged. That study also reported the wooden joints were expected to be more damaged by fire and the joints would require more detailed investigation [10].

4. CONSERVATION TECHNIQUES IN WOODEN BUILDINGS

Various methods have been used to repair and reinforce a historical wooden building. Some of these methods are chemical and contain preservative fluids, and some are structural methods implemented through repairing and reinforcement. Reinprecht [7]. performed a study on conservation methods implemented on damaged wooden element with chemical fluids and noted that damaged wooden elements could be improved to a certain degree using chemical preservatives which would enhance the strength and general appearance of wooden element. It was also mentioned that these methods could be implemented utilizing natural or synthetic preservatives [7]. The structural methods implemented for repairing and reinforcement are generally performed by adding a new element to the wood and thus increasing its strength or removing the decayed parts of the wood and repairing with solid material (wood, metal etc.). The structural repairing and reinforcement method is conducted in two different manners, based on traditional carpentry techniques or modern reinforcement practices (FRP).

4.1. Chemical Conservation Techniques in Wooden Buildings

Repairing performed for a wooden object is generally conducted when the object is extremely damaged or facing the danger of extinction. This procedure is mostly performed when the wooden element is wet or water-logged. Additional interventions are required to reinforce the wooden objects that are structurally weakened on damp points by water and microorganisms. For that purpose, efforts are initially made to prevent the increase in biological organisms on wooden elements or to block the continuation of acid generation. Since the early days of the 19th century, conservation authorities have used various chemical substances on wooden elements and utilized different chemical enhancement methods. The first materials used to reinforce a damaged wooden element are the traditional natural objects including waxes, linseed oil, alum, sugars, melamine-formaldehyde resins, Paraloid B72 and poly (ethylene glycol) (PEG) (Table 3). With the developments in the current technology, various materials ranging from synthetic resins to inorganic materials, bio-based technologies and mixed composites as well as traditional reinforcement materials have been utilized [17]. (Table 3). The traditional and natural reinforcement materials are easily accessible, although certain disadvantages regarding these materials have emerged in time. The study by Christensen et al. reported that the repairing efforts conducted with traditional materials did not conserve the relevant object permanently and that being removable was a critical factor for the reinforcement agents applied on wooden elements [18]. Among the new generation reinforcement agents, biopolymers have significant effects in terms of conserving the fresh wood. The study by Walsh-Korb and Avérous [17]. suggested that biobased materials have become interesting due to their adaptation to wooden elements and being a renewable energy resource. Additionally, biopolymers as waste materials had an impact of reducing the cost. Furthermore, the dimensional stability of a wooden element reinforced with biopolymer was noted to display positive results particularly with keratin, but no clear impacts were seen on the mechanical stability [17].

In regard to the conservation efforts, selection of the method to be applied is as important as the characteristics of the reinforcement agent. More specifically, conservation of the objects such as a statue or table is generally performed through the methods of “brushing” or “injection”, while conservative reinforcement agents are applied on wooden elements. As this approach focuses on conserving a part of an object, a different technique may be implemented when the relevant object is to be conserved holistically ([19]; as cited [15]). In addition to these techniques, the impregnation method can be applied to the wooden element or object. This method is based on the principle of chemicals penetrating into the wooden element under atmospheric pressure or through vacuuming. Within the method generally implemented under atmospheric pressure, the wooden element is submerged into and kept in the relevant chemical solution. More specifically, satisfactory results can be achieved with the chemical solutions that are effective on the extremely damaged wooden elements and have quite low viscosity. Furthermore, the impregnation method performed through vacuuming on the relatively less damaged wooden elements is a convenient technique as it ensures the proper spread of chemical reinforcement agent on the wooden element. The capability of impregnating a part of or the entire wooden element within the conservation approach results in certain limitations in terms of practice. These wooden elements should possess certain traits such as acceptable sizes and portability. Accordingly, spraying chemicals on large wooden objects or elements is a convenient approach in terms of practice [15].

