



Improving plywood performances through hybridisation with plant fibres composites: a comparative analysis of quasi-static properties, failure kinetics and fatigue behaviour

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Received: 30 September 2025

Accepted: 25 February 2026

Published online:
17 March 2026

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ABSTRACT

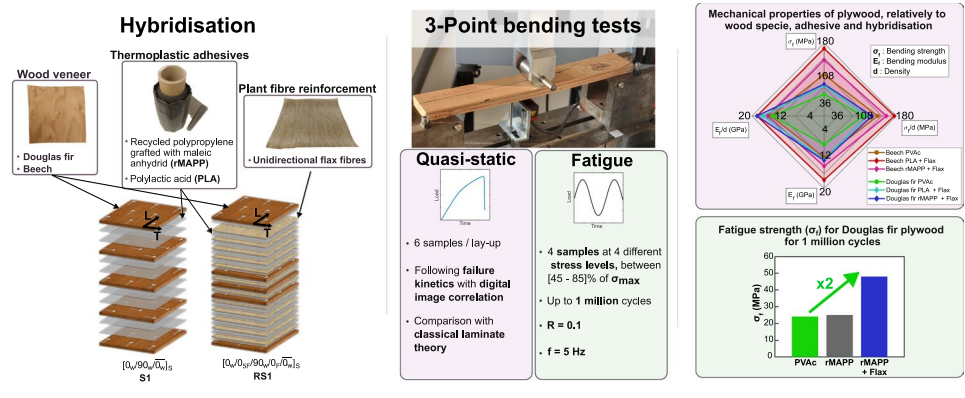
This study explores the hybridisation of wood veneers with plant fibre-reinforced thermoplastic composites. Beech and Douglas fir plywood are made using environmentally friendly adhesives, polylactic acid (PLA) and recycled maleic anhydride-grafted polypropylene (rMAPP). Hybridised plywood is produced by incorporating flax fibres at specific locations within the lay-up. The mechanical performances of these hybrid laminates are assessed through 3-point bending tests. The results show that hybridisation enhances bending modulus and strength in nearly all tested configurations: the bending modulus increased by up to 24% in beech and 31 in Douglas fir, whereas bending strength gains reached up to 27 and 79%, respectively. Predictions based on classical laminate theory align closely with experimental data, validating its use for estimating the elastic properties of hybrid laminates. Additionally, the failure kinetics reveal that hybridisation enables stress redistribution within the composite layers, leading to improved bending strength even when outer veneers are damaged. A fatigue study under cyclic bending loads further demonstrates that hybridisation can double the fatigue strength of Douglas fir plywood over 1 million cycles compared to its non-hybrid counterpart. These findings highlight the potential of hybrid laminates to improve the mechanical performance and durability of wood-based composites for structural applications.

Handling Editor: Jaime Grunlan.

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GRAPHICAL ABSTRACT



Introduction

The ongoing and increasing climatic crisis necessitates that industries explore alternatives to oil-based and high energy-intensive costs materials. New policies suggest increasing the use of wood and wood-based products in construction and expanding their applications to reduce industrial carbon emissions through material substitution while enhancing the carbon sink capacity of natural materials [1].

Given the limited wood resources, it is essential to valorise new wood species, currently limited to low-value applications, often due to their defects and property variability. Douglas fir is a highly interesting wood species due to its good mechanical properties and the remarkable durability of its heartwood. However, its relatively recent introduction to Europe has led to its underuse, and its rapid growth causes a rapid increase in the large-diameter standing stocks [2]. Recent studies suggest that expanding the use of Douglas fir in the plywood industry could be an effective strategy to enhance its valorisation and broaden its range of applications [3].

Laminated products like plywood allow to homogenise mechanical properties and to reduce defect impact, which historically facilitated their use in transportation applications [4, 5]. However, despite these advancements, their mechanical performance remains lower and their property variability higher than most synthetic materials such as glass fibres [6], currently limiting their use to applications that allow for high safety factors.

