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Application of Paulownia wood in the structural reinforcement and geometric restoration of deteriorated wooden panels in cultural heritage artifacts

SUMMARY

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CONTENTS

INTRODUCTIONS

This research aims to address the field of restoration of wooden art objects and contribute to finding alternative solutions for choosing a wood species with properties and qualities similar to those of the constituent wood used in cultural heritage assets, but which have suffered severe damage and require solid wood fillings for destroyed/lost parts (fragments) in order to save an art object.

The field of conservation of cultural heritage, of works of art with wooden supports, differs from other related activities (such as crafts) in that the main purpose of conservation is to preserve cultural heritage, as opposed to creating new objects or maintaining and reconditioning them in a functional sense. Research into the structure of the artwork, the wooden support, is fundamental to the training of a conservator or restorer, through understanding the processes that influence the material. This is essential for the analysis, based on the cause-and-effect principle, of the methods and techniques used or to be applied in the intervention process. Any intervention, regardless of its apparent scope, is not limited to the application of a standardized scientific methodology, but necessarily involves mastering the fundamental techniques required to choose the most appropriate restoration solutions.

The multidisciplinary nature of the sciences can lead to investigations and research that provide arguments regarding the age of the cultural asset, the constituent or subsequently used materials, infestations or biological degradation, and the establishment of the nature and cause that produced them. Perhaps the most important aspect is that all this information forms the basis for the development of an effective conservation project. The goal is to limit or even stop progressive degradation by understanding the behavior of materials over time. In this context, we believe that extending research to the field of wood engineering can generate valuable opportunities for a better understanding of wood, the material that supports works of art, which is affected by various factors of degradation. At the same time, this direction can lead to the identification of alternative technical and material solutions designed to support conservation interventions, thus contributing to the preservation of cultural heritage assets.

CHAPTER 1. CURRENT STATE OF RESEARCH ON THE USE OF PAULOWNIA WOOD (Paulownia spp.) FOR THE REINFORCEMENT OF DAMAGED PANELS OF CULTURAL HERITAGE OBJECTS

1.1. General characteristics and properties of wood that impact the quality of finished products in artistic, and religious applications

1.1.1. Wood durability—classification and evaluation of biotic and abiotic factors that cause degradation

Depending on its anatomical structure and chemical composition, wood of different species has different degrees of durability. High-density wood and wood from the heartwood area will have increased durability to biotic and abiotic factors compared to wood from the sapwood area or wood with lower density (Filipovici, 1965).

Prună (2009) highlights the fact that wood durability can be defined in various ways, emphasising that it represents the ability of wood to resist degradation caused by physical, chemical and biological factors. In this sense, the durability of a wood species against the action of various xylophagous organisms is assessed based on the methodologies set out in European standards SR EN 350-1 and SR EN 350-2, and its classification is made in accordance with the risk classes established by standards SR EN 335-1 and SR EN 335-2, depending on the level of natural durability. Thus, there are 5 levels of durability in relation to wood-destroying fungi (where 5 represents the class with no durability and 1 the class with very high durability) and 2 levels of durability (durable or non-durable) for wood-destroying beetles.

Randall (2000) describes wood pests, fungi, and wood-boring insects, as well as their control and eradication. The paper structures, from an entomological point of view, the diversity of wood-destroying insects and the type of wood that is attacked: both seasoned and conditioned wood, as well as freshly cut wood. Very often, wood is infested (even during growth) before being used in structures or as a finished product (furniture, decorative objects, etc.), a point also noted by Watkinson and Eastwood (2012).

Noldt (2009) presents a series of wood-destroying insects from Central Europe. The author mentions that infestation with xylophagous insects such as *Hylotrupes bajulus, Xestobium rufovillosum* (De Geer), *Anobium punctatum* (De Geer) and the *anobiidae* species *Coelostethus pertinax* can seriously threaten the stability of the pieces, and the infestation can last for decades. In the case of the furniture beetle (*Anobium punctatum*), the wood ends up in a pulverized state. Noldt and Noldt (2013) also develop observations on the assessment and identification of the type of damage and the insect that caused it, based on the emergence hole, the wood dust collected, its shape, volume, and density. Excrement pellets, with different shapes and compositions, do not always mean only milled wood, but most often contain fine sand particles, excrement, or fungal spores.
Ali (2017) explains the rapid spread of infestation and damage caused by insects in historical and archaeological wood, as well as the severity and difficulty of detecting it in its early stages. The

appearance of holes, powder, or excrement cannot be observed as soon as the insects have settled in, and Mustață et al. (2013) argue that, after termites, anobiids are among the most harmful insects. They attack wood in buildings, furniture, icons, etc. They prefer old wood, as it is already infested with bacteria or fungi, which "process the wood," making it easier (for insects) to break down the cellulose fibers.

Goodell et al. (2003) highlight biotic factors as those that degrade wood, causing damage and leading to billions of dollars being spent on the preservation, repair, and replacement of wooden structures each year. Although wood degradation results in a huge waste of resources, without wood-degrading organisms, our world would be buried under cellulose and lignin debris, as these organisms are among the few that efficiently recycle lignocellulosic carbon.

With regard to the assessment of damage to movable heritage objects with wooden supports, Ionescu (2020) classifies the state of conservation of objects into five levels: optimal-minimal-medium-extensive-exitus and develops four methods for assessing this damage: the comparative density method, excessive wood porosity, the volumetric determination method, and the HB and HM hardness methods. Determination by the hardness method is extremely suggestive; an example can be seen in Table 1. Also, based on these classifications and methods, the effectiveness of consolidation treatments can be evaluated (Ionescu et al. 2021, Juliana et al. 2021).

Table 1. Brinell and Mark hardness on the three types of samples: new and healthy wood, untreated degraded wood, and wood with consolidation treatment (after Ionescu et al. 2019)

Sample	No.	HB, N/mm^2	HM, N/mm^2	Degree of damage %	
				in HB	in HM
TD4, Healthy wood	1	18.36	19.07	-	-
	2	17.35	17.95	-	-
	3	15.11	13.43	-	-
	4	17.45	17.00	-	-
	5	16.95	16.62	-	-
	Average	17.20	16.81	-	-
	STANDARD DEVIATION	1.07	1.89		
	VARIATION COEFFICIENT	0.06	0.11		
TD9, Degraded lime wood	1	4.14	2.91	77.4	84.7
	2	4.56	3.85	73.7	78.5
	3	5.30	7.51	64.9	44.0
	4	4.46	4.85	74.4	71.4
	5	4.76	4.65	71.9	72.0
	Average	4.66	4.75	72.9	71.7
	STANDARD DEVIATION	0.38	1.54	4.18	13.93
	VARIATION COEFFICIENT	0.08	0.32	0.06	0.19
TD10, Degraded lime wood treated with Paraloid B72	1	11.52	10.53	37.2	44.7
	2	7.72	5.35	55.5	70.1
	3	9.75	8.74	35.4	34.9
	4	9.86	8.35	43.4	50.8
	5	9.46	8.05	52.5	51.5

reinforcement	Average	9.66	8.20	43.8	51.2
	STANDARD DEVIATION	1.21	1.67	8.02	11.51
	VARIATION COEFFICIENT	0.13	0.20	0.18	0.22

Severe damage to the wooden support can be observed both from the data on hardness determined according to Table 1 and in Figs. 1 and 2. The wood reaches an advanced stage of degradation, the wood substance reaching a pulverulent state, and the remaining anatomical and structural fragments no longer provide mechanical resistance. Under these conditions, the stability of the objects is endangered by collapse under their own weight and permanent loss.

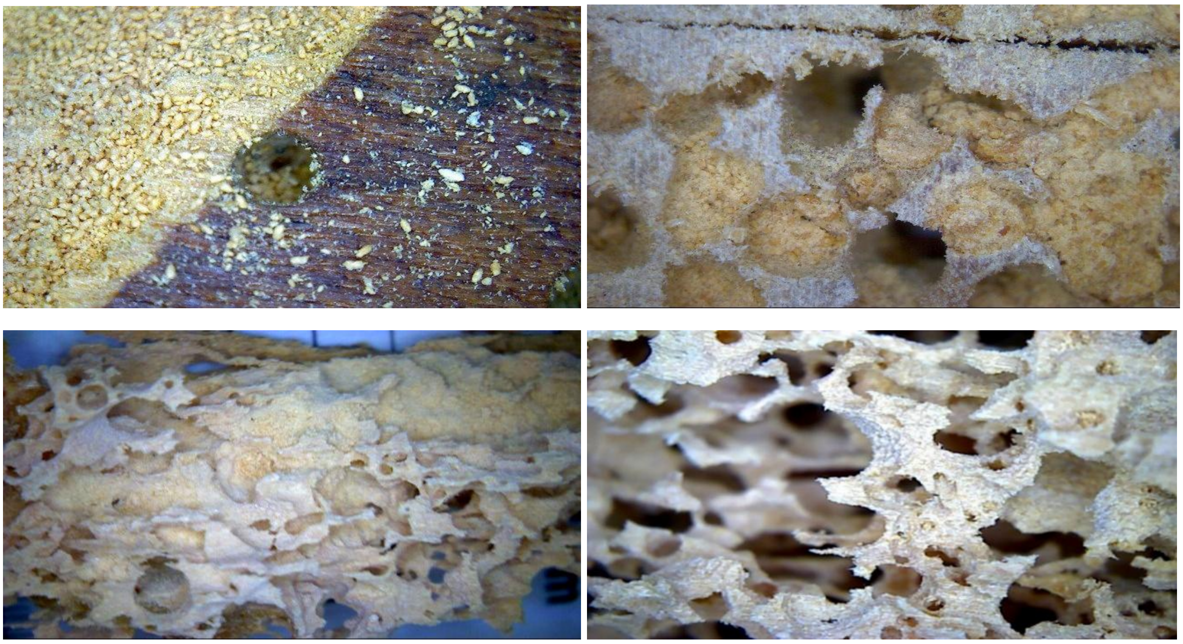


Fig. 1. Structure of lime wood damaged by wood-boring insects: sawdust resulting from chewing, tunnels, and tunnels with compacted sawdust (*original images from the Restoration Laboratory*)

Fig. 2. Severe damage to the wooden support resulting from decimation by wood-eating insects (*original images from the Restoration Laboratory*)

1.1.2. The physical and mechanical properties of wood that are relevant to the research topic. Improvements achieved through enhancement treatments

The diversity of wood varies considerably between different species, including within the same genus and family. This variation can even be observed within the same wood species, influenced by factors such as soil type, climatic conditions, and geographical area. In order to obtain high-quality finished or semi-finished products, it is crucial to use a homogeneous wood species (WoodDataBase, Lark-Horovitz 1936), as differences in density, structure, and other characteristics can lead to major defects or reduced product quality.

The physical and mechanical properties of wood are fundamentally determined by the species of tree from which it comes and the orientation of the cutting plane in relation to its internal structure. Wood is a versatile material, frequently used as a raw material in the manufacture of furniture and decorative objects.
Gezici-Koc et al. (2016) describe wood as a "hygroscopic and porous material in which the distribution and interaction of water plays a crucial role in the processing and durability of wood. It undergoes fluctuations in moisture content due to water absorption and desorption." Understanding the water absorption and desorption characteristics of wood is of practical importance because the mechanical properties or dimensional stability of wood are influenced by moisture content.
Wood moisture influences both physical and mechanical properties. Swelling and shrinkage are the results of water absorption/desorption, and the consequences are reflected in dimensional instability along all three structural axes, as wood is an anisotropic material (Avramidis, 2018).

According to the literature, the resistance of wood to mechanical stress is determined by a number of structural and physical-mechanical factors. These factors include: the dimensions of the test specimens (length and surface area), the speed and amplitude of load application, the physical properties of the material (density, moisture content, temperature), chemical composition, and the anatomical characteristics of the wood (width of annual rings, proportion of earlywood and latewood). The strength of wood also depends to a large extent on its anatomical structure.

Table 2 shows the main physical and mechanical properties of the wood species lime (*Tillia spp*.), commonly found in heritage buildings, balsa (*Ochroma pyramidale*) and Paulownia (*Paulownia spp*.), as reported in the literature. These three species were selected because they are the subject of this research. Balsa wood is used as a benchmark in current research for applications in the field of restoration (used as a filler material for heavily damaged objects), while for Paulownia and linden wood, additional research will be conducted in the same field (restoration), as presented in the following chapters.

Table 2. Comparison of physical and mechanical properties between wood species: lime, balsa, Paulownia, found in relevant literature (wooddatabase; Ionescu, 2020; Koman et al. 2017; Kusiak, 2020; Avram et al. 2023)

Nr. crt.	Physical and mechanical characteristics		Wood species		
			Lime	Balsa	Paulownia
1	Growth area		Europe	America	Asia And North America
3	Density	0%	420	120	250

4	[kg/m^3]	12%	535	150	280
5	MOR [MPa]		85	19.7	37.9
6	MOE [GPa]		11.72	3.72	4.39
7	Compression resistance in [MPa]		44.9	11.7	20.8
	Hardness	Janka (N)	3100	300	1330
		Brinell (N/mm^2)	20.24	1.80	9.13
	Swelling [%]	Radial	4.44	-	2.17
		Tangențial	7.94	-	3.73
		Volumetric	13.39	-	6.28
		Raport T/R	1.78	-	1.71
8		Radial	5.01	2.35	2.49
9	Shrinkage [%]	Tangențial	7.48	6.18	3.94
10		Volumetric	12.59	8.62	6.5
11		Raport T/R	1.5	2.6	1.6

Even though the three species have different distribution areas (lime in Europe, balsa in America, and Paulownia in Asia and North America), they are found worldwide and are used in various applications. Linden is considered a uniform species with high density, while balsa has a density 71.5% lower than lime wood and Paulownia has a density 47.6% lower than lime wood (for 12% moisture content). Thus, in terms of density, Paulownia is closer to linden than to balsa. In conclusion, it is essential to understand and evaluate the homogeneity of wood in various applications and to choose the right species according to the physical and mechanical properties and specific requirements of each application.

In the field of restoration, the improvement or consolidation treatments used are those applied by impregnation or film coating with natural or synthetic resins (Wang and Schniewind 1985, Schniewind and Eastman 1992, 1994; Schniewind and Kronkright 1984; Mańkowski et al. 2015). These are applied to old wood (often in various stages of degradation) and are subordinate to the heritage object. Such treatments are not intended to improve the performance of the wood, but to limit progressive deterioration and extend the "lifespan" (of the wooden support) that sustains an artistic creation of cultural identity.

Ionescu (2020) states that dimensional stabilization should be conceptualized as a set of interventions aimed at improving the instability of shape and dimensions, generated by variations in humidity, structural defects, etc., through the application of specific treatments. In this context, it becomes essential to have a deep understanding of the physical and mechanical properties of wood, as well as its behavior at different stages of degradation. In his study, the author set out to obtain information and formulate answers regarding the influence of the microclimate on heritage objects, which were monitored over a specific period of time.

Froidevaux (2012) highlights the need for a deep understanding of the factors that cause damage to cultural heritage assets, emphasizing that "understanding the current state of panel paintings and predicting their behavior in various climatic conditions is essential for conservation and restoration."

The author analyzes the mechanical, physical, and chemical processes associated with the natural aging of wood and paint layers, emphasizing that although the wooden support is less affected by moderate climatic fluctuations, the primer and paint layers are much more vulnerable and prone to cracking. This phenomenon can lead to the irreparable degradation of the artwork.

1.2. Procedures for interventions on the restoration of cultural heritage objects with wooden supports, taking into account heritage legislation and conservation principles

Restoration is defined by Brandi (1996) as a series of interventions aimed at restoring the functionality of an object belonging to human creation. Any intervention must be based on scientific reasoning. **Only the material of the work of art is restored**. Ensuring the stability of the material guarantees the unique potential of the work without producing a historical and artistic forgery. According to Brandi (1996), the life of a work of art must be extended and, above all, it must be allowed to return to its place of origin or be given a new function or destination.
Article 12 of the Venice Charter (1977) also emphasizes that elements intended to replace lost (missing) parts must blend harmoniously into the whole. They must also retain their distinct character from the original elements, so that the restoration process does not lead to the falsification of the art and history document.

The use of other materials/wood species to replace missing, severely damaged, or lost elements is also presented by Abdallah et al. (2016) when, following the discovery of an ancient Egyptian offering table made of cypress wood, they used beech wood and balsa wood dowels to restore the new elements during the restoration process.

Săvescu and Săvescu (2010) argue that the development of a biological attack has the effect of reducing the weight of the wood mass, noting that "the wooden support is oversized for the weight of the paint layer it supports." Furthermore, biological agents attack the wood so severely that they break the resistance structures, that it endangers the existence of the religious object.

In agreement with Săvescu 2010, Ionescu (2014, 2016, 2020) argues that biological infestation, especially xylophagous attack, causes severe damage. The properties of the wood (physical, chemical, and mechanical) are so affected that the cultural asset reaches the point of collapse. The author proposes the consolidation of severely damaged heritage assets by creating prostheses with balsa wood. The authors (Săvescu 2010, Ionescu, 2014, 2016, 2020) argue for this decision in these extreme cases, replacing the original filling material, lime wood (frequently used in the manufacture of polychrome panels - icons, iconostases, paintings on wood from the Romanian cultural heritage), with balsa wood because it has low density (160 ÷ 180 kg/m3) and good dimensional stability.
We encountered such an example of damage to objects from the national heritage (Fig. 3. a., b.) in our current work at the restoration laboratory. In the fragments of the 17th-century iconostasis that belonged to the Vizantea Monastery in Vrancea, the damage to the wood was so severe that, even with the most careful handling, the panel presented a high risk of collapsing under its own weight (Fig. 3. a., b., c., d., e.). The damage was so severe that even identifying the wood species used was difficult to examine because the wood had a powdery appearance caused by xylophagous insects.