Table 3. *Properties of some consolidants from past to present.*

CONSOLIDANT		PROPERTIES
TRADITIONAL REINFORCERS (Unger et al., 2001).	Linseed oil	Warm linseed oil flows within the wooden element evenly, ensuring proper penetration. Even after 10 years, solidification within the wooden element is not quite possible for linseed oil. However, linseed oil does not strongly conserve wooden elements.
	Tung oil	Tung oil does not properly conserve wooden elements. The oil does not fully solidify under cold weather conditions. However, moisture prevents the oil from getting dries, and it may even leave stains on the surface. A brownish layer may emerge on the surface.
	Beeswax	Pure beeswax is effective against the minor damage (by small insects or fungi) on dry wood. Its reinforcing effect is stronger than resins. Wax enables easy processing and becomes more stable in time. It is water-repellent, allowing reversibility. A large amount of wax can be achieved utilizing the full impregnation method on the wood, but the reinforcing impact may still be low in this case.
	Carnauba Wax	It is better for reinforcing dry wood than the beeswax but its rate of penetration into the wood is worse. It may cause color change on the wooden surface.
	Paraffin	It does not properly conserve the dry wood since it is difficult for paraffin to penetrate into the wood. Moreover, distortions can be seen in the wooden element in hot paraffin. With the application of paraffin, the appearance of wooden surface may change significantly.
	Dammar (resin)	It becomes more stable on the wooden surface and bears a water-repelling trait. As the material itself is transparent, its application on the wooden element does not create disturbing looks. As the damage on the wooden elements that contacted with water increases, the conservative characteristic of the material improves.
	Shellac	Its conservative trait is more effective for the small dry woods. A wooden element to which Shellac is applied can be better against mechanical tensions, but the strengthening effect of Shellac is not significant. A wooden element treated with Shellac resists to water better in the short term, while becoming more fragile and harder at the same time.
	PEG	It offers a proper conservation even for large wooden elements. Color may change from dark brown to gray and black on the wooden surface following the procedure. If the aim is the sufficient penetration of PEG into the wood, the solution concentration in the impregnation tank or in the spray form should be applied slowly in gradually increasing amounts. If used under room temperature, PEG solutions will be made convenient by the organisms causing biological damage on the wooden elements. Therefore, if PEG will be employed under room temperature, biocides should be added in the solution to fight against these organisms.
	Sucrose	It creates a natural appearance on the wood after the application phase. It acts as a water-repellent under weather conditions where the humidity rate is low. A wooden element treated with sucrose can be easily removed from the wooden surface when needed. A wooden element treated with sucrose may be utilized again through traditional methods. Sucrose is not medically harmful.
	Phenol-Formaldehyde Resins (PF)	PF resins do not properly penetrate into the dry wood and result in color change on the wooden surface after the application. Therefore, they are not preferred for repairing the valuable cultural assets.

	Urea-Formaldehyde Resins (UF)	It is quite difficult to remove the UF resins from the dry wood surface after application. Therefore, these resins are not suitable for use with valuable cultural assets. The resin creates a dark color on the wooden surface, and it may cause cracks while making the wooden element fragile.
	Melamine-Formaldehyde Resins (MF)	These resins ensure dimensional stability of the drywood; they even help increase the elastomechanical traits of the wooden element and ensure a proper resistance to fungi when used through the impregnation method. However, it is not easy to remove them from the surface of the wooden element and therefore not suitable for use with the valuable cultural assets. MF resins are more resistant to water than UF resins, but their resistance becomes quite poor under outdoor conditions.
NEW GENERATION REINFORCEMENT AGENTS (Christensen et al., 2012)	Nanoparticles	Their capability to spread over and penetrate into the wooden element may be low, and they may be too alkaline for the wooden element. Furthermore, they cannot neutralize the acidic substances. They may display an intensive resistance when applied on wooden element. Their stabilizing impact has yet to be known.
	Nanotubes	They are quite compatible with the wooden material. They are resistant to solvents. Penetration into wooden element is difficult, and the rate of penetration is poor. Following the application, the surface may become blackish.
	Aliphatic polymer	It is a flexible material. When applied in situ, its penetration into the wooden element is satisfactory. However, its trait of stabilizing the wooden element is not satisfactory. Following the application, removal from the wooden surface is not easy.
	Bio mineralization	This material has yet to be tested fully, and it may be incompatible with the wooden element. Following the application, re-repairing efforts are possible on the wooden surface if needed.
	Biomimetic	This material is compatible with the wooden element. It is generally nontoxic. Water can be utilized as an ideal solvent. Additional reinforcement may be necessary on the wooden surface.