As a result, studies investigating the use of wood products in fatigue-sensitive applications are less

common and often date back several decades. Kommers et al. [5] realised in 1960 a study for the “Army Navy-Civil Committee” on timber or plywood samples from various wood species. This study revealed comparable fatigue strength under repeated bending across the different wood forms (planks and plywood), with values ranging from 40 to 50% of their static bending strength at 1 million cycles, and from 30 to 40% at 10^8 cycles. It also suggested the existence of an asymptotic fatigue limit, below which specimens would not fail due to fatigue. However, this hypothesis has been questioned by subsequent studies that did not observe such a threshold [7, 8]. The review of Tsai and Ansell [7] also reports fatigue strength values for wood and wood products between 25 and 40% of their static bending strength at 1 million cycles. These values are far inferior to those of CFRP (70–85% [9]), which restricts the suitability of wood products for applications involving fatigue loading.

In this context, the hybridisation of wood products with fibrous composite materials aims to enhance their mechanical properties while reducing variability, thereby increasing material reliability and enabling more efficient resource use. Although this approach has proven effective, it is predominantly implemented using synthetic fibre composites and petroleum-based thermoset matrices [10].

Plant fibres, such as flax and hemp, whose specific mechanical properties can be compared to glass fibres, offer an alternative for the hybridisation of wood products. The recent regain of interest for these fibres in the scientific community and the development of varieties selection, cultivation and fibre transformation process allowed for the development of competitive,

high-performance composites, with a reduced variability [11]. Plant fibres display a fatigue strength of about 55% of their ultimate tensile strength [12]. Stiffening observed during the early fatigue cycles further supports their relevance for fatigue-loaded applications [13].

Jorda et al. [14] tried to hybridise plywood with natural fibres, but reported no significant enhancement in laminate mechanical performance. However, other studies have demonstrated improvements in mechanical properties after hybridisation across various wood and fibre species, therefore showing that the resulting efficiency of hybridisation is highly dependent on the quantity and positioning of the reinforcements [15–18].

Furthermore, none of these studies have investigated the effect of hybridisation on the failure kinetics of modified plywood. Such analyses are needed to identify how hybridisation modifies the failure mechanisms of laminated wood products, but also to get a deeper understanding of the reinforcement mechanisms. Merhar [19] investigated the failure of conventional plywood and evaluated which failure criteria, originally developed for composite materials, best predict the bending strength of plywood based on the strength of its constituent veneers. The study demonstrated that most of these criteria tend to underestimate the bending strength. This difference is attributed to the fact that these models do not account for the influence of adjacent layers in delaying failure of weaker layers, particularly the reinforcement provided by longitudinal layers to transverse layers.

Regarding failure behaviour, hybridisation can significantly modify the mechanical response of laminated structures. Wisnom et al. [20] investigated the failure mechanisms of glass/carbon hybrid composites and demonstrated that what they call the “hybrid effect” leads to an increase in both failure strain and apparent failure stress of the carbon plies. This effect is associated with the progressive fragmentation of the carbon layer. Failure initiates with the rupture of the weakest fibres, governed by the statistical distribution of fibre strength. In non-hybridised carbon composites, such local fibre breaks rapidly develop into critical clusters, leading to unstable crack propagation and premature laminate failure. In contrast, in hybrid composites, the beginning of fragmentation is followed by stress redistribution within the laminate, while the surrounding glass plies, characterised by a higher

maximum strain, provide mechanical constraint that delays cluster growth and crack propagation. As a result, failure progresses through a continuous fragmentation process, allowing a greater fraction of the intrinsic strength distribution of the carbon fibres to be exploited. By analogy, hybridising plywood with high-strain, high-strength composite plies may promote similar mechanisms, potentially delaying failure initiation and modifying failure kinetics in bending, thereby enhancing the structural performance of hybrid laminated wood products.

Finally, thermoplastics also offer a viable alternative to the conventional adhesives used in the plywood industry, which are predominantly petroleum-based and formaldehyde-containing, with known carcinogenic properties [21]. Previous study have demonstrated the good interlaminar shear strength obtained for plywood glued with recycled polypropylene grafted with maleic anhydride (rMAPP) or with a polylactic acid (PLA) resin [22].