Fig. 3. a, b, c, d, e. Severe deterioration of the wooden support. a. Painted side; b. Back of the panel; c., d., e. Details of the deterioration in the wood core (original images from the Restoration Laboratory)

The main objective of consolidation treatments, from a conservation perspective, is to protect the original substance. However, the choice of a consolidation method depends primarily on the state of conservation of the object and whether its stability is endangered. Radical consolidation is necessary when the wood reaches the point of collapse (Unger et al. 2001, Ionescu 2016, 2020) and there is a risk of it collapsing under its own weight.

In such conditions, when the continued existence of a cultural asset is at stake or improvements in its physical and mechanical properties are necessary, it is not reversibility that should be taken into account, but the preservation of the cultural asset by any means necessary (Unger et al. 2001).

1.2.1. Impregnation treatments applied to degraded wooden supports in heritage objects. Reports on the impact of solvents on the physical properties of the wood

During art restoration interventions, it is crucial to consider the behavior of materials, as they can influence the support and paint layers (Avram et al. 2023). An improvement in wood performance should be achieved without additional adverse effects (Lahtela and Kärki 2016). Solvents are frequently used, either to dissolve polymers for consolidation purposes or for antiseptic treatments, and controlled impregnation with monomers in wood can improve its resistance to deterioration (Wu et al. 2017). The assessment of the degree of impregnation (Ionescu et al. 2021) should be a ratio between the maximum level of treatment and its effectiveness, and can be evaluated by weight gain (WPG) (Wu et al. 2017) and hardness determinations (Ionescu et al. 2021).

Consolidation treatments applied to art objects are closely related to the degree of deterioration: a support may be degraded over a small surface area and volume, but there may be frequently encountered situations where the surface and volume in particular are severely damaged, resulting in significant losses through a reduction in wood density between 20% and 70% compared to healthy constituent/reference wood. Such situations will require multiple and complex treatments (Ionescu 2021, Avram et al. 2022).

Depending on the nature of the absorbed liquid, the extent of swelling varies. Nayer (1948) cited by Bossu et al. (2018) reported greater swelling in polar liquids, characterized by high binding capacity, which is explained by the greater and faster penetration of liquids into the walls of wood cells. These results were also confirmed by Mantanis et al. (1994, 1995), who tested a wide variety of pure solvents applied to several wood species (Maher 2006; Lahtela and Kärki 2016) and reported that both the hydrogen bonding capacity and the size of the solvent molecules contribute to the degree of wood swelling. It was observed that the swelling of wood in nonpolar or low polar organic solvents produced significantly less swelling than water or solvents with increased polarity (Avram et al. 2023).

1.2.2. Reinforcement by filling with wood material in the case of severely damaged objects

The need for interventions on severely damaged art objects, referred to as radical, requires additions (Fig. 4), geometric restoration (Fig. 5), partial replacements, or transpositions through reinforcement with solid wood to take over the lost functions and properties of the damaged wood. This wooden support serves to extend the "lifespan" of the artistic creation, which, in addition to its economic value, has cultural, identity, and geopolitical significance.

Fig. 4. Damaged panel reinforced with solid wood—balsa (Ochroma pyramidale) (*original images from the Restoration Laboratory*)

Fig. 5. Filling and reconstruction, using solid balsa wood, carried out at the "Ionescu Constantin" laboratory in Sibiu (*original images from the restoration laboratory*)

A thorough understanding of the composition of materials and execution techniques is an essential element in the restoration process. This knowledge allows the use of materials compatible with the original ones, reducing the risk of further degradation caused by chemical or physical interactions between materials with different characteristics and behavior over time. Thus, in the process of "prosthetics" for severely damaged objects, in order to achieve optimal and beneficial results for the art object, the choice of adhesive must be taken into account, as well as the qualities of the wood material chosen to be integrated into the structure of the art object. An important factor in the gluing process is both the quality of the adhesive and the degree of moisture content of the wood.

1.3. Wood species used in the creation of art and religious objects in Europe

The wooden or wood-supported art and religious objects that make up a large part of Romania's movable cultural heritage were mainly made of lime wood (*Tillia spp.*) (icons, iconostases) or softwood. This observation can be supported by the large number of icons/panels that have entered the IONESCU CONSTANTIN ȘTEFAN restoration laboratory in Sibiu (approx. 30-50 icons/year, resulting from intense activity over approx. 13-15 years); Popescu et al. (2005) also mention that lime wood is often used to make art and religious objects; in their study, the authors investigated several religious objects from the inventory of two places of worship in northern Romania.

Of course, the "preference" for a particular wood species took into account the geographical area and the accessibility of raw materials, costs, and the quality of the wood species. As a general conclusion, analyzing Table 3, it can be seen that in Europe, oak was the most commonly used species for making art and religious objects, followed by softwoods, poplar, and linden.

Table 3. List of the main wood species used for making panels for art and religious objects in Europe

Geographical area	Wood Species		Reference
Region / Country	Frequently used	Rarely used	
Italy	poplar, fir	walnut, linden, chestnut, oak	*Uzielli (1995), Wadum (1995)*
Spain	Poplar, pine	walnut, oak	*Veliz (1995)*
Portugal	red cedar, chestnut, pine	oak	*Veliz (1995)*
The Netherlands	oak		*Wadum (1995), Vadum et al. (2022)* Davies și Moortgat (2021)
North Germany	oak		*Wadum (1995)* Davies și Moortgat (2021)
South Germany	oak		*Wadum (1995)*
Bavaria	**linden**, spruce, pine	beech	*Wadum (1995)*
France	oak	walnut, poplar	*Wadum (1995)*
Tyrol	pine		*Wadum (1995)*
Saxony	fir		*Wadum (1995)*
England	oak		*Wadum (1995)*
Denmark	oak		*Wadum (1995)*
Norway	fir	Oak, pine	*Wadum (1995)*
Russia	**linden**	cypress	https://russianicons.wordpress.com/2013/12/13/an-icon-begins-with-wood/

North Russia	fir, larch, cedar, pine, spruce, oak		https://russianicons.wordpress.com/2013/12/13/an-icon-begins-with-wood/
Romania	**linden**, oak (usually in the northeast and south of the country) fir, spruce (usually in the center of the country)	poplar, walnut	According to the practice of the IONESCU CONSTANTIN ȘTEFAN restoration laboratory, Sibiu; Popescu et al. (2005); Ionescu 2014, 216.

1.5. Characteristics of Paulownia wood (Paulownia spp.). Arguments regarding its potential use in the restoration of cultural heritage

As a wood with potential in various engineering and industrial applications, Paulownia is becoming increasingly popular in Europe. Demonstrating good dimensional stability and a predominantly straight grain (Dogu et al., 2017; Barbu and Tudor, 2023) and due to its low density and accelerated growth rate, Paulownia is emerging as a species with significant potential for integration into European timber markets, being suitable for a wide variety of applications, especially in the field of light uses. At the same time, it can represent a sustainable alternative to tropical species of high economic value, such as balsa (Barbu and Tudor 2023).

Although it has a wide range of uses, Paulownia wood has not yet been used in the field of art restoration as a filling material for severely damaged objects.
However, given the known qualities of this species in terms of dimensional stability, there is a practice of using this wood to make storage boxes for artifacts that are highly sensitive to environmental factors, especially variations in relative humidity. In this context, Murose (2009) presents the complexity of the conservation, restoration, and preservation of urushi artifacts—objects of particular importance in Japanese culture. Thus, after the restoration of such an object, it requires special attention in terms of preservation and storage. The author argues that Paulownia wood "works well in absorbing and depleting moisture from the air, protecting the environment inside the box from sudden external changes."

Analyzing the information in the literature, we can conclude that the properties of Paulownia wood can be taken into account for restoration.
When the intensity of insect attack exceeds 250 holes per dm2 and their diameters range from 1.4 to 2.4 mm, severe damage of over 55% of the wood volume occurs. Structural damage to anatomical elements leads to a loss of cohesion and a reduction in density and mechanical strength.

With the loss of density caused by volumetric losses as a result of xylophagous attack, the mass of the panels is reduced to 30-40% of the initial mass. In these situations, by introducing extensive additions with solid wood, the mass of these additions may exceed the mass of the existing panel and cause dimensional instability with consequences for the polychrome layers. Thus, it is preferable to introduce a filling material with mechanical properties similar to those of the constituent material, but the physical properties must be as low as possible. Therefore, choosing a species—in this case Paulownia, a light hardwood with superior dimensional stability to lime—may be an option for restoration interventions on heavily damaged panels.

Kusiak et al. (2020) present the growth in diameter of the linden tree (Tillia cordata Mill) at different ages and in different planting areas (low, moderate, or high stress areas).
Analyzing the information provided by the above-mentioned authors, it can be concluded that Paulownia wood has a diameter growth of up to 90 mm/year, while lime wood (Tillia cordata), for example, would have an annual growth of between 41÷52 mm (Fig. 6). Thus, afforestation can be considered both for soil stabilization and, above all, for the use of Paulownia as a substitute material to reduce the exploitation of traditional forests and preserve native species.

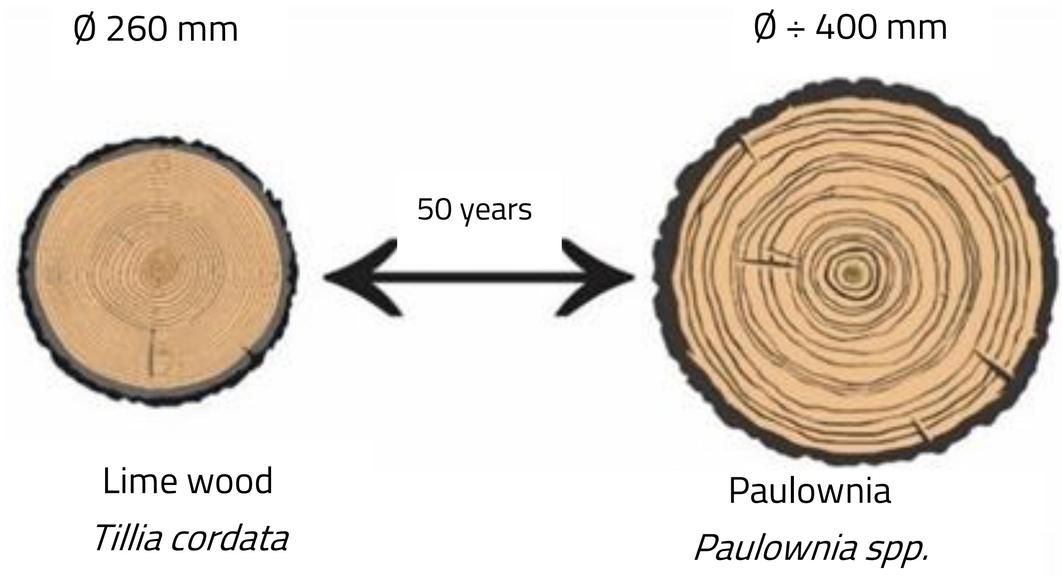


Fig. 6. Difference in diameter growth between the two wood species

From an economic point of view, but also in order to preserve or save native forests, we can argue for the use of Paulownia in certain areas of production — furniture, decorative objects, paneling, etc.— or, where necessary, in the restoration of heritage objects through partial additions/reinforcements, etc., with multiple purposes: 1. To save/preserve linden forests, which represent less than 6% of the total forest area in the country, according to the NATIONAL FOREST INVENTORY (2008-2012), while statistical data published in 2021 (INS) reported a percentage of 7.7% for softwoods, which include linden, poplar, and willow; 2. From an economic point of view, Paulownia wood can be less expensive than linden or balsa wood for restoration applications; 3. The growth time of the tree to reach maturity and provide quality timber is shorter in the case of Paulownia.

CHAPTER 2. THE OBJECTIVES OF THIS DOCTORAL THESIS

This paper aims to make a significant contribution to the field of cultural heritage studies by providing answers to original experimental research, focused on the development, adaptation, or advancement of innovative, scientifically validated materials and techniques with direct applicability in the conservation and restoration of cultural assets.

Based on a critical analysis of research in the field, several issues have been identified that have not been studied and analyzed, or that have been less studied. Based on these issues, the main objectives of the thesis have been developed, which will be detailed below:

The main objective of the thesis is to integrate Paulownia wood (*Paulownia spp.*)—a species not used in restoration—and to investigate the possibilities of improving the consolidation treatments of wooden panels, heavily damaged by xylophagous insects, in order to save cultural heritage assets.

Secondary objectives:

O1. Study of current research in line with the research topic.

Analysis and investigation of works of art, techniques, and materials currently used in the restoration of cultural heritage assets. This study took into account the legislative aspect as well as current practice in the specialized literature regarding the implementation and use of new materials, other than those from which the heritage object was originally made (in this case, lime wood), due to the significant differences between the properties of old wood and those of newly introduced wood in terms of physical and mechanical characteristics.

O2. Physical and mechanical investigation of Paulownia wood.

This wood material can replace or compensate for the role and function (lost) of the original material, without causing further damage or deterioration to the severely damaged cultural heritage assets.

O3. Monitoring the behaviour of historic (damaged) lime wood (*Tillia spp.*) and healthy lime wood, and Paulownia wood under the action of solvents frequently used in restoration treatments: consolidation or antiseptic treatment. These solvents interact with the wood material and can have negative effects on the artistic creation, namely the valuable paint layer.

O4. Comparison of Paulownia wood with other species already used for fillings

The comparison is made both with the species/wood - lime, most commonly found in movable cultural heritage assets, but also with Balsa wood, which does not excessively weigh down the consolidated heritage object.

O5. Research and observations on the quality of gluing damaged historic lime wood with healthy lime and Paulownia wood. The analysis is made both in terms of the shear strength of the adhesions and in terms of observing the qualities of the adhesives sold/used in restoration when subjected to accelerated aging tests.

O6. Analysis and comparison of the damage caused by healthy lime wood and Paulownia wood to damaged historical wood following the application of mechanical forces. This analysis is necessary in order to observe the compatibility of the adhesions.

CHAPTER 3. EXPERIMENTAL RESEARCH ON THE USE OF PAULOWNIA WOOD FOR FILLING AND REINFORCING SEVERELY DAMAGED CULTURAL HERITAGE ASSETS, USING STANDARDS AND TECHNOLOGIES DERIVED FROM WOOD ENGINEERING

Research into wood materials that can be used for restoration work can be considered forward-looking, with a beneficial impact from an ecological point of view and direct application in the field of heritage conservation. In choosing experimental research that would benefit the field of restoration, several of the principles of restoration highlighted by Brandi (1996) were taken into account and considered benchmarks for the present research: stability, reversibility, compatibility, aesthetic legibility, and potential unity.

It is important that cultural property be understood and interpreted as a whole, as a composite element. It is made of different materials, joined or superimposed (Fig. 7), which behave differently and are composed as follows: wooden support, successive layers of protein glue in different concentrations, the preparation layer—the primer, over which the pictorial layer—the artistic creation—and the protective varnish are placed. Thus, the wooden support and the complex preparations serve to reinforce, balance, equalize, and finish the surface, over which the artistic creation (with an aesthetic and thematic role) is developed. Throughout its history, this composite ensemble has accumulated and transmitted education, culture, civilization, and, last but not least, identity.

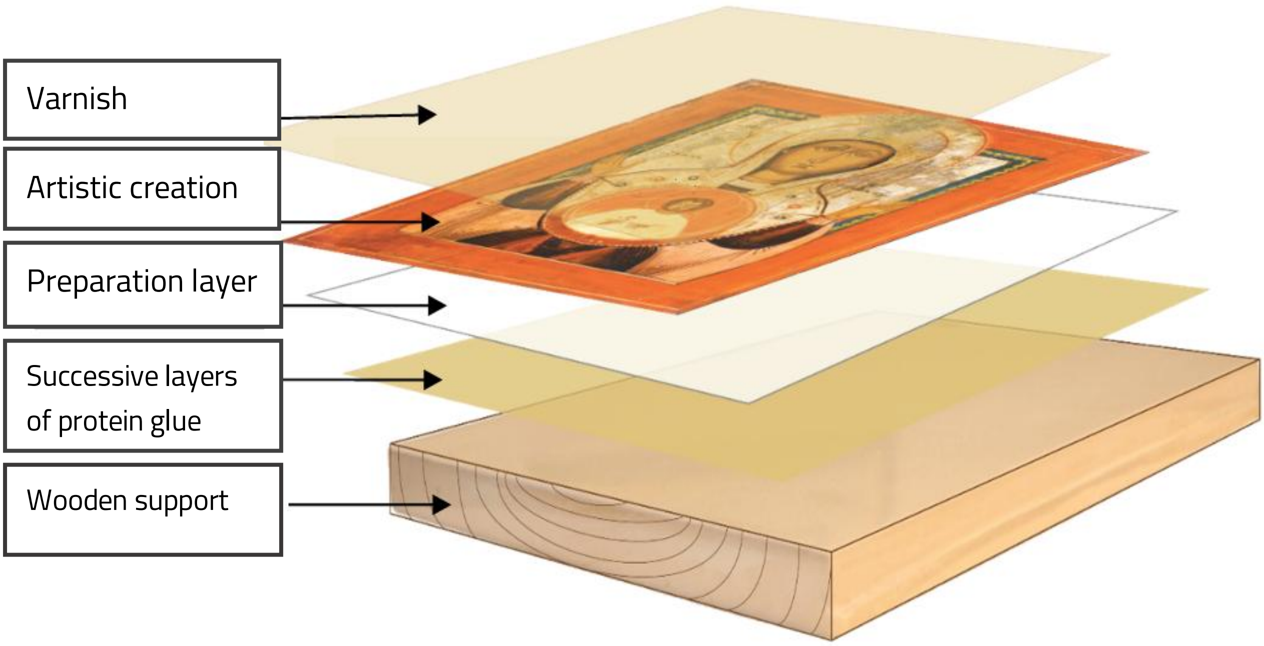


Fig. 7. The elements that make up a cultural art object (a painting on wood)

3.1 Macroscopic and microscopic characterization of the two wood species: lime (*Tilia spp.*) and Paulownia (*Paulownia spp.*)

This study aimed to observe the characteristics of two wood species: linden and Paulownia.