A clear example of impregnation procedure performed on historical traditional wooden structures can be seen on Kutluca Mosque in Perşembe, Ordu, Türkiye. Having undergone a restoration process in 2015, this mosque consisted of wooden elements that were impregnated through immersion (Figure 3). Relevant cases where wooden elements were processed through impregnation can be seen in the repairing activities performed with chemical preservatives in Türkiye since the impregnation method is practical and easy to use. Therefore, it is safe to state that practicality and ease of use is a major criterion considered while selecting a wooden structure conservation method.

Figure 3. *The procedure of impregnation done on new wooden elements to be used for restoration[20].*

4.2. Structural Conservation Techniques in Wooden Buildings

The structural repairing efforts for a wooden element becomes a necessity due to the damage caused on wooden elements by fungi, insects or atmospheric effects. Selection of this method for repairing a wooden element is affected by certain conditions such as aesthetic dimension, practicability, practicality and costs. However, conservation of authentic elements as much as possible is the primary goal within the efforts regarding a historical building.

The material and method utilized to conserve historical buildings should be authentic and recyclable and require minimum number of interventions for that purpose. Use of authentic methods and material solely (e.g., use of a very rare wooden element in a building) will reflect as extra cost to a building. In regard to the efforts of repairing wooden buildings, Wheeler and Hutchinson [21] suggested using methods that would allow recycling such as utilizing metal binding substances. However, they also noted that certain deformations might occur due to moisture [21].

Repairing of wooden elements can be performed through various techniques and material based on practicality. The practical repairing and reinforcement methods can be classified under the following topics: complete replacement (removal), partial replacement, addition of elements (member augmentation), prosthesisation, repair of cracks, repair and strengthening of connections, strengthening of sections, post-tensioning and stiffening to in plane actions. Some of these methods are used frequently in the present day, while some are not utilized as much due to insufficient material and methods.

4.2.1. Complete replacement

The replacement method is one of the direct techniques that can be utilized on the damaged wooden elements. Removal of the damaged part on a wooden roof element affected by biological organisms such as termites and replacement of this part with an evenly-cut wooden element is among the efforts made in terms of complete replacement [22]. However, the damage can be terminated when complete replacement is preferred in place of partial replacement. Newman [22] noted in regard to the replacement efforts for wooden buildings that this method was not economical for minor damages on large wooden beams and columns [22].

One of the complete replacement efforts performed on historical traditional wooden elements can be seen on Selimiye Mansion which is present in Ordu and still being restored now. The load-bearing capacity of authentic wooden elements was reduced due to the large amount of decay on the wooden elements of the roof which, therefore, was repaired with new wooden parts (Figure 4). Complete replacement was also performed on the load-bearing wooden studs present outside the structure. Moreover, decaying studs were replaced with the new wooden ones. The wooden elements that had a physical contact with the ground in their original form no longer touched the surface since a metal plate was placed between the rock on the ground and the wooden pieces. Therefore, repairing was conducted by fixing the wooden elements to the metal plates (Figure 5).