This study aims to develop a hybrid laminate tailored for applications in the transport industry, using second-grade veneers, thermoplastic adhesives and unidirectional flax tape. The stacking sequence was optimised in a previous work [23] to ensure a significant flax contribution, thereby avoiding the low flax content reported in some studies that led to negligible effects. An experimental 3-point bending campaign is first presented to assess the impact of hybridisation on the mechanical behaviour of various laminate configurations. The mechanical properties obtained with the selected lay-up are discussed, along with the improvements achieved through hybridisation. The experimentally measured bending moduli are then compared with theoretical predictions based on classical lamination theory to assess the validity of this approach for predicting the mechanical properties of hybrid laminates. The failure kinetics of the samples are also analysed to provide insight into the mechanisms by which hybridisation enhances bending strength. The comparison with classical lamination theory, combined with the analysis of failure kinetics, brings significant originality to this work relative to existing studies on wood product hybridisation with plant fibres, as it enables a deeper understanding of the mechanisms underlying the effects of hybridisation on the material. Finally, the suitability of the developed laminates for transportation applications is investigated through a fatigue study, conducted to evaluate the performance of hybrid plywood under

cyclic loading, an aspect that, to the authors' knowledge, has not been previously explored.

Experimental

Materials

The studied materials consist of veneers from beech (*Fagus sylvatica*) and Douglas fir (*Pseudotsuga menziesii*), sourced from Centre-Val de Loire and Bourgogne-Franche-Comté (France), respectively. The veneers were peeled and supplied by LaBoMaP (Laboratoire des Matériaux et Procédés) in Cluny, France. Beech veneers have a thickness of 2 mm, while Douglas fir veneers were peeled to 3 mm to facilitate handling due to their brittleness in the transverse direction. Douglas fir veneers are considered secondary-grade due to the presence of knots and cracks. After cutting, the veneers were dried and stored under ambient conditions. Whenever possible, veneers from the same tree were used within each test to minimise variability arising from differences between individual trees.

This study examines three different adhesives. The first is a recycled polypropylene derived from agricultural waste, supplied by Adivalor (Lyon, France). To enhance its adhesion properties with wooden materials, it is mixed with 5 wt% of maleic anhydride-grafted polypropylene (rMAPP), specifically Polybond® 3200, which contains 1 wt% of pure maleic anhydride (MA), supplied by Brenntag (Chassieu, France). The mixture is processed into 100 µm thick films using a calender extruder. It has a melt flow index (MFI) of 6 g/10 min (measured at 230 °C with a 2.16 kg load). It has an elastic modulus of 1.6 GPa, a tensile strength of 29.0 MPa and a ultimate tensile strain of $918 \pm 45\%$ (values measured by [24], at ambient temperature).

The second adhesive is a polylactic acid (PLA) resin provided by Natureplast (Mondeville, France) and labelled "PLE 005", with a crystallinity index ranging between 30 and 40%. It is also processed into films, with a final thickness of 100 µm using a calender extruder. This PLA adhesive has an MFI of 10 g/10 min (measured at 190 °C with a 2.16 kg load), a tensile modulus of 3.5 GPa, a tensile strength of 50 MPa and an ultimate tensile strain of approximately 5% (values given by the supplier, at ambient temperature). The PLA films are conditioned in a climatic chamber at 60 °C during at least 3 h before use.

As a reference adhesive, a commercially available polyvinyl-acetate-based wood glue (PVAc), Paracol Wood D3®, supplied by DL Chemicals (Waregem, Belgium), is also included in the study. It has a tensile modulus of 1.7 GPa and a tensile strength of 15 MPa (values indicated by the supplier).

The reinforcements consist of unidirectional flax fibre tapes (FlaxTape®) provided by Ecotechnil (Valliquerville, France). This tape has an areal density of 110 g/m². Prior to manufacturing, the fibres are conditioned for at least 48 h at 23 °C and 50% RH to minimise variability in mechanical properties due to moisture content [25]. Flax fibres are reported in the literature to have a tensile modulus ranging from 37 to 75 GPa, a tensile strength between 595 and 1510 MPa and an ultimate tensile strain varying from 1.6 to 3.6% [11].