3.1.1 Characterization of lime wood (*Tillia spp.*). Comparative analysis of the properties of healthy wood and wood degraded by xylophagous insects

From a macroscopic point of view, lime wood had between 85 and 105 annual rings and an average density of 518.75 kg/m3. The moisture content inside the annual ring ranged between 6.5% and 10%, while between the annual rings the moisture content was between 7.6% and 9.8%

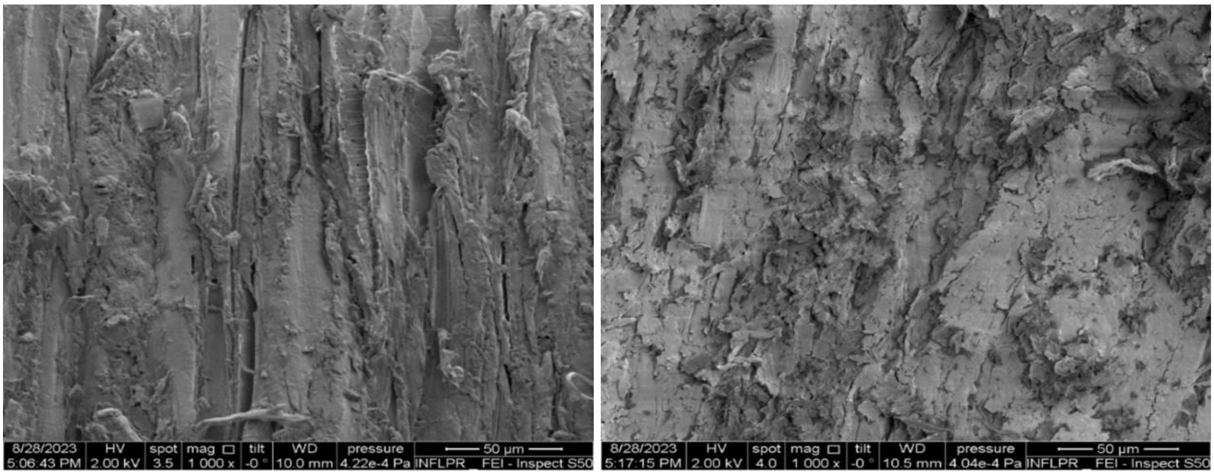


Fig. 8. SEM image – healthy linden tree (left) and damaged linden tree (right, magnified 1000x)

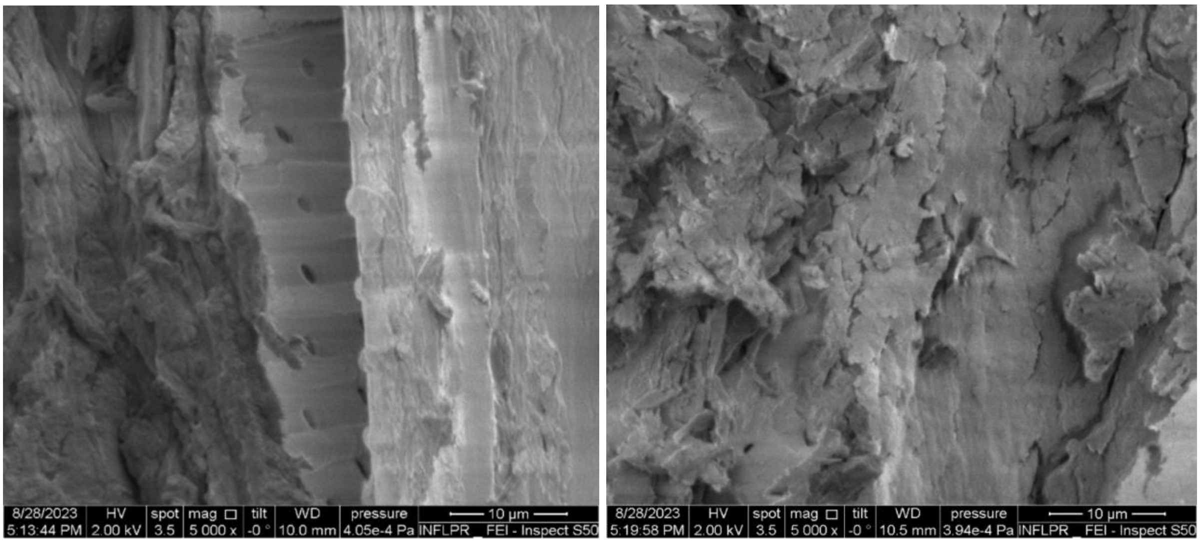


Fig. 9. SEM image – healthy linden tree (left) and damaged linden tree (right, magnified 5000x)

In Figs. 8 and 9, where the magnifications are 1000x and 5000x, respectively, the deep degradation of the lime wood on the tangential section can be observed. The damaged lime wood appears dry, dehydrated, and rigid.

The SEM investigation was carried out at the Institute of Atomic Physics, Măgurele, with the kind assistance and involvement of Dr. Andrada Lazea-Stoyanova.

3.1.2 Characterization of Paulownia wood (*Paulownia spp.*)

From a macroscopic point of view, lime wood had between 4 and 8 annual rings and an average density of 295.66 kg/m3. The moisture content inside the annual ring ranged between 6.8% and 11.5%, while between the annual rings the moisture content was between 8.52% and 10.3%

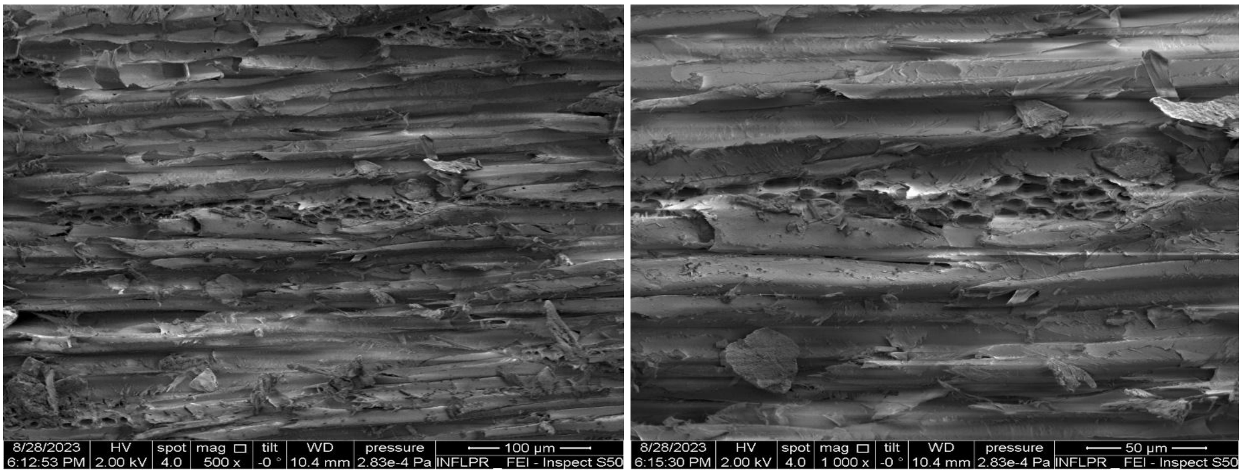


Fig. 10. Tangential section of Paulownia wood. SEM image, magnified 500-1000x

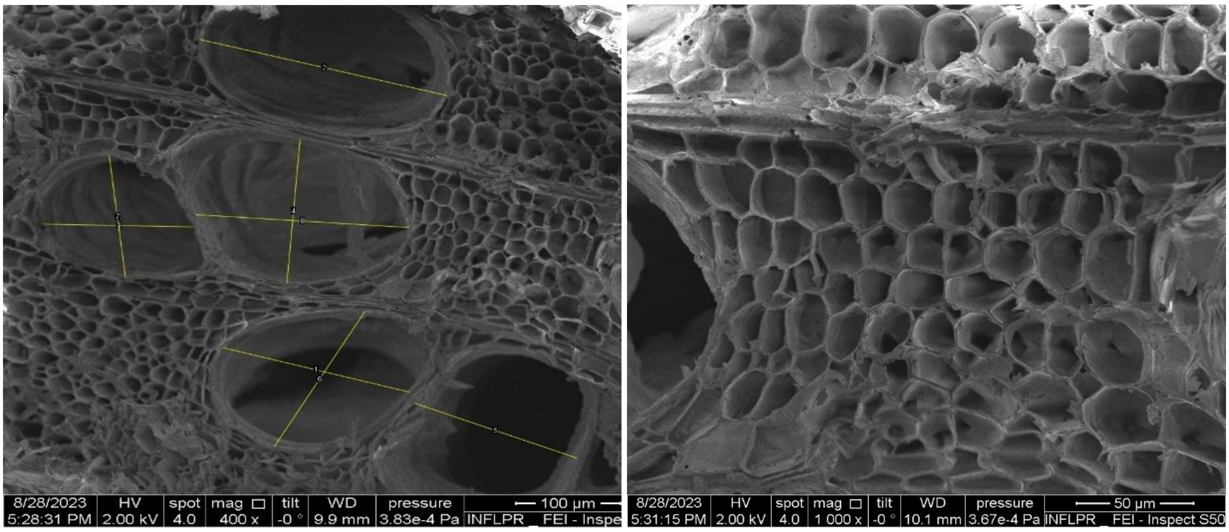


Fig. 11. Cross section of Paulownia wood. SEM image, magnified 500-1000x

Early wood vessels have a considerable diameter of approximately 100–200 µm, as confirmed by measurements and specialist literature. Their distribution is uniformly radial, shown in Fig. 35 as a circular or semicircular alignment in cross section.

The wood structure includes short and narrow medullary rays, formed by thin-walled cells.

In conclusion, according to the literature (Park et al. 2023, Zhao et al. 2022, Dogu et al. 2017), the SEM images analyzed (Figs. 10, 11) correspond to the known anatomical characteristics of Paulownia wood: highlighting the porosity of the species and the specific honeycomb appearance.

3.2. Comparative study of the physical and mechanical properties of Paulownia wood (*Paulownia spp.*), lime wood (*Tillia spp.*) and balsa wood (*Ochroma pyramidale*)

This study aims to analyze the uniformity of three homogeneous wood species—linden (Tillia spp.), balsa (Ochroma pyramidale), and Paulownia (Paulownia spp.) – from a structural perspective, in correlation with their physical and mechanical properties and behavior towards water (water absorption, swelling, and shrinkage). In this study, lime wood is used as a reference element. The aim is to highlight the particular properties of Paulownia wood, proposed as a viable alternative to replace lime wood in various applications. The paper is based on the premise that linden and balsa are not suitable options for partially replacing or reinforcing very old wood in heritage objects, while Paulownia may be a more advantageous solution in terms of its properties and conservation.

3.2.1. Methodology for determining physical and mechanical properties

To characterize the physical and mechanical properties, test specimens were prepared from linden, balsa, and Paulownia wood, according to the specific standards for each type of determination, which were conditioned in a controlled microclimate of U=55-60% T= 20°C.
The lime wood came from the warehouse of the "Ionescu Constantin Ștefan" Restoration Laboratory in Sibiu, which provided high-quality wood, 30 years old, thermo-hygroscopic conditioned, naturally dried, and without defects. The paulownia wood was purchased from Paulownia Europa in Cristian, Brașov, harvested from its own production, and the balsa wood was imported, purchased from a specialist store for model aircraft construction.

Fig. 12. Test specimens for mechanical testing

The **density of the wood was calculated** based on ISO 3131:1975, defined as the ratio between the mass and volume of the sample.
Water absorption was calculated based on standard EN 13183-1/2002, and **shrinkage and swelling** on the radial and tangential sections were determined based on standards ISO 4858:1981 and ISO 4859-1982.

The modulus of rupture and static bending modulus of elasticity were measured in the mechanical testing laboratory of Transilvania University in Brașov and determined based on ISO 13061-4:2014 and 13061-3:2014 standards. Before testing, the samples were conditioned to obtain an average moisture content of 12%. The test specimens were 20x 20x 300 mm in size.
The distance between the supports was 240 mm. The force was applied centrally to the test piece at a speed of 10 mm/minute.
The compressive strength parallel to the grain used in the study was obtained at the moment of failure, when the wood layers in the samples were sheared or crushed and the force dropped sharply.

The force application speed was 10 mm/minute. Therefore, the parallel fiber compression strength of the wood was determined as the ratio between the maximum breaking force and the breaking surface area, in accordance with ISO 13061-17.

Brinell hardness was measured according to EN 1534:2003; test specimens were prepared and tested from three species: linden, balsa, and paulownia, with 10 specimens per species, measuring 50 x 50 x 20 mm. For Brinell hardness, the 10 mm ball indenter had a preset pressing force of 100 N for balsa wood and 400 N for linden and Paulownia wood, with a pressing time of 25 seconds.

3.2.2 Results obtained regarding physical properties

Wood density

For comparison, the density of the samples in a completely dry state was examined. It was observed that the density of lime wood had the highest value, namely 461.8 kg/m^3, and that of balsa wood had the lowest value, 118.3 kg/m^3, while Paulownia had a density of 304.2 kg/m^3 (Fig. 13.).

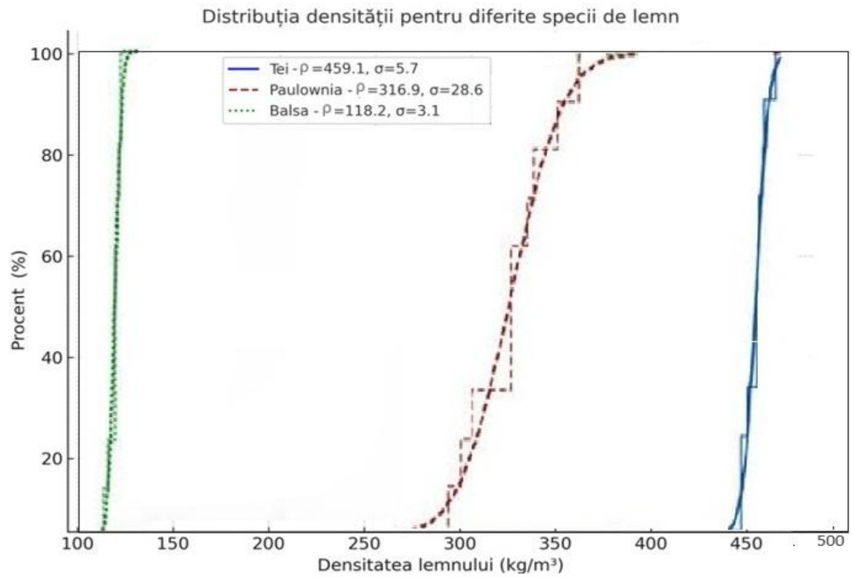


Fig. 13. Cumulative distribution function (CDF) comparing the density of three types of wood: linden, paulownia, and balsa, expressed in kg/m³

The steep or gradual shape of the curves reflects the degree of homogeneity or variation in density within each type of wood. By comparison, it can be concluded that balsa, with its very low and uniform density (low standard deviation), is suitable for applications where minimum weight is essential. Paulownia, with intermediate density but greater variation between samples, is a light wood with a more heterogeneous structure. It offers a balance between low weight and strength. Linden is the densest of the three tested, concentrated in a narrow range of values, indicating a stable and homogeneous structure.

Water absorption results

The water absorption values for the three wood species are shown in Figure 14. It is noteworthy that Paulownia wood had the lowest water absorption, with a percentage of 27.3%, while balsa wood had the highest absorption capacity, reaching 85.3%.

During the experiment, hourly measurements were taken to observe the time required to reach fiber saturation for lime and Paulownia wood: in the case of linden, 27 hours were required, while for Paulownia wood, 9 hours were required. After these hourly intervals, the wood stopped changing size.