Figure 4. *Complete replacement on the historical wooden roof that is still being restored [23].*

Figure 5. *Complete replacement on the historical wooden stud; from left to right: fixing metal plates to the rock, fixing new wooden studs to the metal plate, view of wooden studs from the frontal facade [23].*

4.2.2. Partial replacement

A certain part of a wooden element may be damaged due to biological attacks or the bearing strength decreasing in time. In these cases, only the damaged part is removed and replaced with a part of the same kind [22]. In the partial replacement method, authentic parts are partially lost, which is one of the negative aspects of this method in terms of conservation. One of the negative aspects of this method is the problem of how the wooden piece replacing the authentic part will adapt to the entire authentic wooden element and how it will transfer its load. Partial part replacements are performed in accordance with the structural loads on the element, and relevant connections are ensured (Figure 6 (A) and (B)) [24].

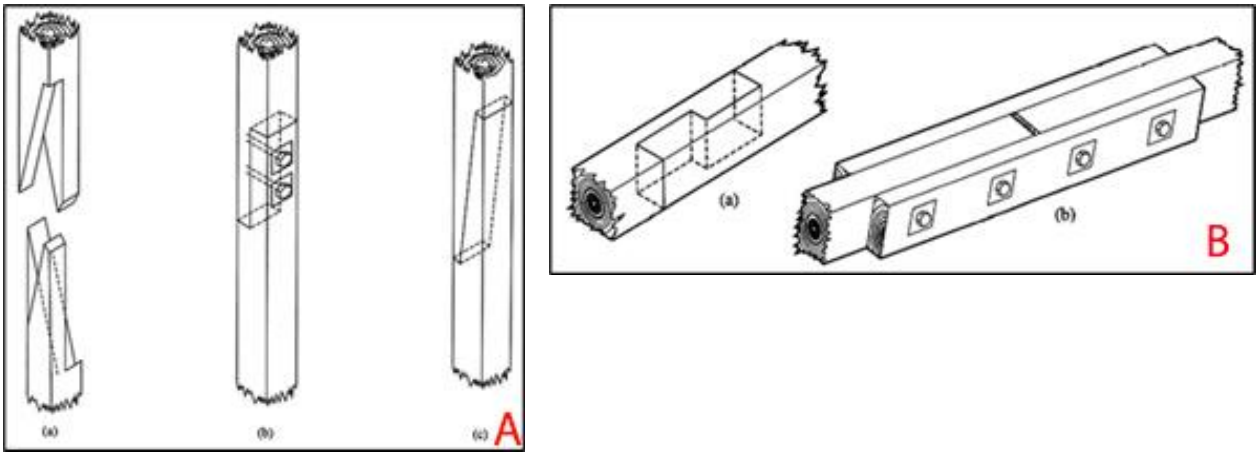


Figure 6. *(A) Splices for replacement compression timbers: (a) 'scissor-scarf'; (b) simple, bolted scarf; (c) 'self-locking scarf [24].*
(B) Splices for replacement timbers in tension or bending: (a) 'tabled scarf joint'; (b) bolted 'fishplate' joint [24].

One of the partial replacement procedures performed on historical traditional wooden structures can be seen in the restoration efforts made for the historical wooden buildings in Zeytinlik Neighborhood of Giresun. The decaying wooden elements in these structures were removed and replaced with the new wooden elements to conserve the authentic junction details (Figure 7). Accordingly, it is safe to state that wooden structure conservation procedure is an essential method to ensure the authentic wooden sections and junctions are protected and maintained.

Figure 7. *Partial replacement in the historical and traditional wooden carcass wall system [25]*

4.2.3. Addition of elements (member augmentation)

The wooden member augmentation method is based on the principle of increasing a wooden element's load bearing capacity or strengthening it or adding the relevant elements for that purpose. The added elements are generally wooden or steel, connected to the authentic wooden element with bolts. The most commonly used techniques of the method are splicing and scabbing. Although the difference between two methods is quite minor, the splicing method is generally applied on the areas arising from rupturing, separation or other faults on the load transfer section (Figure 8) ([26], as cited in [27]).