Laminates are produced through thermocompression at 180 °C under a pressure of 1 MPa. The heating time varies depending on the material: around 45 min for non-reinforced beech laminates and 1 h for non-reinforced Douglas fir laminates. For reinforced laminates, heating times increase to around 50 min for beech and around 65 min for Douglas fir. The fabrication process has previously been studied and is extensively described in Prunier et al. [22].

Methods

Lay-up

Two stacking sequences are used for this study and are shown in Figure 1. These laminates are made of 5 veneers that follows a crosswise orientation pattern, typical of the usual lay-up found in industrial plywood. These stacking sequences have been optimised in a previous study [23]. The laminate S1 (sequence 1) follows a stacking sequence $[0_W/90_W/\overline{0}_W]_s$, "W" indicating a wood veneer. The RS1 (reinforced sequence 1) stacking sequence follows the same veneer stacking sequence as S1, but with the addition of several plies of flax-rMAPP or flax-PLA composites between the veneers, giving laminations of $[0_W/0_{5F}/90_W/0_F/\overline{0}_W]_s$ and $[90_W/0_{5F}/0_W/0_F/90_W]_s$, respectively, F indicating a flax layer. When reinforcements are present, each flax layer is surrounded by two adhesive films.

After manufacture, plywood is cut into 5 or 6 samples using a table saw, following the recommendations of the EN310 standard for bending tests on wood panels [26]. Figure 2 shows the shape and dimensions

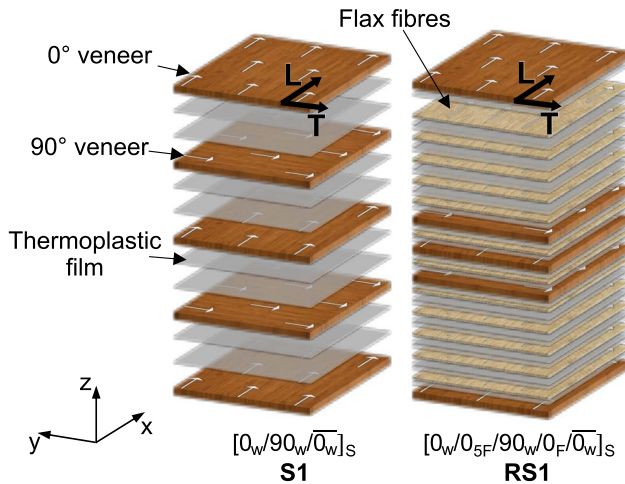


Fig. 1 Schematic representation of the lay-up of 5-ply plywood with (RS1) and without (S1) reinforcement, used for bending and fatigue tests. In the lay-up sequence, W indicates a wood veneer, and F a flax fibre layer

of the Douglas fir and beech samples, with flax fibre reinforcement. The thickness shown is representative of an average sample, but may vary from sample to sample.

Quasi-static 3-point bending

The 3-point bending test used in this study is based on standard EN310 [26].

In order to limit the effect of plane shear stress, the standard imposes a condition on the ratio between the length (l) of the sample and its thickness (e), as

$$l = 20 \times e. \quad (1)$$

The bending modulus E_f is expressed according to the equation

$$E_f = \frac{l^3(F_2 - F_1)}{4be^3(a_2 - a_1)}, \quad (2)$$

where F_1 and F_2 are two load values taken from the elastic part of the test force–displacement curve. According to EN310, F_1 corresponds to 10% of the maximum load value F_{max} and F_2 corresponds to 40%. The values a_1 and a_2 represent the mid-span deflection values when $F = F_1$ and $F = F_2$, respectively. Sample dimensions are represented by thickness e , width b and length l .