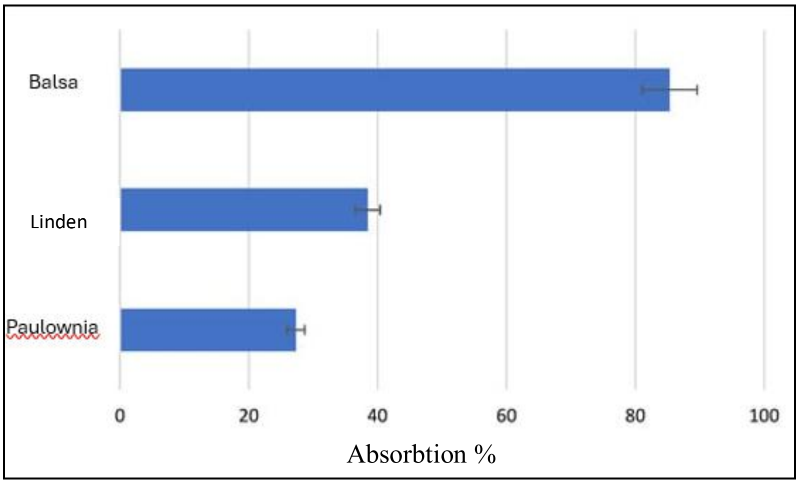


Fig. 14. Water absorption for the three wood species: balsa, linden, and paulownia

Results regarding the swelling and shrinkage of the three wood species

Compared to lime wood, Paulownia has a lower volumetric swelling of 64.69%, and balsa has a lower volumetric swelling of 67.11%. The difference in shrinkage between balsa and Paulownia is 6.84%.
It can be seen that the highest volumetric shrinkage is evident in linden wood (12.28%), while Paulownia wood has a volumetric shrinkage of 10.27%. It can be seen that the highest volumetric shrinkage is evident in lime wood (12.28%), while Paulownia wood has a volumetric shrinkage of 5.37% and balsa wood of 5.39%. Compared to lime wood, Paulownia has a lower volumetric shrinkage of 56.27%, and balsa has a lower volumetric shrinkage of 56.10%. The difference in shrinkage between Paulownia and balsa is approximately 1%.

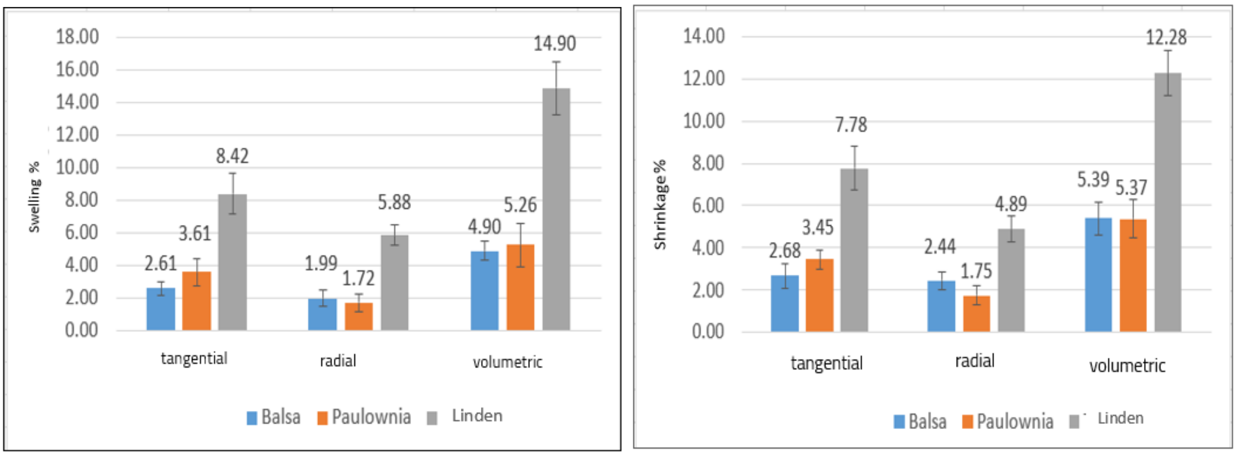


Fig. 15. a, b. Average values for swelling and shrinkage on the two sections: tangential, radial, and also volumetric, for the three species tested

3.2.3 Results obtained regarding mechanical properties

Modulus of elasticity (MOE) and modulus of rupture (MOR)

The data obtained show that lime wood had the highest strength, with a MOR of 92.3 N/mm², followed by Paulownia wood with 62.1 N/mm², while the lowest value was observed for balsa wood, with 14.1 N/mm² (Fig. 16. a.).
In terms of the modulus of elasticity (MOE) under static bending (Fig. 16. b.), it was found that: lime wood had the highest elasticity of the three species tested, with an MOE of 6782 N/mm², followed by Paulownia (4890 N/mm²), while balsa wood had the lowest value, only 927 N/mm².

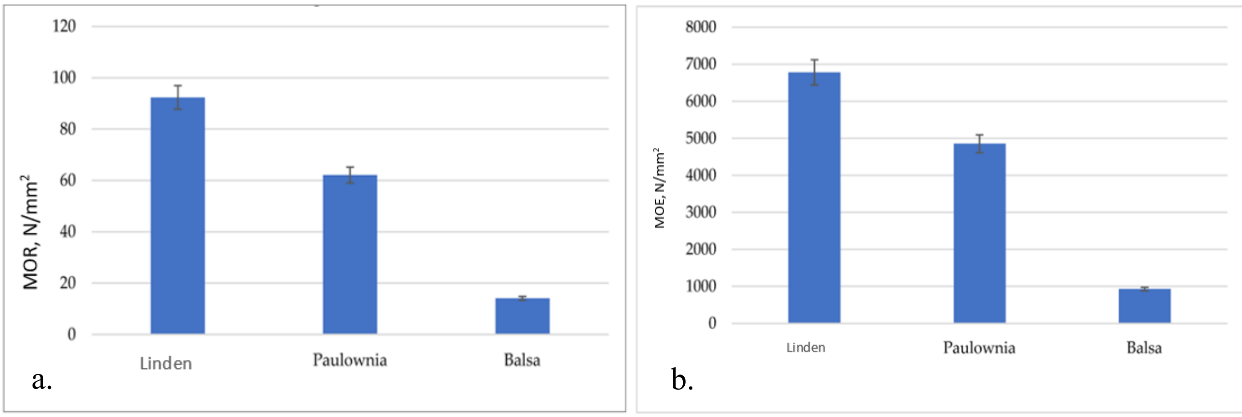
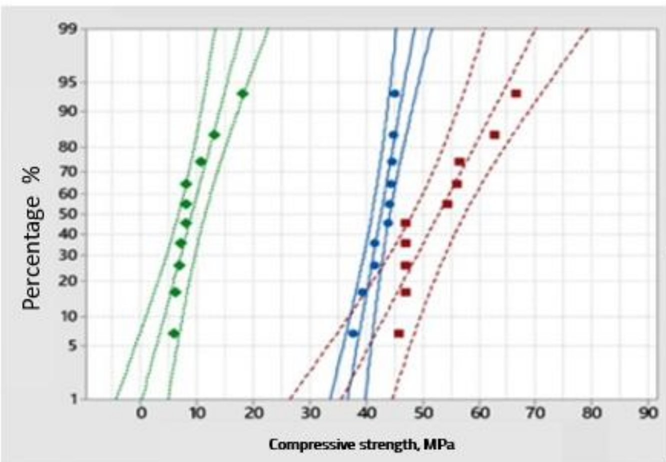


Fig. 16. a., b. MOR result for the three wood species tested (a); MOE result for the three wood species tested (b)

Compressive strength parallel to the grain

The compressive strength of Paulownia wood is 19.40% lower than that of lime wood*, and* in the case of balsa wood, the compressive strength is 82.59% lower. Comparing paulownia wood with balsa wood, it can be seen that paulownia wood has a 78.66% higher compressive strength. The curves show the distribution of the measured values and illustrate how frequent certain strength levels are. Linden had the highest compressive strength, at 52.85 MPa, but also a greater variation between samples. Paulownia had a strength of 42.47 MPa, with more consistent values. Balsa had the lowest strength, averaging only 9 MPa, but there was also greater variation between samples.



Wood species	Avg. (σ),MPa	STDV
Paulownia	42.47	0.71
Linden	52.85	1.36
Balsa	8.87	1.33

Fig. 17. Compressive strength distribution (MPa)

Brinell Hardness

The values obtained for Brinell hardness (BH) are shown in Fig. 18 and highlight significant differences between the three wood species analyzed, especially in the case of balsa wood compared to the other two species. Lime wood had the highest hardness, with a value of 20.4 N/mm², followed by Paulownia, with 14.45 N/mm², which is about 30% lower than linden. Balsa had the lowest hardness, at 9.45 N/mm², which is about 50% lower than linden and 35% lower than Paulownia.
It was also found that, for all three species, the Brinell hardness values are higher in the tangential section than in the radial section.

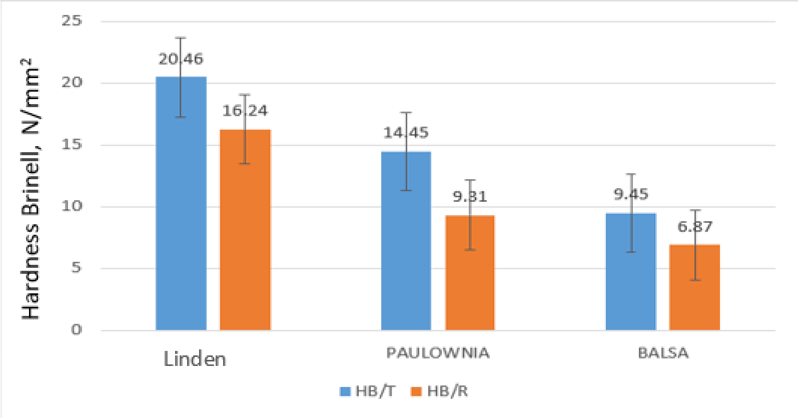


Fig. 18. Brinell hardness for the three wood species tested. Radial and tangential section

3.2.4. Conclusions

This study aimed to conduct a comparative analysis of the three wood species investigated, in order to assess their potential for use in the conservation and restoration of heritage objects.
A general trend observed was that the degree of wood shrinkage decreased proportionally with the decrease in density, this behavior being constant regardless of the direction of analysis—radial or tangential.
The reference point for the analysis was healthy lime wood (*Tilia spp.*), as this is the traditional material used for structural repairs in severely damaged art objects. The need to identify a suitable substitute is based on the desire to use a wood species that does not affect the artistic character or the physical-chemical balance of the restored piece – either through incompatible dimensional behavior (swelling/shrinkage) or through excessive specific mass in relation to the degree of degradation of the object.
Analysis of the data obtained showed that Paulownia wood has properties comparable to those of lime wood, which makes it a viable substitute in applications such as modeling, restoration, conservation, or sculpture.

3.3. Observations on the behaviour of lime wood (degraded and healthy) and Paulownia under the action of solvents (water, white spirit, acetone)

Restoration treatments, whether preventive or curative, applied to prevent or stop bio-pests or for consolidation purposes, most often require multiple repetitions. In this context, wood undergoes dimensional changes through repeated swelling and shrinkage, as well as deformation. This stress is inevitably transferred to the polychrome layers.

Unlike the specialized literature, the novelty of this study refers both to the dimensional changes caused by swelling, but especially to the deformations: bending and twisting that occur during partial immersion when the wood comes into contact with the selected solvents. The study also highlights and evaluates the behavior of historic wood severely damaged by xylophagous insects, found in cultural heritage objects, where one of the surfaces (the tangential surface) has a polychrome layer composed of protein glue, primer, and pigments.

The aim of the research was to observe and understand the effect of solvents used in restoration treatments on historical linden wood, moderately or severely damaged, from art objects. The experiment was also extended to healthy lime wood and Paulownia wood. Through this experiment, we observed only the behavior of the selected solvent as a vector for the penetration of treatments in this type of restoration, without developing the flow of a specific treatment process.

3.3.1. Materials, method, and equipment used

Three solvents commonly found in various polychrome wood restoration treatments, for curative or preventive purposes, were used: water, white spirit, and acetone. Both water and white spirit are vectors that transport active substances to combat pests: fungi and xylophagous insects. In addition, both white spirit and acetone are frequently used to solubilize resins used for consolidation.

When selecting the historic wood material, it was important that one side be polychromatic, but without aesthetic or cultural significance, and it was recovered from assemblies that needed to be replaced with healthy wood for structural reasons. The use of polychrome test pieces was intended to simulate the behavior of a painted layer, which may undergo changes under various conditions. The polychromy consisted of: primer (a mixture of protein glue and calcium carbonate) and a single layer of red paint (iron oxide).

Nine test pieces were cut manually in the longitudinal direction, thus obtaining 18 test pieces with dimensions L=90 x l=130 x h=12 mm (± 2 mm), of which 9 test pieces had a polychrome surface (P) and 9 test pieces without polychromy (FP) – respectively the reverse side of the panel. The remaining 6 specimens, with a thickness of 27 mm, were immersed two at a time in each type of solvent. We wanted to observe the changes both on the 27 mm thick specimens and on those cut to 10-12 mm.
We opted for partial immersion in solvents (Fig. 19), i.e., 1/2 of the thickness of the samples, based on the fact that, in current practice, polychrome art objects cannot be completely immersed in solvents or treatment liquids.

Fig. 19. Example of the immersion procedure of the samples.

Based on this analysis, it was considered necessary to extend the research to healthy linden and paulownia wood.

The purpose of these observations on healthy wood was to understand the behavior regarding dimensional changes and mass increases under solvent absorption conditions when preventive treatments are necessary and on degraded polychrome panels, where new wood was added. We therefore considered it necessary to simulate the effects of the solvents used during preventive or curative treatment on new wood.

Both linden and paulownia wood were processed on combined carpentry machines, performing the following operations: straightening and thickness levelling, formatting, cutting and trimming to the specified dimensions. Two distinct types of test specimens were prepared for the experiment, with thicknesses of 20 mm (±1 mm) and 10 mm (±1 mm) and dimensions of 90x 130 mm (length x width). Thirty specimens were made from each dimensional category for each wood species. This distribution allowed for a rigorous comparative evaluation between the two types of material.

The deformation variations were determined using a magnetic device equipped with a HBM Machines dial gauge, with a range of 10 mm and a graduation of 0.01 mm, while the depth of curvature was measured using the Parkside PTM 2 A1 digital device. The dial gauge was calibrated at the beginning of each experimental set, depending on the type of test pieces analyzed (thick or thin), and remained unchanged throughout the measurements for that set. The dial gauge measures dimensional and geometric shape deviations and can be useful for comparison with the reference dimension; therefore, it does not measure absolute dimensions but differences from the reference. It has a rotation range of 1 mm and a scale from 0-100.

Linear swelling was calculated in accordance with ISO 4859-1982, and the determination was given as a percentage.

The amount of solvent absorbed (M_{ABS}) in grams was calculated using formula (1a.), and formula (1b.) was used to determine the absorbed volume (V_{ABS}).

$$M_{ABS} = m_u - m_i \ \text{[g]} \qquad (1\ \text{a.})$$

Where,00

M_{ABS}= absorbed quantity expressed in g

m_u= wet mass after extraction from the solvent in g; m_i= initial mass before treatment in g

$$V_{ABS} = \frac{M_{ABS}}{\rho_{solvent}} \, [cm^3] \qquad (1\ \text{b.})$$

Where,

V_{ABS}= absorbed volume expressed in cm^3

M_{ABS}= absorbed quantity expressed in g; $\rho_{solvent}$= density of the solvent expressed in g

The deformation, expressed as dimensional variation, was determined according to the relationship presented in equation (2). The experimental values were obtained using both a device with a magnet and a dial gauge, as well as a digital measuring device. Reference points were marked on the surface of the specimen, and measurements were taken in the same areas before and after the immersion process to ensure the accuracy of the comparative determinations.

$$\Delta = l_u - l_i \ \text{[mm]} \qquad (2)$$

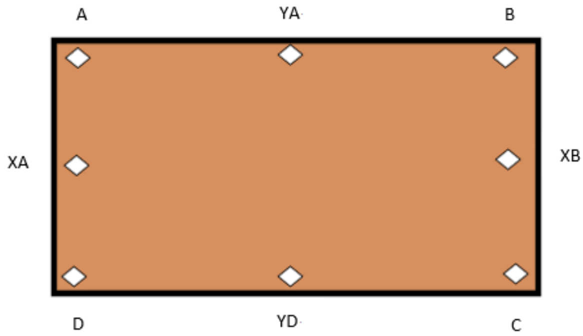
Where,

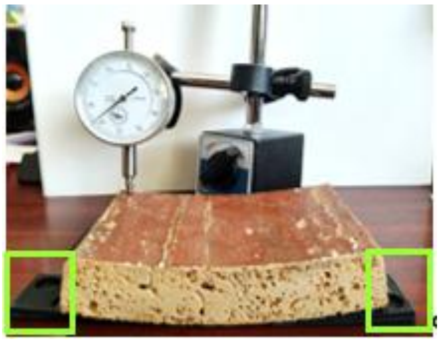
Δ= variation expressed in mm

l_u= value of the point measured on the measurement axis after immersion expressed in mm

l_i= value of the point measured on the initial measurement axis (before immersion) expressed in mm

To absorb and balance both initial deformations and those resulting from extraction from the liquid, compensation wedges with a length of 60 mm and an inclination of 1 mm to 70 mm were used. Conventional measuring points were taken on the horizontal axes D-YD-C; A-YA-B; XA- XB, as shown in Fig. 20 a., b.





a. b.

Fig. 20. a., b. Marking the measuring points on the test pieces and the coordinates on the axes (a); Measuring the deformation with the dial gauge and highlighting the compensation shims (b.)