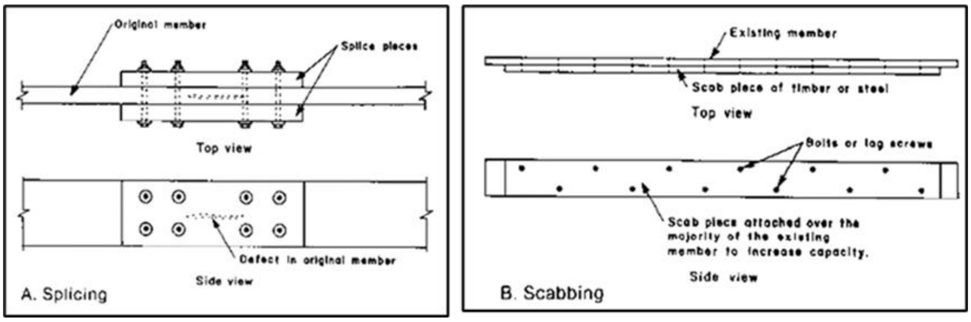


Figure 8. *Splicing and scabbing methods of member augmentation [27].*

4.2.4. Prosthesisation

Prosthesisation is the name of the technique where a certain part of an element is cut and replaced with a new element ensuring the structural sustainability while utilizing the connection method. From a general perspective, it is applied for the damages arising from biological attacks on areas close to the supports of floor columns and roof frames, and on the ends of elements. The damaged part that is removed can be replaced with a wooden element and the connections between two elements can be ensured using steel FRPs and epoxies. In the event that the prosthesisation method is applied through the traditional connections, the relevant connection elements or all wooden connection elements can be steel bolts, studs and straps [28]. (Figure 9 and Figure 10). Descamps et al. [29] conducted a study and reported that the prosthesisation-repairing effort made with wooden material is a proper solution, enabling the formation of a new joint using the geometry and material of the previous element. However, they also noted that the procedure of cutting the element is complicated and that the full pre-fabrication is challenging and requires highly-qualified labor. According to them, this procedure is widely used on columns, roof beams and ends of beams with the glued rods in historical buildings (Figure 11). They also added that the epoxies have many advantages in the prosthesisation conducted with metal rods [29].

Figure 9. *Prosthesis application with steel screws [30]*

Figure 10. *Prosthesis application with traditional steel straps [30].*

Figure 11. *The decayed beam end is removed, and the prefabricated softwood replacement beam end is nearly in position. Reinforcement bars are placed in holes drilled in the existing oak [21].*

The prosthesisation procedures performed with FRP elements are classified as modern reinforcement techniques in the literature. FRP rods are mostly used in the prosthesisation of beam ends (Figure 12) [31].

Figure 12. *The beam end prosthesisation effort made with FRP rods are performed in the following order: inclined cut of decayed end, linking grooves and insertion of a final wedge [31]*

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4.2.5. Repair of cracks

The crack damage present on wooden element can arise from shrinkage, overloading and poor designing decisions. These damages may result in longitudinal separations and fissures on the wooden building element. The longitudinal separation damage can be prevented using bolted steel and wooden parts (Figure 13(A)) [22].