The maximum stress σ_{max} reached is calculated using the following equation

$$\sigma_{max} = \frac{3F_{max}l}{2be^2}. \quad (3)$$

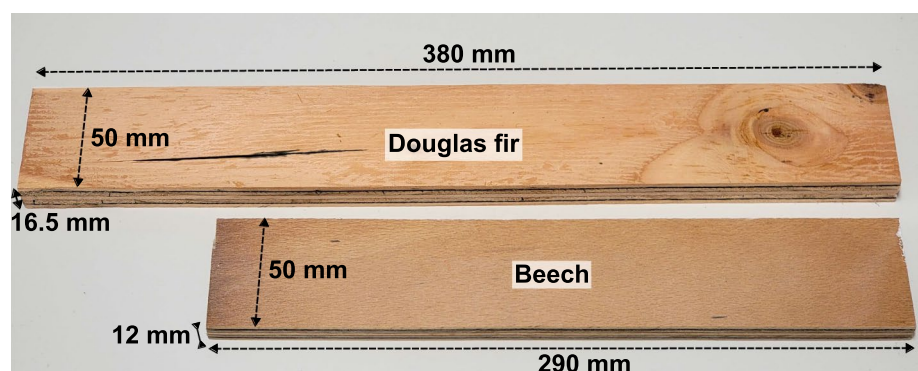
Table (1) shows the different species/adhesive/lay-up configurations tested in 3-point bending.

Tests are carried out on an Instron ElectroPuls E10000 machine, as well as on an MTS C45 machine (Figure 3). 10 kN load cells are used for all tests. A laser sensor located under the sample, with a measurement range of 10 mm, is used to measure the mid-span deflection. The tests are displacement-controlled, with a crosshead displacement speed of 6 mm/min and a data acquisition frequency of 50 Hz. Strain fields in longitudinal, transversal and planar

Table 1 Summary of the configurations wood species/adhesive/lay-up, tested in quasi-static 3-point bending

Wood species	Adhesive	Lay-up
Beech; Douglas fir	rMAPP; PLA	S1; RS1
Beech	PVAc	S1
Douglas fir	PVAc	S1

Fig. 2 Picture of 3-point bending samples made of beech and Douglas fir with flax fibres reinforcements (RS1)



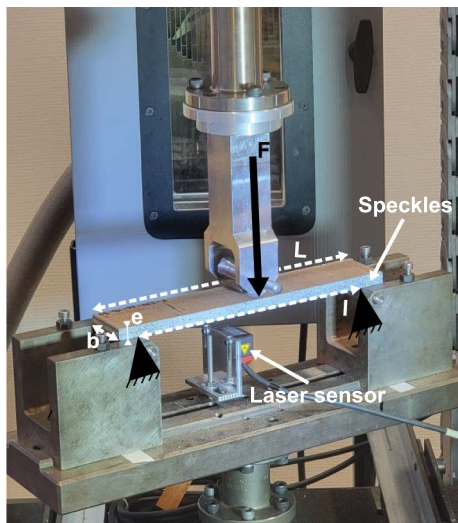


Fig. 3 Experimental set-up used for 3-point bending tests

shear direction are measured during the test by digital image correlation.

Digital image correlation (DIC)

Digital image correlation techniques are used as a way to measure the strain fields in the samples during the bending tests. Speckles are realised by spray-painting the sides of the samples. The analysis is then realised using the software INSPECT Correlate[®], part of the Zeiss Quality Suite[®]. Strain fields in different directions can then be analysed at key stages of the test to gain deeper insight into the failure mechanisms and kinetics of the specimen.

X-ray microtomography observations

Some specimens are imaged using X-ray computed tomography (CT) on an EasyTom system from RX Solution, with X-ray projection images acquired via a 2530DX detector at a resolution of 2176×1792 pixels². Following reconstruction, grey-level-based segmentation techniques are applied to highlight different components within the scans, including wood cell walls, flax fibres, adhesive regions and voids. Segmentation using machine learning is carried out either through the deep learning segmentation tool in VG StudioMax 2023.1 or the Trainable Weka Segmentation (TWS) plugin in Fiji [27]. In the case of TWS, the classification process uses the mean grey-level intensity and

Table 2 Summary of the wood species/adhesive/lay-up configurations and associated stress levels tested in fatigue

Wood species	Adhesive	Lay-up	Stress levels (% $\sigma_{\max}$)
Douglas fir	rMAPP	S1	50;60;65;70
Douglas fir	rMAPP	RS1	70;75;80;85
Douglas fir	PVAc	S1	45;50;60;70

variance of labelled pixels, which are assigned to pre-defined classes.