3.3.2. Results obtained for degraded lime wood: absorption and deformations that appeared during immersion

The choice of a fast-evaporating solvent will cause dimensional changes, cracks, and fractures in the wooden substrate. In the case of slow-evaporating solvents, the advantage of deep penetration of the applied treatment is evident, which can ensure increased efficiency in consolidation. On the other hand, this characteristic is accompanied by the disadvantage of additional mass accumulation on the substrate, and the evaporation process takes significantly longer, which can negatively affect the working times in the restoration process.

Liquid absorption and dimensional changes due to swelling

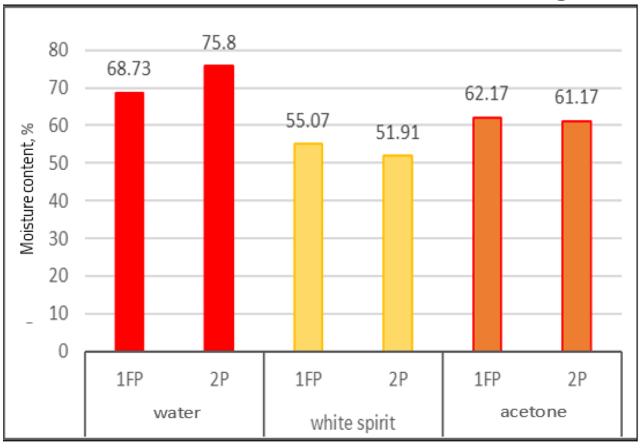


Fig. 21 Moisture content of the samples in percent, after immersion in solvents for 15 minutes

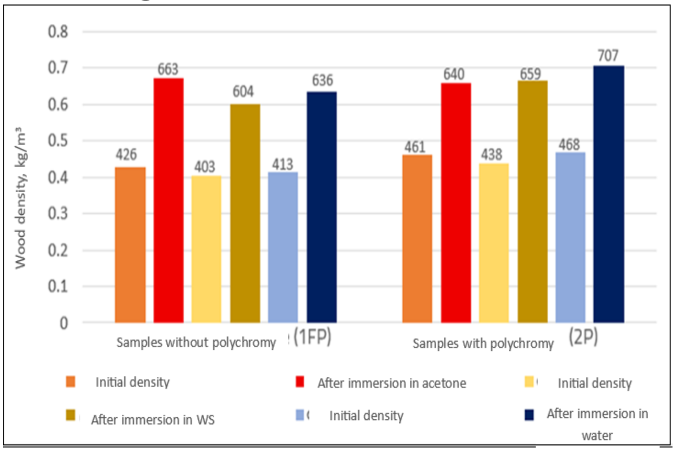


Fig. 22 Densities (kg/m^3) of the samples cut before treatment and after extraction from solvents. Each block of colors, grouped in pairs, represents the samples before and after immersion in solvent

Table 4. Swelling in the tangential direction of thin specimens (without polychromy and with polychromy) with a section thickness of 12 mm

Solvent Sample code		Difference in swelling between initial and after partial immersion (15 minutes)			
		Initial dimensions mm	After immersion dimensions mm	Swelling mm	Dimensional change %
Water	1FP**	130.89 (0.98)*	136.28 (0.84)*	5.39	4.12
	2P***	130.84 (0.73)*	137.56 (0.98)*	6.72	5.14
White spirit	1FP**	132.07 (0.68)*	132.48 (0.68)*	0.41	0.31
	2P***	132.85 (0.82)*	132.91 (0.25)*	0.06	0.05
Acetone	1FP**	130.05 (0.87)*	138.97 (2.61)*	8.92	6.86
	2P***	130.05 (0.87)*	140.28 (0.90)*	10.23	7.87

** Standard deviation; **1FP wood without polychromy; ***2P wood with polychromy*

Table 5. Swelling on the tangential section of the 27 mm thick test pieces.

Solvent/ Sample code		Difference in swelling between initial and after partial immersion (15 minutes)			
		Initial dimensions mm	After immersion dimensions mm	Swelling mm	Dimensional change %
Water	1	130.40	133.02	2.62	2.00
	2	129.15	131.53	2.38	1.84
White spirit	3	128.94	129.63	0.69	0.53
	4	129.83	130.19	0.36	0.27
Acetone	5	129.61	134.69	5.08	3.92
	6	129.46	134.61	5.15	3.97

În cazul epruvetelor fără strat policrom, modificarea dimensională rezultată în urma imersie în acetonă este cu 60,38% mai mare comparativ cu cea provocată de apă. Pentru epruvetele cu strat policrom, această diferență este și mai accentuată, acetona cauzând o variație dimensională cu 65,66% mai mare decât apa.

Comparativ cu solventul white spirit, acetona provoacă deformări semnificativ superioare: de peste 203 ori mai mari în cazul epruvetelor fără policromie și de aproximativ 212,7 ori mai mari în cazul celor cu policromie.

Aceste diferențe evidențiază impactul major al naturii solventului asupra comportamentului higroscopic și dimensional al lemnului degradat, aspect esențial în contextul conservării și restaurării patrimoniului cultural, pentru alegerea materialelor, a metodelor de pregătire și realizare efectivă a unui flux tehnologic de restaurare curativă sau preventivă.

Totodată se poate concluziona că raportul de umflare este influențat atât de grosimea eșantionului de lemn, cât și de durata expunerii acestuia la acțiunea solventului, manifestându-se cu intensitate variabilă în funcție de acești factori.

Dimensional changes—deformations of wood caused by solvents

Following the experiment, changes in flatness were also observed.

Concave and convex curvatures as well as torsions can be seen.

Results for samples in water

The samples immersed in water curved concave and convex. Fig. 23 shows an example of concave curving towards the polychrome surface, causing agglomeration, detachment in the roof and then gaps on the painted surface. When the curvature is convex towards the polychrome layer, it will stretch with the curvature of the wood, but as it does not have the same elasticity, cracks and gaps will occur.

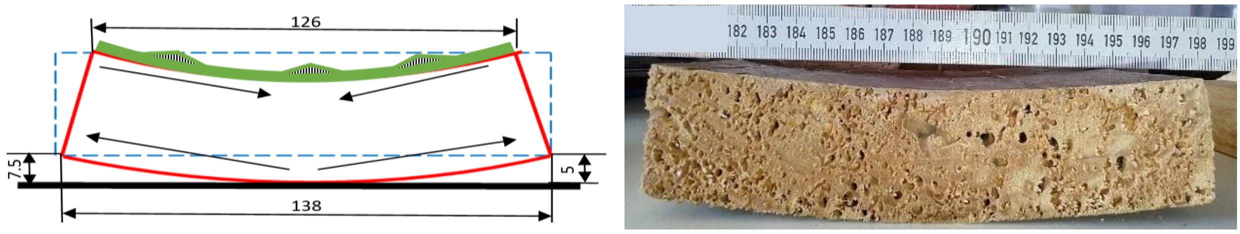


Fig. 23. Graphical representation of concave deformations relative to the polychrome surface, causing detachments in the roof (*in two slopes similar to the architecture*).

There is a pronounced deformation, oriented in the opposite direction to the initial shape of the sample, suggesting a marked mechanical reaction to water absorption. The differences between the values measured before and after treatment indicate a degree of deformation in the range of 13.96%–26%, reflecting significant hygroscopic behavior.

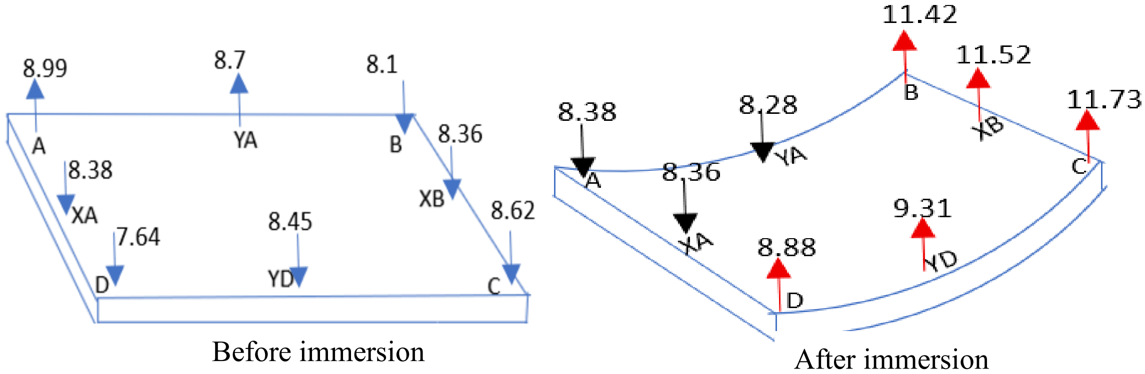


Fig. 24 Schematic representation of deformations on the three measurement axes, on the historic (damaged) lime wood specimen with a thickness of 27 mm, partially immersed in water

The thin test pieces also changed: during partial immersion and after removal from the water, strong bending occurred, with a deflection of between 4 mm ÷ 10 mm (Fig. 25, Fig. 26 a.), as well as torsion (Fig. 26 b.) with values between 4 ÷ 7 mm.

Fig.25. Significant warping after removal of the cut specimens from the water

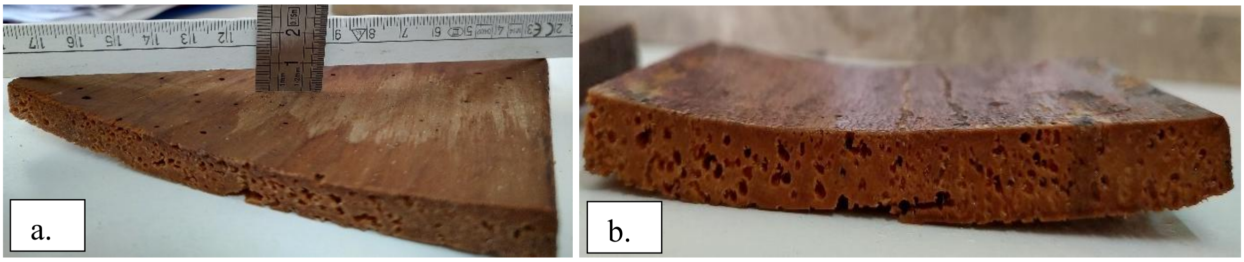


Fig. 26. a., b. 10 mm curvature after removal from water (a.); torsional deformation after removal from water (b.)

Results obtained with white spirit

The swelling, but especially the deformation, is uniform across the entire test piece and very low, almost insignificant compared to the other solvents, both for the 27 mm thick test pieces and for the 12 mm thick ones. These deformations do not affect the shape and stability of the specimens or the polychrome layer (Figs. 27, 28).

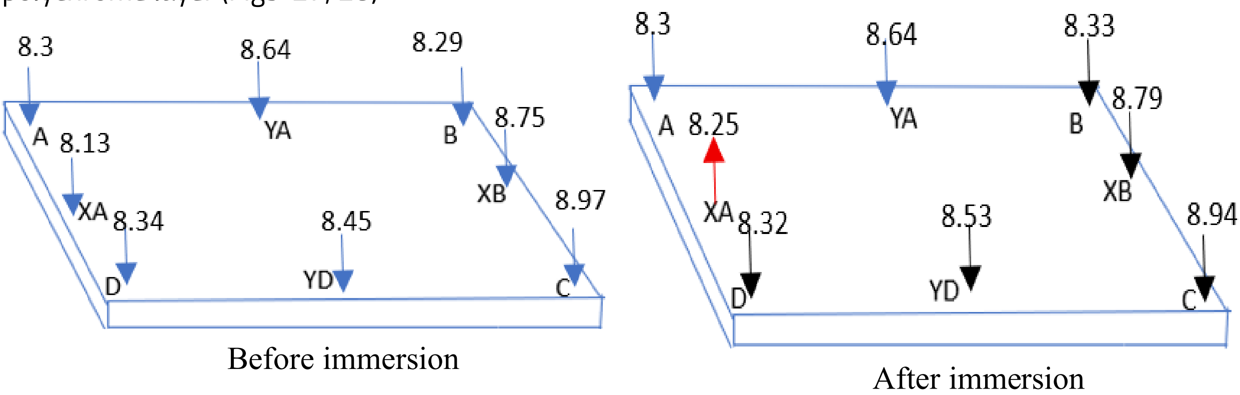


Fig. 27. Schematic representation of the thick test piece after immersion in white spirit, where insignificant deformations can be observed both visually and in terms of value, according to measurements.

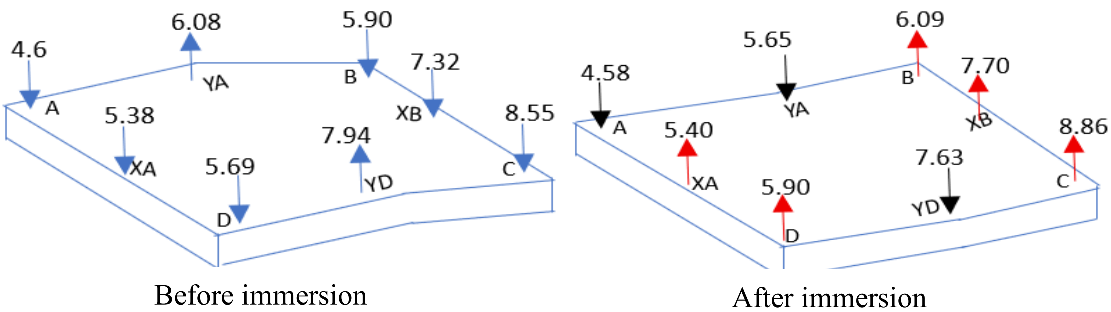


Fig. 28. Schematic representation of a thin test piece after immersion in white spirit, where it can be seen both visually and in terms of values—according to measurements—that the deformations produced are very small.

Results obtained for acetone

Following immersion in acetone, the 27 mm thick specimens showed significant bending deformations, while the torsion phenomenon was relatively low; however, an accentuation of the material's swelling tendency was noted. In the case of the 12 mm thick test specimens, bending and torsion deformations of approx. 5-6 mm were recorded, with uneven manifestations varying depending on the nature of the sample.

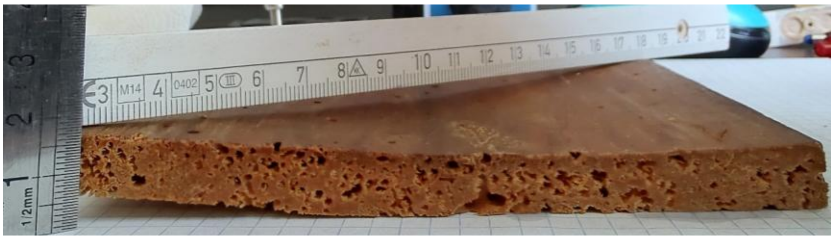


Fig. 29. Thin specimen without painting with strong torsion.

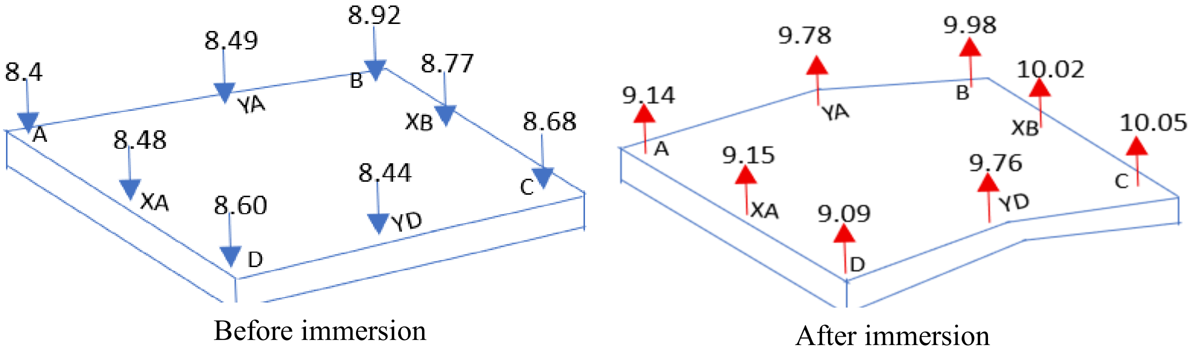


Fig. 30. Schematic representation of changes following immersion in acetone of a thick test piece

The deformations identified in the thin specimens include torsions with amplitudes ranging from 2 to 6 mm, and the average curvatures are in the range of 1.5–4 mm.

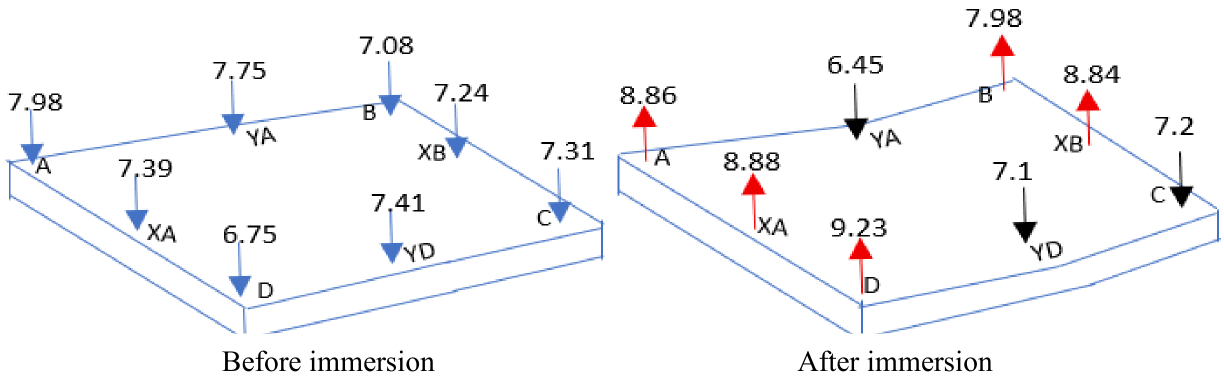


Fig. 31. Schematic representation of the pronounced deformations observed in thin (12 mm) samples of historic lime wood

3.3.4. Results obtained for healthy wood from linden *(Tillia spp.)* and Paulownia (*Paulownia spp.*): absorption and deformation during immersion

Liquid absorption and dimensional changes of swelling

Since this study was conducted with specific reference to the field of restoration, when it is necessary to supplement severely damaged objects with healthy wood of the same type and dimensions (preserving the type of cutting, fiber arrangement, and wood species), the swelling measurements were recorded only in the tangential direction, where the influence of swelling, shrinkage, or deformation can have negative effects on the polychrome layer.