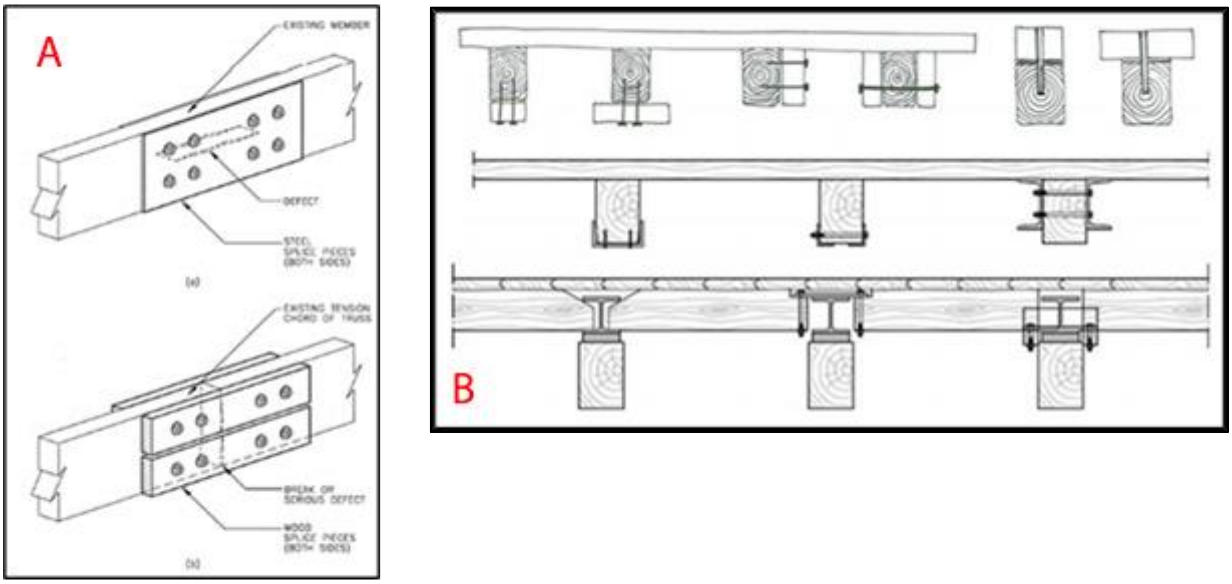


Figure 13. *(A) Reinforcing damaged members by adding side pieces: (a) using a steel splice plate to reinforce a beam with a serious defect; (b) using wood side pieces to repair the broken bottom chord of a truss [22]. (B) Examples of reinforcement techniques of timber floor beams [30].*

4.2.6. Repair and strengthening of joints

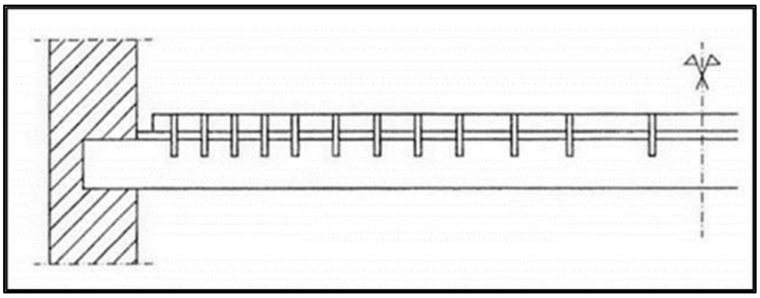
Problems generally occur in the joints on the wooden roof truss while reinforcing the wooden joints. The study by Parisi and Piazza *[32]* highlighted that repairing activities performed on the joints of wooden roof trusses still follow an intuitive path. According to that study, carpentry joints operating and transferring force based on the principle of compaction and friction are reinforced with metal elements to prevent separation and improve the mechanical characteristics, except for certain cases *[32]*.

4.2.7. Strengthening of sections

The technique is generally performed when the load bearing capacity of the floor is to be increased or the vertical diversion rate of the beam is high, while adding additional elements to the wooden beam element to ensure reinforcement (Figure 13 (B)). The elements nailed or screwed on the main beams consist of steel plates, wooden elements or wood-based panels [30].

4.2.8. Strengthening of timber floors

Repairing and reinforcement activities may be performed to strengthen the wooden floors, to improve the flexural capacity and rigidity (vertical static load) or to enhance the structural reaction against the in-plane seismic loads (horizontal dynamic load) (Figure 14(A) and (B)) ([33], [34]; as cited [35].The reinforcing technique which is named as “Timber flange connected by dowels to main beams” consists of placing a new plank connected by means of dowels above each beam of the existing frame.