Fatigue tests

To date, plywood and wood-based panels in general have rarely been used in applications requiring fatigue performance. As a result, no test standard exists for defining the fatigue properties of these materials. The test parameters selected here are therefore based on EN310, which is used for quasi-static bending tests, and on the laboratory's experience in this field. The experimental set-up is similar to that used for 3-point bending tests (Figure 3).

Each laminate is subjected to four different stress levels, with four samples tested at each level. Each stress level corresponds to a percentage of the maximum stress at failure obtained in the 3-point bending tests. A loading frequency of 5 Hz is chosen to limit the effect of self-heating on the samples. The loading signal used is sinusoidal. The load ratio R , defined as the ratio between the minimum and maximum load, is 0.1.

The test duration is limited to 1,000,000 cycles in order to limit the duration of the test campaign. Table 2 summarises the wood species/adhesive/lay-up and associated stress levels for fatigue-tested samples.

For this testing method, Douglas fir is the only species studied. This choice is made to enable an in-depth analysis of this species, which is the one requiring valorisation. As for the adhesive, rMAPP was chosen, in line with the results of a preliminary study of interlaminar shear strength before and after ageing [22]. PVAc adhesive is also studied to provide a reference value. The maximum stress levels to which the samples were subjected are defined regarding the mechanical strength values measured in quasi-static 3-point bending tests. They are chosen for each configuration studied progressively over the course of the study, to best illustrate the fatigue performance range of each configuration.

Theoretical approach: classical lamination theory

The aim of this approach is to determine the optimum lamination to meet the material's specifications and to visualise the stress distribution in the thickness of the laminate in order to better understand its mechanical behaviour.

The “corrected” lamination theory is adapted from the work of Wei et al. [28] and considers the diffusion of the adhesive in the veneers by considering it as a new ply, whose properties are a mix between those of the wood cell wall and those of the adhesive.

The mechanical properties used to predict plywood properties are taken from the literature and from tools used to estimate mechanical properties, such as the law of mixtures. The values and methods used to calculate missing values are presented more in depth in the A.1.

Statistical analysis

The analysis employs a range of statistical methods to interpret the results. When the data distribution is normal, results go through a one-way ANOVA test to examine if the values originate from the same distribution. To further investigate significant differences, Tukey's range test is applied for multiple comparisons. Tukey's tests results are marked by letters, indicating values originating from the same statistical distribution. The *p* value represents the probability of observing the obtained results, or more extreme ones, under the assumption that the two datasets originate from the same distribution (i.e. the null hypothesis is true). A *p* value below 0.05 is considered statistically significant and suggests that the two datasets likely come from different distributions.

For samples where the data distribution does not meet the normality requirement for ANOVA, a Kruskal–Wallis test, a nonparametric alternative, is used to determine whether the samples originate from the same distribution. This is followed by Dunn's test, which performs multiple comparisons to identify significant differences in result means. To control Type I errors, the Holm–Sidak correction method is applied.

Additionally, values falling outside $Q1/Q3 \pm 1.5$ times the interquartile range (IQR) are classified as outliers.

Results and discussion

3-point bending

Experimental results

The bending modulus and stress at failure obtained from 3-point bending tests for the different laminates are presented in Figs. 4 and 5, with detailed values provided in Table 4.

Mean values are indicated by coloured bars, grey for non-reinforced laminates and blue for reinforced ones. Tukey statistical test results are annotated with letters next to mean values, indicating significant differences between groups.

For specific mechanical properties, mean values, standard deviations and statistical test results are marked with light blue diamonds, bars and letters, respectively. These values are obtained by dividing mechanical properties by the laminate density. The density measurements, averaged over four samples extracted from bending samples, are listed in Table 3.