Analyzing the information obtained from swelling in the tangential direction, it can be concluded that, although absorption is higher in Paulownia wood in thin samples, swelling is clearly lower by about 50% compared to lime wood.

In thick samples, acetone swells lime wood by about 90% more than Paulownia wood, and water causes greater swelling of lime wood by about 80% compared to Paulownia. In the case of white spirit solvent, swelling is extremely low in both wood species, regardless of immersion time and sample thickness.

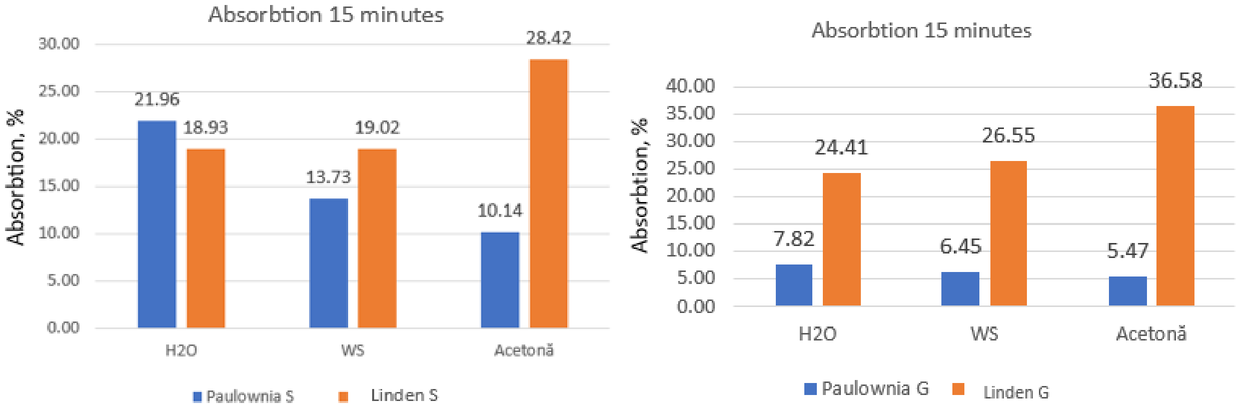


Fig. 32. Liquid absorption in the first 15 minutes, by partial immersion for the two types of specimens: healthy Paulownia wood with a thickness of 10 and 20 mm

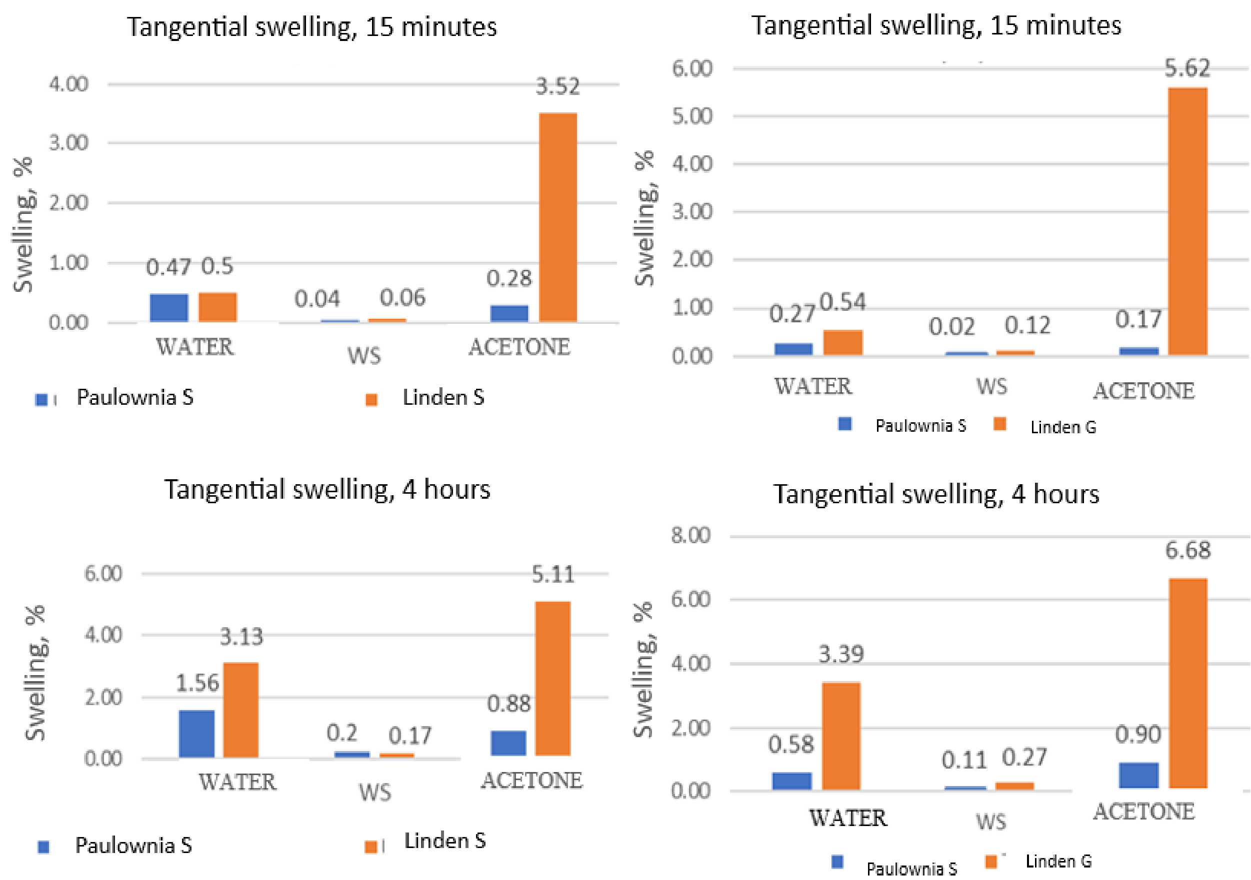


Fig. 33. Swelling resulting from the first 15 minutes and after 4 hours of total immersion for the two types of specimens: healthy Paulownia with a thickness of 10 and 20 mm

Modifications in the deformation of healthy wood samples

After the experiment, changes in flatness were observed. It is evident that both concave and convex curvatures, as well as twists, appeared. It was also found that the deformations were not always influenced by the annual rings, and the curvatures did not appear exclusively in the direction opposite to that of the annual rings.
In choosing these example times, we took into account restoration practice, where treatments are short, approx. 15-20 minutes. In the case of immersion for 4 and 24 hours, we wanted to record the behavior of healthy wood from a wood engineering perspective.

Results for immersion in water

During partial immersion of Paulownia wood for 15 minutes, thin samples show various slight deformations, slightly concave (e.g., in the case of test piece IV), or deformations occurring on a single axis. In the case of thick specimens immersed in water for 15 minutes, the changes are very small, with values ranging from 0.04 to 0.19 mm. The deformation can be observed both visually and in terms of values in Fig. 35.

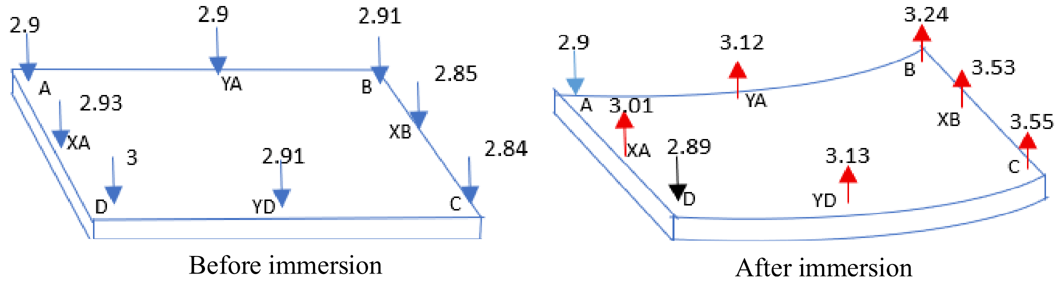


Fig. 34. Schematic representation of the deformations obtained from measurements with a dial gauge on thin (10 mm) Paulownia wood specimens immersed in water for 15 minutes

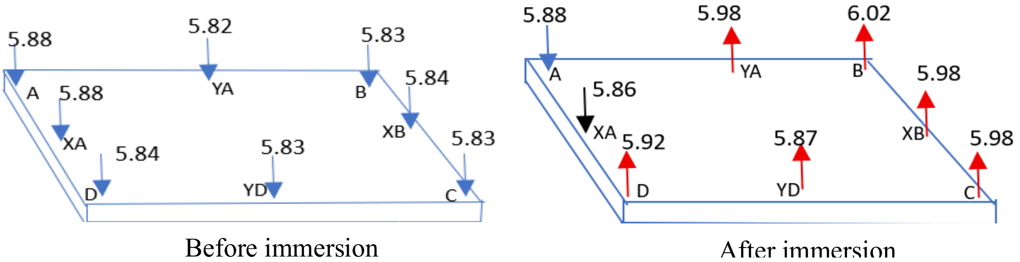


Fig. 35. Schematic representation of the deformations produced in Paulownia wood specimens, 20 mm thick, partially immersed in water for 15 minutes

In the case of lime wood, thin test pieces subjected to partial immersion treatment show, in the first 15 minutes, pronounced swelling, obvious concave or individual deformations located on the axes, as well as twisting. Deformations are evident on all test pieces

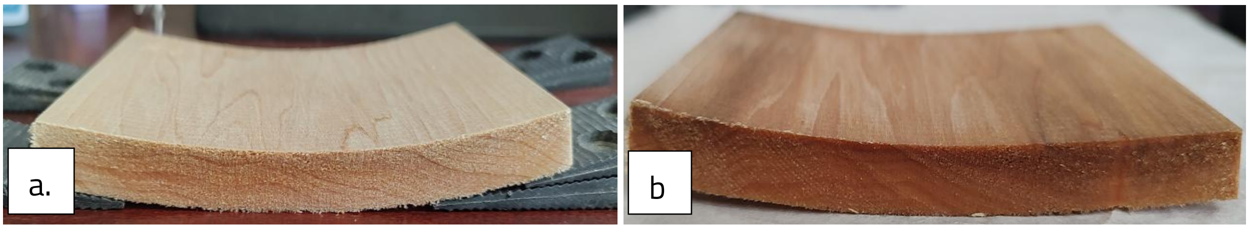
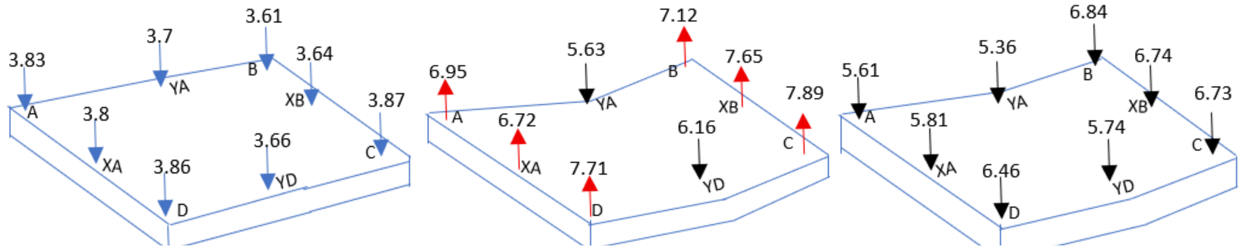


Fig. 36. a., b. Thin lime wood test piece after 4 hours of immersion in water (a.). The same test piece after 24 hours of immersion in water (b.)



Before immersion After 4 hours of immersion After 24 hours of immersion

Fig. 37. Schematic representation of test piece no. II made of healthy lime wood, with a cross-section of 10 mm. Stages of deformation from initial to 24 hours of immersion in water

In the case of thick lime wood specimens immersed for 4 hours and 24 hours, deformation, twisting, and swelling occur, but to a lesser extent than in thin specimens subjected to the same conditions.

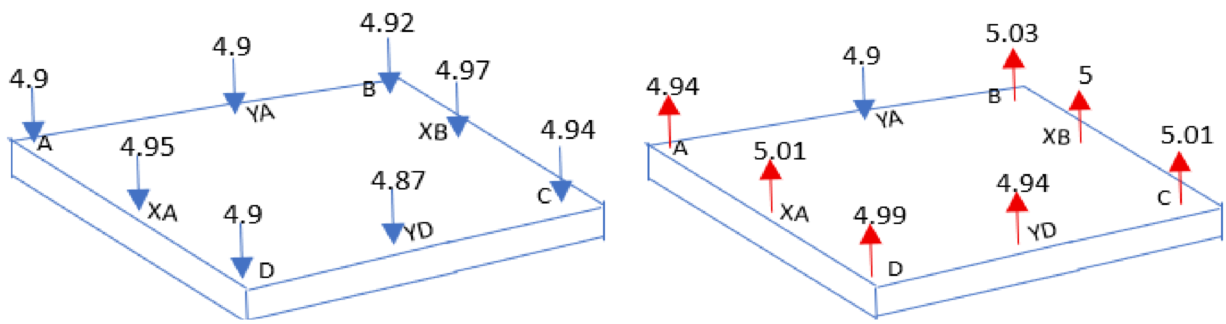
Paulownia wood has superior dimensional stability, showing much lower variations in both dimensional changes and deformation compared to lime wood.

Results for immersion in white spirit

In the case of thin specimens, slight deformation was observed in the first 15 minutes of immersion, but under all other experimental conditions, i.e., at 4 and 24 hours, both thin and thick specimens of both wood species showed a clear tendency toward compression of the wood, without swelling or deformation. These structural changes are evenly distributed over the entire surface of the samples, suggesting a balanced behavior of the wood material in the presence of white spirit solvent.

Results for immersion in acetone

Following the analysis of the information obtained after 15 minutes of immersion in acetone of the Paulownia wood samples, it was found that the material did not show any visible deformation or twisting, but instead exhibited slight dimensional swelling without affecting the structural integrity (Fig. 38). Similar behavior was observed in thicker samples, indicating good dimensional stability regardless of cross-section (10 mm or 20 mm)



Before immersion After immersion

Fig. 38. Schematic representation highlighting the deformation and swelling of Paulownia wood samples after immersion in acetone for 15 minutes

The partially immersed lime wood specimens deformed excessively after 15 minutes (Fig. 38), changing from their initial flat shape to concave or convex curvature and even torsion (Fig. 39). At the same time, major swelling also occurs. Accentuated curvatures are also evident in the case of thick lime wood specimens partially immersed in acetone.

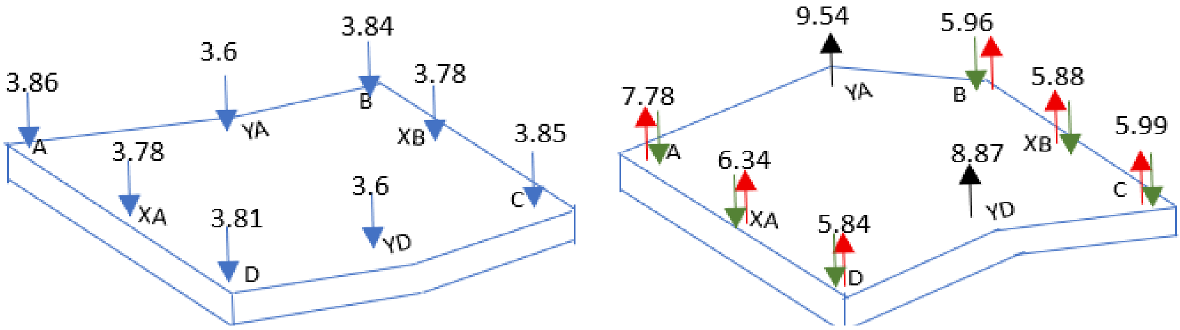


Fig. 39. Schematic illustration of excessive bending in thin lime wood specimens

3.3.5. Conclusions

This study focused on understanding the changes and deformations that occur in polychrome panels of heritage assets during restoration treatments.

The data obtained provides us with a better understanding of the mechanisms behind these changes. This information is essential for developing an intervention process that reduces or limits damage without accentuating it through reaction to treatment

Wet treatments applied to polychrome panels, which show significant degradation caused by xylophagous insects, must be prepared and applied rigorously.

The liquid solutions used for treatment can cause:

1. dimensional changes—swelling during treatment and shrinkage after evaporation and drying of the wood.
2. deformations—concave/convex curvature and torsions.

Changes and deformations occur simultaneously on the composite of the artwork.