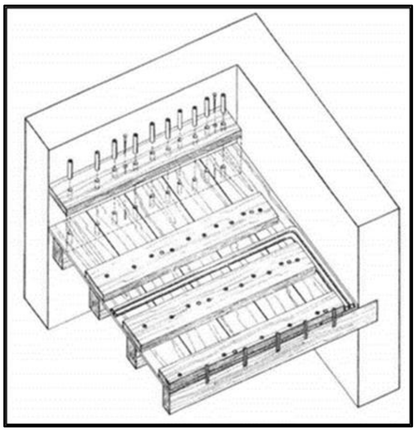


***Figure 14. (A)** Longitudinal cross section of the proposed intervention[35]. **(B)** Axonometric view of the proposed intervention [35].*

5. EVALUATION

The traditional historical wooden buildings have a unique value thanks to their authentic connection details, methods, and materials, as well as the technology and carpentry skills of the relevant eras. Wooden elements get distorted and spoiled in time due to decreasing strength against external weather conditions and certain biological organisms. These issues are generally caused by fungi, bacteria, or insects as suitable conditions such as humidity and temperature emerge on the wooden element. The damage caused by these organisms generally results in physical and chemical distortions in the internal and external structure of the wooden element. Unfortunately, the damaged organisms result in irreversible issues on the relevant parts of wooden elements. The damages arising from atmospheric effects are smaller than those caused by biological organisms. Atmospheric damages generally affect the physical traits of wooden elements (causing swelling, shrinkage, cracks, etc.). U.V. rays, among these factors, have been noted to cause certain distortions in the chemical structure of wooden elements. Regardless of the reason, materials of wooden elements may get distorted, and relevant elements and authentic details may get lost if regular maintenance activities are not performed.

Accordingly, the repairing and reinforcement efforts regarding a traditional historical wooden building should be performed by the experts in this discipline. Before the intervention to the damage in a building, experts should determine which factor caused the damage. Moreover, while considering the repairing as mentioned earlier and reinforcement methods, making decisions based on the location of the damage on the wooden element as well as relevant dimensions, practicability, cost, and aesthetic values will be a convenient approach. While making such a decision, the architectural value of the relevant element should be considered as the primary factor. Accordingly, the interventions to be made will avoid the approaches that will reduce the aesthetic and architectural value of the element.

In the following steps, chemical or structural repairing methods can be applied, considering the type, dimension, and location of the damage. Moreover, chemical repairing activities can be performed using the traditional agents or synthetic, inorganic, bio based, or complicated composite reinforcement agents obtained with advanced technology. Traditional reinforcement agents are mainly used and experienced in repairing wooden elements, but they could be stronger in long-term conservation.

With the polymer technology of the present day, various reinforcement agents can be applied to wooden elements. However, most of these reinforcement agents cannot sufficiently stabilize the material and penetrate it or cannot stay stabilized without releasing toxic fumes. Alum salt, a traditional reinforcement agent [KAl (SO4)2·12H2O], cannot penetrate properly and creates an acidic layer on the wooden element before fading away. Moreover, Poly [polyoxy ethylene, POE or Polyethylene glycol (PEG)], which is one of the most used traditional reinforcement agents, loses its structure in time and no longer conserves the wooden element. As another traditional reinforcement agent, melamine-formaldehyde (Kauramin) is preferred in modern applications. However, melamine-formaldehyde is a proper stabilizing agent for wooden elements, and it can turn wooden elements into plastic blocks by filling the gaps in them [18].

Additionally, the inorganic reinforcement agents applied recently are preferred more as they penetrate wooden elements adequately and allow for easy application. The bio based reinforcement agents, which are other recent developments, are more suitable to the structure of wooden elements as they are produced with natural materials (wood, bone etc.), and they are environmentally significant owing to being recyclable. The structural repairing efforts are preferred to chemical repairing for more extensive and more severe damages. In terms of structural repair, either traditional or modern reinforcement methods can be selected.