The elasticity of the components of the cultural property matrix is not uniform and similar and, as such, behaves differently to the stresses and forces to which it is subjected during treatment. Not knowing the limits and, above all, the impossibility of controlling them causes cracks, gaps, fractures, and damage to the art object.

3.4. Shear strength of the adhesives

The purpose of this study was to observe the quality of bonding between healthy wood and damaged wood for filling and reinforcement applications in cultural heritage restoration. At the same time, we considered it relevant for this research to interpret the quality of adhesives and gluing under mechanical forces, as well as the impact on damaged lime wood. In order to measure the shear strength of the adhesives, we first determined the contact angle for the wood species used in the experiment: degraded lime wood, healthy lime wood, and Paulownia wood.

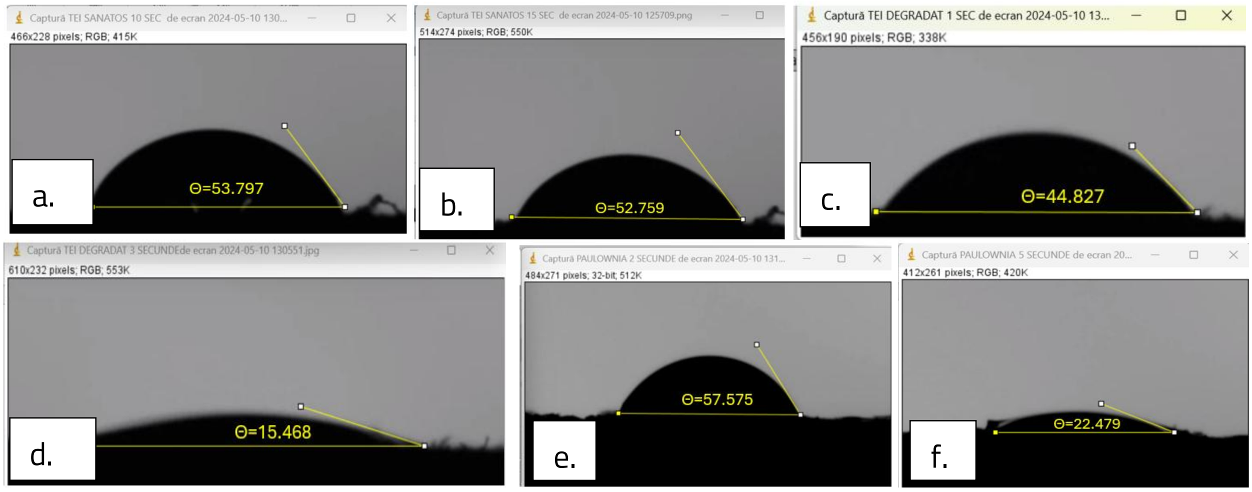


Fig. 40.a., b., c., d., f. Measurement of the contact angle for the three types of specimens: a., b. - healthy linden; c., d. - degraded linden; e., f. - Paulownia

3.4.1. Materials, method, and equipment used

For the shear strength of adhesives, we prepared two types of test specimens, with dimensions according to ASTM D905/98. The test specimens were prepared as follows: lime wood (*Tillia spp.*) damaged and glued to healthy lime wood, and Paulownia wood (Paulownia spp.) glued to damaged lime wood.

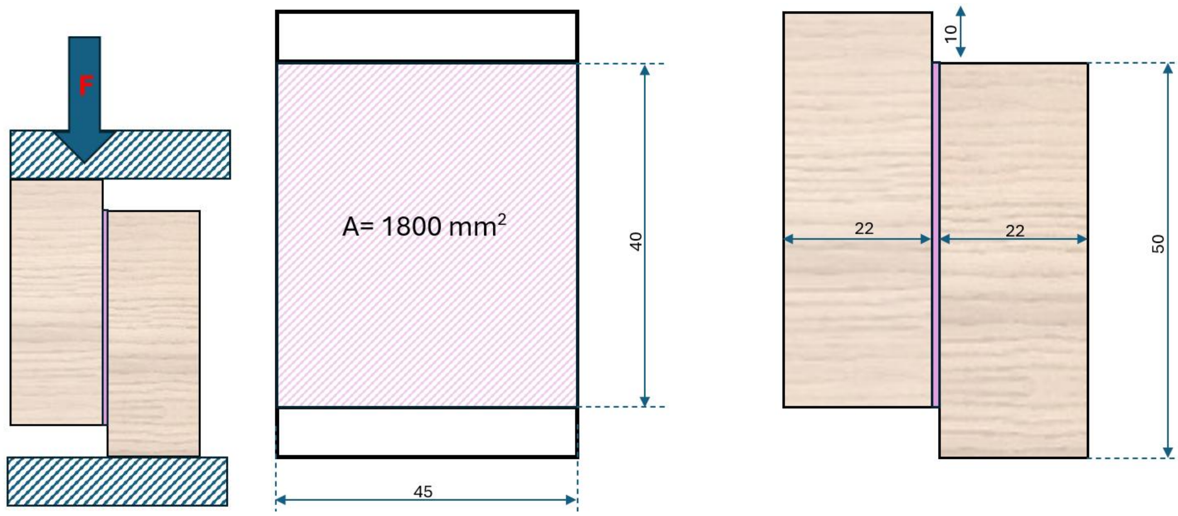


Fig. 41. Test specimen layout for adhesive shear testing, according to ASTM905-98

The adhesives chosen for gluing were selected from the range of adhesives used for the restoration of heritage assets, and both hot-melt and cold-melt adhesives were selected. The hot adhesive was strong protein glue (bone glue, CTS brand) in a concentration of 40%, and the cold adhesive was a synthetic aceto-vinyl adhesive from the CTS product range. The other two types of gluing consisted of the use of the two-component epoxy Basite K and W with adhesive characteristics and a combination of the two-component Balsite K+W and the synthetic adhesive Vinavil 59.

The pressing force of all glued pieces was between 0.42 N/mm^2 and 0.6 N/mm^2, depending on the level of degradation of the lime wood (historical), in order to avoid crushing it under the pressure of the presses. The tests were carried out in the Mechanical Testing Laboratory of the Transilvania University of Brașov.

3.4.2. Results

The 40% protein glue recorded the best results of all the adhesives tested, followed by the synthetic adhesive Vinavil 59. In comparison, Balsite adhesive showed significantly lower adhesive efficiency, with variations between 5% and 53%, influenced by the wood species used and the state of preservation of the historic wood.
The combination of Balsite + Vinavil 59 led to a slight improvement in the gluing properties, but without matching the performance of the protein glue. Of all the variants tested, the 40% protein glue and Vinavil 59 stood out with the highest shear strength values.
Balsite, both in pure form and in combination with Vinavil 59, showed moderate results, but these can be considered acceptable and necessary or important in the context of restoration applications.
The results obtained highlight the importance of the type of adhesive chosen on the mechanical behavior of structural joints.

3.4.4. Conclusions

Analyzing the quality of the adhesives, it can be seen that they have good adhesive properties for applications in the field of restoration. Depending on the filler material and the adhesive chosen, damage to the historic wood occurs in varying percentages.

In the case of 40% protein glue, on Paulownia wood samples with degraded lime wood, 80% of the Paulownia wood is destroyed. Meanwhile, 20% represents the degradation of the historic wood through deformation under the action of mechanical forces.
In the test specimens of healthy lime wood glued with degraded lime wood, 60% of the historic wood is destroyed, 20% represents the breaking of the adhesive surface, and another 20% represents the cracking of the healthy lime wood.

For Vinavil 59 adhesive, in tests on Paulownia wood glued to degraded lime wood, both species are destroyed in a proportion of 40%, resulting in deformation (settling). Another 40% represents the destruction of the Paulownia filler wood, and 20% represents fracturing in the historic wood.
In the case of healthy linden glued to degraded linden, 80% of the historic wood is destroyed by fracture, and 20% represents fracture at the adhesive surface.
The following situation can be observed: the historic wood that has undergone fracture at the adhesive surface shows an optimal or minimal level of damage.

In the case of gluing test pieces with the two-component Balsite K and W, Paulownia test pieces with degraded lime wood, it can be observed that in 70% of the test pieces the adhesive surface and the Paulownia wood fracture without causing stress or degradation of the historic wood. 30% represents partial destruction of the historic lime wood and the adhesive surface.
In the test specimens made of healthy lime wood associated with degraded lime wood, in 60% of cases the adhesive surface fractures and 40% represents destruction of the historic wood.
In the case of combined gluing: two-component Balsite K+W + Vinavil 59, in 60% of cases the adhesive surface of Balsite and Paulownia wood breaks, and 40% results in partial destruction of the historic wood.

For the healthy lime wood with degraded lime wood test specimens, in 80% of cases, the surface of Balsite K+W fractures, and the surface of the Vinavil 59 adhesive remains intact; 20% represents the destruction of the historic wood.

3.5. Accelerated aging tests for composite panels

The accelerated aging test aimed to simulate real situations that may occur in the historical life cycle of cultural objects, where extreme variations in temperature and humidity may occur. At the same time, the secondary purpose was to observe possible changes in deformation/torsion, adhesive detachment, or cracks in the wood that appeared during the accelerated aging period.

3.5.1. Materiale, metodă și aparatură utilizată

For accelerated ageing, two types of specimens were prepared, glued with adhesives used in the restoration of heritage assets, and both hot-gluing and cold-gluing adhesives were selected. The adhesives selected were the same as those used in subsection 3.4.-*Shear strength of adhesives*.
For the shear strength of the adhesives, after removal from the accelerated aging climatic chamber, test specimens were cut and prepared (Fig. 24), with dimensions according to standard SR EN 302-1/2013.

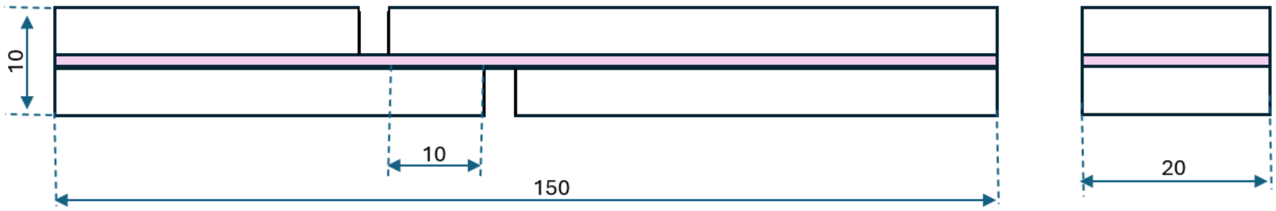


Fig.42. Representation of the type of test specimen tested, according to standard SR EN 302-1/ 2013

3.5.2. Results

Following the accelerated aging treatment, it was found that the samples tested in the climatic chamber for 24 hours/phase did not show any visible changes in deformation, adhesive delamination, or cracks in the paint layer or splitting at the surface or depth of the historic wood at the end of the 4-day process.

According to the results presented in Tables 37 to 44 (*in the thesis*), the adhesives did not undergo any significant negative changes following the accelerated aging process. It can be seen that, after this treatment, fractures occurred predominantly in the degraded wood, and not in the adhesive layer.

This behavior supports the hypothesis that the accelerated aging process accentuates the deterioration of historic wood, while the performance of the adhesive remains stable.

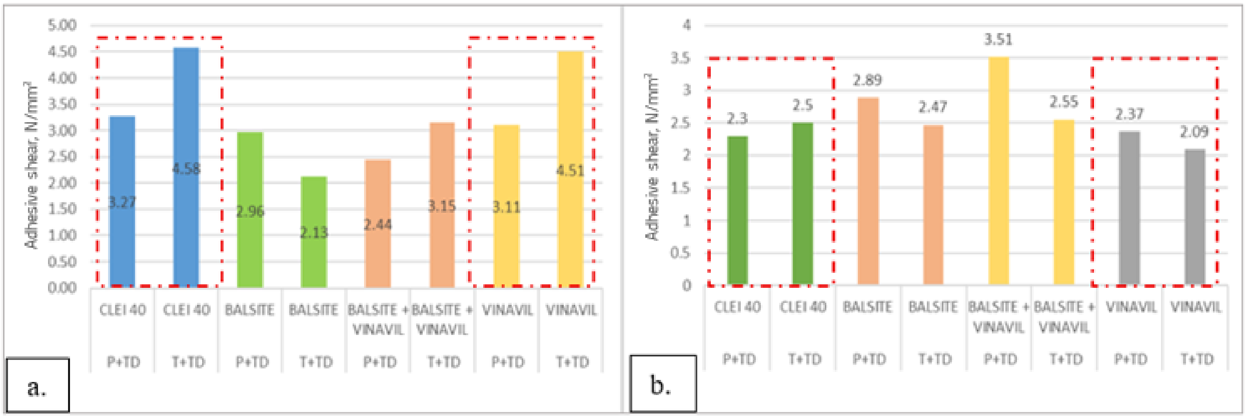


Fig. 43. a., b. Differentiated results regarding adhesive shear: a. test specimens without accelerated aging treatment, tested with ASTM 905/98 (before) and b. test specimens after accelerated aging, using standard SR-EN 302-1/ 2013.

3.5.4. Conclusions

Analyzing the results obtained from mechanical tests on the shear strength of the adhesive, both for samples subjected to accelerated aging and for those that did not undergo such treatment, it can be concluded that: gluing degraded wood to healthy wood does not result in increased resistance, regardless of the adhesive chosen. This is not from the point of view of the quality of the adhesives, but from the point of view of the historic wood damaged by xylophagous insects, which shows irregular damage and different levels of degradation.

From the point of view of the quality of the adhesives, for applications in the restoration of movable heritage, we find that all the variants chosen for testing classified these adhesives as having good gluing properties. It is recommended to select the adhesive according to the state of preservation of the historic wood.

It can also be observed that Paulownia wood (*Paulownia spp.*) causes less damage to damaged historical wood by approx. 30% to 70% compared to healthy lime wood *(Tillia spp.)*, but of course depending on the level of damage to the historical wood.

With regard to accelerated aging, no changes in flatness or surface cracks/fractures were visible on the tested specimens. However, we observed a higher frequency of historical wood fracturing, thus assessing that historical wood continues to degrade during accelerated aging.

CHAPTER 4. CASE STUDY. PROPOSAL FOR THE CONSOLIDATION OF AN ICONOSTASIS FRAGMENT WITH PAULOWNIA WOOD

4.1. History of the Iconostasis fragment

Fragment with uncertain positioning in an iconostasis frieze, originating from the old church/monastery of Vizantea, dedicated to the Holy Cross, identified in the LMI with the code MI-A-06569, today partially in ruins.

When it was discovered and brought to the "Ionescu Constantin Ștefan" restoration laboratory in Sibiu, this fragment no longer had any reference points for its correct positioning within the severely damaged panel (Fig. 43) due to xylophagous insects, and the lime wood *(Tillia spp.)* support was badly damaged and required urgent consolidation and rescue.

Fig. 43. Panel from the iconostasis frieze, dated 1650. Area marked where the fragment is believed to have been positioned.

Fig. 44. The recovered fragment of the iconostasis frieze.

4.2. . Characterization of the fragment

The intensity of xylophagous insect infestation was 270 holes/dm^2 with an average hole diameter of 1.54 mm, as determined using the Image J image processing software (Fig. 46.). This damage was caused by xylophagous insect infestation, which resulted in surface and deep damage (damaged volume, approx. 55.86%). From a mechanical point of view, the hardness of this fragment was tested using the Mark 10 device (using the Ionescu 2020 method) and compared with the reference values. It was found that this fragment had an average hardness of 2.39 N/mm^2, representing a loss of 86.1% compared to the reference hardness of healthy lime wood of 17.2 N/mm^2.

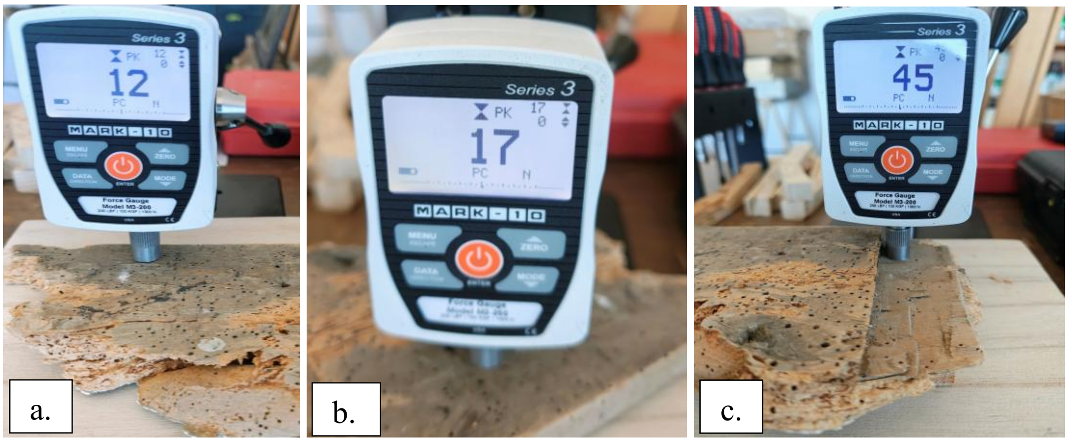


Fig. 45. a., b., c. Measuring the hardness of the historical fragment using the Mark device

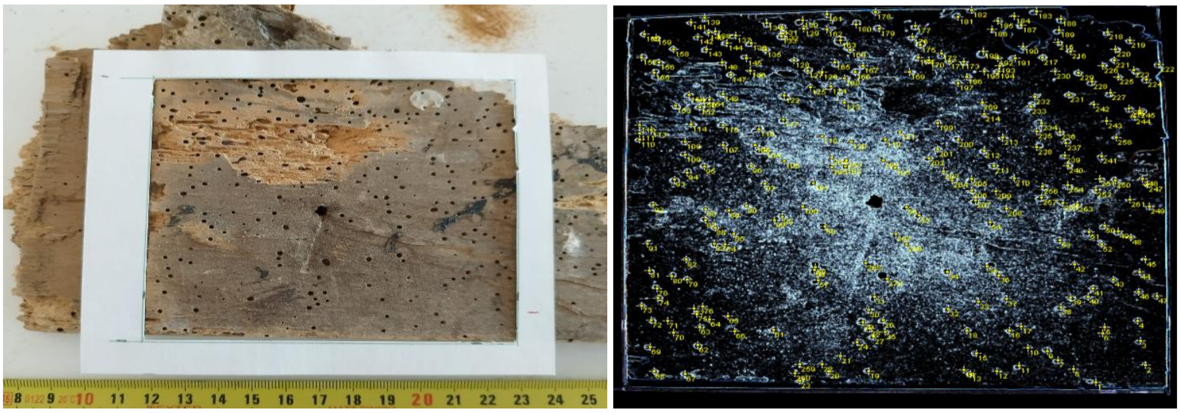


Fig. 46 a., b. Intensity of xylophagous attack per 1 dm^2 (a); Identification and counting using Image J software (b).