Regarding the original details within historical buildings, traditional methods will be suitable for conserving the relevant details. Similarly, despite the priority being granted to the traditional methods in the Venice Charter, modern methods are noted to be used in places where more than traditional ones are needed [36]. Although reinforcement is performed with traditional methods, the wooden material will not carry the characteristics of the relevant era, and the transition details created by the carpenters of the era will not be reflected by the artisans of the present time, which emerges as an undesired situation in the efforts of repairing traditional wooden buildings.

Compared to the traditional reinforcement methods, repairing activities performed with F.R.P. methods will be more suitable for buildings with less architectural value. In addition, avoiding using F.R.P. in cases where a building has authentic connection details will be convenient. The repairing efforts made with F.R.P. will result in extra costs for the historic building. However, compared to the traditional reinforcement method, repairing procedures performed with F.R.P. can be undertaken by anybody with the know-how. Furthermore, carpenters, who are few, are needed when reinforcement is conducted with the traditional method.

6. CONCLUSION

The historical and traditional wooden buildings hold a significant place among the other buildings thanks to their authentic connection and transition methods as well as their architectural styles. Conservation of these buildings is a significant topic in terms of passing down the traditional architectural style to the future generations. Every civilization and community have made certain interventions to the buildings within their own borders while utilizing certain conservation approaches. These interventions contain the use of different methods and materials specific to every civilization. The structure and traits of wooden elements were mentioned first to understand different intervention methods and approaches seen on historical and traditional wooden elements. Moreover, the distortions and spoilage seen on wooden materials were investigated and classified. Then, chemical and structural repairing-reinforcement methods that were employed on the historical wooden buildings and reached the present day were mentioned. With recent developments seen in conservation technologies, chemical repairing efforts that started with traditional reinforcement agents (linseed oils, tung oils, bees wax, colophony etc.) have been made using various materials ranging from synthetic resins to inorganic materials, bio based materials and mixed composite reinforcing agents. Although traditional reinforcement agents have been used for numerous times in relevant procedures, they are poor in terms of penetrating into the wooden element as well as stabilizing and conserving the wood for a long time, compared to the recent reinforcement agents which perform better in this regard. Following the examination of repairing practices performed for the historical traditional wooden buildings in Türkiye, it was observed that traditional chemical preservatives were mostly preferred, which was a practice itself done by impregnating wooden elements through immersion. Accordingly, it is safe to state that methods which are easy to implement, practical and economical were utilized more in conservation procedures.

Structural repairing and reinforcement methods consists of the techniques based on mechanical repairing. These techniques are used in restoration efforts as traditional or modern methods. Some of the traditional methods are not preferred in modern times, but they have been frequently preferred in the practices based on modern reinforcement procedures. Both techniques can be utilized in wooden building repairing efforts. However, the practical, aesthetic and economic dimensions of the techniques may be the determinant factors in selecting the technique to be implemented. The repairing efforts made with FRP elements result in a great cost for the property owner. However, the fact that FRP method can be practically performed by the people who know how to utilize the FRP material and without the need for qualified traditional carpenters is among the advantages of this method. Furthermore, the FRP method can achieve high values in terms of mechanical strength compared to the repairing made with traditional techniques. The traditional repairing methods offer a conservation approach passed down to the following generations with the authentic constructional values as well as traditional materials and techniques since the date of Venice Charter [36]. The architectural aesthetic problems seen in FRP repairing efforts are not experienced. The traditional techniques are not as practical as the FRP as they require carpenters or craftsman.

In conclusion, the interventions to be made to the historical wooden buildings should focus on the architectural and aesthetic value of the building first and employ the methods that will ensure the least amount of loss in the authentic materials. These efforts should be made considering the economical and practical aspects, and relevant experts should perform conservation and repairing activities.

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