4.3. Proposal for filling with solid wood material - Paulownia

It is proposed to use two types of filling on the same fragment, so that half of the fragment will have one type of filling and the other half will have another type.

To reinforce the historical fragment, two types of filling will be made and prepared

1. Paulownia wood from a single board, arranged tangentially, similar to the wood in the historical fragment
2. Layered laminated Paulownia wood, with the core arranged transversally, at 90°

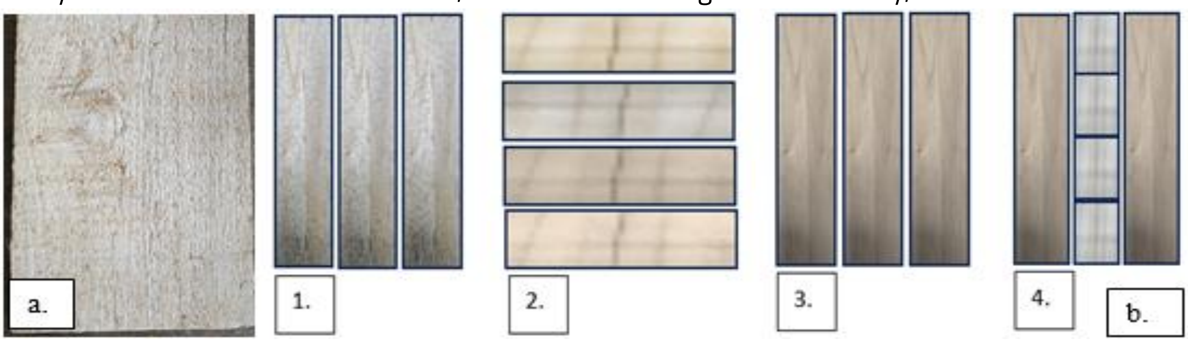


Fig. 47. a., b. The two methods of completing the panels. a. from a single board. b. laminated panel with a core arranged transversely

We wanted to put into practice the material researched and the results obtained, and to monitor the overall behavior in the restoration laboratory: historic wood with a polychrome layer and Paulownia wood, prepared in two ways: solid wood from a single board and laminated wood.

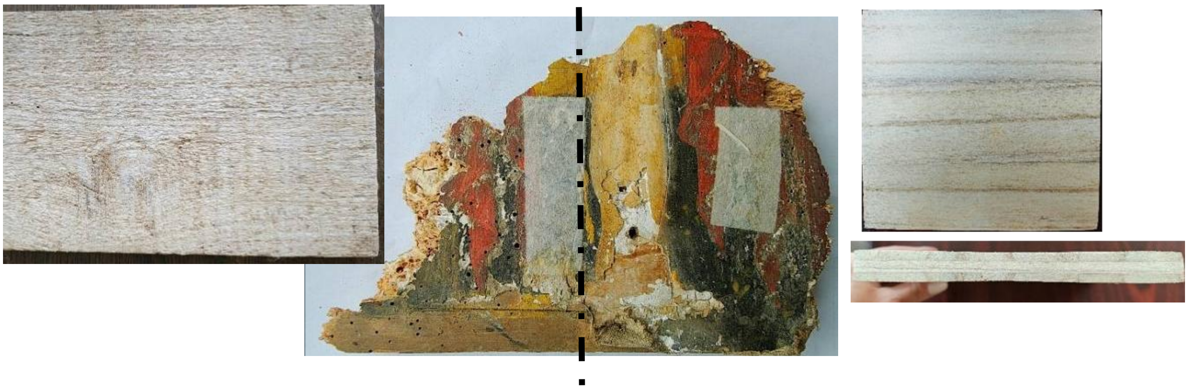


Fig. 48. Example of the arrangement of the two types of filling on the historical fragment

CHAPTER 5. GENERAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS, DISSEMINATION OF RESULTS, FUTURE RESEARCH DIRECTIONS

5.1. General conclusions

The choice of a material such as Paulownia wood (*Paulownia spp.*) for the consolidation of wooden supports in cultural heritage objects can be an alternative solution with superior advantages compared to the properties offered by balsa wood (*Ochroma pyramidale*) or those of healthy lime wood *(Tillia spp.)*.

Paulownia wood has superior physical and mechanical properties (low dimensional changes, high density, superior mechanical properties) to balsa wood and similar to lime wood (commonly found in cultural heritage works), with the proviso that it cannot be used in load-bearing structures where the loads are high.

From the study of the density of paulownia, lime and balsa wood, it was concluded that a current density of 340 kg/m^3 for Paulownia wood is low enough not to overload the damaged cultural heritage object, but also high enough to ensure optimal strength for the new assembly created by completing the geometry.

In terms of water impact, Paulownia wood had the lowest absorption, 27%, compared to 38% for lime wood and 85% for balsa wood. Thickness swelling had the same effect on the wood species analyzed, namely 5.2% for Paulownia wood and 14.9% for lime wood.

Studies and observations were conducted on the behavior of degraded lime wood in solvents during cleaning, antiseptic treatment, or consolidation, using different solvents—water, white spirit, and acetone. Maximum swelling values were obtained in acetone (6.8%), water (4.1%), and white spirit (only 0.3%). These swellings were accompanied by proportional deformations, with reduced deformations for Paulownia wood.

The mechanical properties of Paulownia wood proved to be consistent with its low density, showing moderately reduced values compared to other species. Thus, the static bending strength was 62 N/mm², compared to 92 N/mm² recorded for lime wood; compressive strength was 42 N/mm², compared to 52 N/mm² in linden, and Brinell hardness reached 14 N/mm², compared to 20 N/mm² in the same reference species. By comparison, balsa wood showed significantly lower values for all the characteristics analyzed, but these are consistent with the extremely low density of this species.

Following studies on the behaviour of degraded wood used as a support material in severely damaged polychrome lime wood panels, compared to healthy lime wood, significant differences in mechanical properties were found. Thus, healthy wood had a Brinell hardness of 17.2 N/mm², while degraded wood had a value of only 6.4 N/mm², indicating a nearly threefold decrease in this characteristic, which is essential for the structural integrity of the wooden support.

The wettability of Paulownia wood, assessed by measuring the contact angle of the drop with the material surface, was found to be very similar to that of degraded lime wood. In contrast, undegraded lime wood showed poor hydrophilic behavior in this respect. The contact angle value in the moderate to strongly hydrophilic range indicates good compatibility between the surfaces brought into contact by gluing, which promotes effective adhesion and coherent integration of the reinforcement material.

Studies and observations on the gluing properties of four adhesives/adhesive materials
used for gluing fragments of damaged lime wood and new healthy wood (using the adhesive layer gluing test) showed that, in the combination of healthy lime wood with degraded lime wood, the following occurred
destruction of the degraded wood in the shear tests. We consider the use of Paulownia wood as a filler material to be advantageous because, in the event of mechanical action, the damage occurs to the Paulownia wood, leaving the damaged lime wood intact. In the same context, we can also appreciate the easier reversibility of this wood material, without creating stress on the original wood. We can appreciate that there is also compatibility between these two wood species in terms of gluing: Paulownia wood sticks easily without causing additional stress to the original damaged lime wood.
For the accelerated ageing test, panels were made from damaged wood at different levels, with healthy lime wood and Paulownia wood added, bonded with different adhesives and subjected to extreme humidity and temperature conditions in an acclimatisation chamber. During the test, the adhesives showed no negative changes, with fractures occurring in the damaged wood. Average gluing strengths of 3 N/mm^2 were obtained.

From an economic point of view, but also in order to preserve or save native forests, we can argue in favor of using Paulownia in certain areas of production—furniture, decorative objects, paneling, restoration of heritage objects through partial filling/reinforcement, etc.—with multiple purposes: 1. To save/preserve linden forests*, which* represent less than 6% of the total forest area in the country, according to the NATIONAL FOREST INVENTORY (2008-2012), while statistical data published in 2021 (INS) announced a percentage of 7.7% for softwoods, which include linden, poplar, and willow; 2. From an economic point of view, Paulownia wood can have lower costs compared to lime wood; 3. The growth time of the tree to reach maturity for quality timber is shorter for Paulownia. Paulownia stands out as a species with promising prospects for exploitation on European timber markets, being compatible with a wide range of applications, particularly in the field of light uses. In addition, this species has the potential to replace expensive tropical woods such as balsa, thus offering a sustainable and economical alternative.

5.2. Original contributions

As part of this paper, we conducted an extensive study of the literature in this field, addressing complex issues related to Paulownia wood in comparison with lime wood and balsa wood. At the same time, we analyzed the specialized literature in the field of wood restoration with regard to the conservation of historic wood severely damaged by xylophagous insects in cultural heritage assets.
We found an extensive bibliography on the investigation of these cultural assets, but from the point of view of consolidation interventions on severely degraded wood, the literature is limited.

1. Based on the research conducted, I believe that I have succeeded in producing benefits for the field of heritage restoration, which means that I have achieved the main goal and secondary objectives.
2. I tested and proposed the possibility of using Paulownia wood, a species not previously used in the field of heritage wood restoration, for filling and reinforcement.
3. I characterized the physical and mechanical properties of Paulownia wood with a view to its use in restoration for the completion and restoration of the geometry of degraded cultural heritage

objects. These properties were compared with two wood species: healthy lime wood and balsa wood. The comparisons between the wood species mentioned were carried out as follows: healthy lime wood with damaged lime wood;

deteriorated lime wood with Paulownia
healthy lime wood with Paulownia
deteriorated lime wood with balsa
deteriorated lime wood with balsa

4. I researched, tested, and proposed Paulownia wood as a filling and reinforcement material for severely damaged panels. Tests show that Paulownia wood has good dimensional stability and low density, so it does not add excessive weight to the severely damaged historic panel. It has mechanical properties similar to healthy lime wood, while also providing mechanical strength to the historic panel, whose statics are endangered. In terms of moisture absorption, it is highly hydrophilic, making it compatible with damaged lime wood in the context of gluing. Furthermore, its dimensional stability in relation to deformation under the action of a humid environment (water, solvents) is insignificant, resulting in minimal stress transfer to an assembly composed of historic polychrome wood and healthy wood fillers.

5. Using Image J software, we measured the contact angle of the drop on the wood surface to determine the wettability of the tested wood species.

6. I developed a new gluing concept using the two-component Balsite. This can be considered as a gluing material, as it has been shown to have good adhesive properties in shear tests. Furthermore, it is a good equalizer for damaged or excessively porous surfaces, and after drying, another adhesive with superior properties can be applied to complete and consolidate the panels of severely damaged heritage objects.

7. I have argued that this wood material (Paulownia), introduced as a novelty in the field of restoration, in applications for the consolidation of wooden supports severely damaged by xylophagous insects, does not cause additional stress to the historical object, and evolutionary degradation is significantly reduced.

8. I transferred the research from the theoretical to the practical level and proposed a viable technical solution for saving historical panels with paintings and sculptures from the Romanian cultural heritage. In this context, we made a laminated panel, with a transfer core, from Paulownia wood to complete a fragment of a 17th-century historical panel on one side of the fragment, and on the other side, we made a solid Paulownia wood addition from a single board. The whole thing will be monitored for at least 12 months.

9. Registration with OSIM of a patent for an invention developed by the research team consisting of Avram Anamaria, Ionescu Constantin Ștefan, and Lunguleasa Aurel. The patent has registration number (11) 137192 A0 (RO-BOPI 12/2022), with the title *Minimally invasive device used in the restoration of wooden heritage objects to determine hardness and resistance using a piercing tip dynamometer.* This method is intended for use in the field of restoration to assess the state of conservation and degradation of wooden panels and cultural heritage objects.

Therefore, I believe that the objectives set out in the thesis have been fully achieved, both from a theoretical perspective and in terms of the practical applications developed. The results obtained highlight a significant contribution to the enrichment of knowledge in the field of restoration of wooden art objects, contributing to the scientific basis of interventions and the optimization of conservation strategies.

5.3. Future research directions

This research paper does not aim to exhaust the subject matter defined by the objectives set, but, like any scientific endeavor, focuses on specific activities and actions. Consequently, it can be said that there are numerous research directions that can be addressed or expanded in the future, these deriving directly from the results of the study, among which the following can be mentioned:

- ✓ Research on the durability of Paulownia wood against rot and wood-decaying fungi
- ✓ Tests and research on the durability of wood against xylophagous insects
- ✓ Research on the application of heat treatments—torrefaction of Paulownia wood. Additional research on the applications of Paulownia wood after heat treatments
- ✓ Characterization of other wood species found as supports in heritage assets and observed in terms of compatibility with Paulownia wood, when additions and reinforcements are needed in restoration applications
- ✓ Research and observation of the behavior of historic wood in contact with other solvents used in restoration treatments
- ✓ Establishment of a hierarchy regarding the relationship between toxicity and effects on historic wood (with repercussions on creation)

5.4. Dissemination of results

During my four years of doctoral studies, I published six ISI articles, registered a patent, and participated in international and national conferences. All of these are presented below:

6 ARTICLES PUBLISHED (ISI Web of Science)

1. **Avram**, A., Lunguleasa, A., Spirchez, C., Ionescu, C.Ș. (**2023**). Differences and Similarities between the Wood of Three Low-Density and Homogenous Species: Linden, Balsa, and Paulownia. Appl. Sci. 13, 10209. https://doi.org/10.3390/app131810209
2. **Avram** (Moraru-Avram), **A.**, Ionescu, C.Ș. and Lunguleasa, A. (**2023**). Effects of Solvents Used for Conservation/Restoration Treatments on Damaged Linden Panels of Cultural Heritage Assets, Applied Sciences, 13 (20) 11148. https://doi.org/10.3390/app132011148
3. **Avram, A.**, Ionescu, C.Ș., Lunguleasa, A. (**2023**). A consolidation of degraded lime wooden support from heritage objects using two types of consolidant, *BioResources*, 18(3):4580-4597. https://www.proquest.com/scholarly-journals/consolidation-degraded-lime-wooden-support/docview/2857625777/se-2. doi: https://doi.org/10.15376/biores.18.3.4580-4597
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5. **Avram, A.,** Ionescu, C.Ș., Lunguleasa, A.(**2022**). Some Methods for the Degradation-Fragility Degree Determination and for the Consolidation of Treatments with Paraloid B72 of Wood Panels from Icon-Type Heritage Objects. *Forests*, *13*, 801. https://doi.org/10.3390/f13050801
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1 BREVET INVENȚIE

Avram, Anamaria; Ionescu, Constantin Ștefan; Lunguleasa Aurel Minimally invasive device used in the restoration of wooden heritage objects to determine hardness and strength using a pin-point dynamometer, RO137192 (A0) – 2022-12-30. Patent application number RO20220000532 20220831.

PARTICIPATION IN INTERNATIONAL AND NATIONAL CONFERENCES

2023 – November—Transylvania University of Brașov, Faculty of Furniture Design and Wood Engineering, Brașov, **Anamaria Avram**, Constantin Ștefan Ionescu, and Aurel Lunguleasa, "Effects of Solvents Used for Conservation/Restoration Treatments on Damaged Linden Panels of Cultural Heritage Assets," The 13th edition—Wood science and engineering in the third millennium (**ICWSE 2023**)

2021 – june – Lucian Blaga University, Engineering Faculty, Sibiu, Ionescu Constantin Ștefan, Lunguleasa Aurel, **Avram Anamaria**. and Spirchez Cosmin Gheorghe „Evaluation of the efficiency of the consolidation treatment with Paraloid b72, performed on artworks with degraded wood support” The 10th International Conference on Manufacturing Science and Education (**MSE 2021**)

2021 – November – National Museum of Unification, Alba Iulia, **Avram Anamaria** "Cultural heritage interpreted as a composite element. Damage caused by the matrix" Scientific Session UNITY, CONTINUITY, AND INDEPENDENCE IN THE HISTORY OF THE ROMANIAN PEOPLE.

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