It should be noted that the stress-at-failure values presented correspond to equivalent stress, calculated following the EN310 standard [26], which assumes the material being homogeneous.

The results regarding the choice of adhesive will be presented first, for each wood specie studied, and then, the results regarding the effect of hybridisation on the mechanical properties will be discussed.

Table 3 Density (ρ) for each configuration (materials and lay-up)

Adhesive	Lay-up	ρ (kg/m ³)	SD	CoV (%)
<i>Beech</i>				
rMAPP	S1	784	11.1	1.4
	RS1	891	10.9	1.2
PLA	S1	854	10.1	1.2
	RS1	953	8.7	0.9
PVAc	S1	771	4.9	0.6
<i>Douglas fir</i>				
rMAPP	S1	551	15.2	2.8
	RS1	663	10.2	1.5
PLA	S1	592	34.4	5.8
	RS1	716	33.8	4.7
PVAc	S1	552	28.3	5.1

SD standard deviation, CoV coefficient of variation

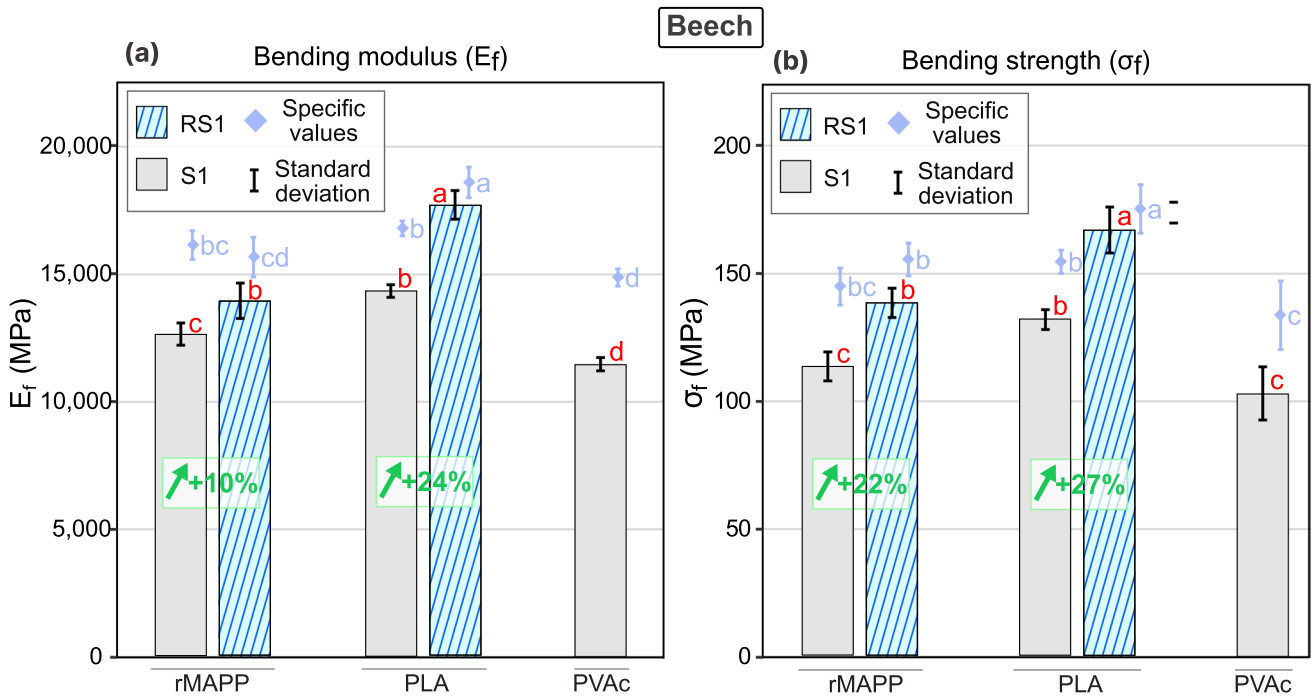


Fig. 4 Bending modulus (a) and bending strength b for S1 and RS1 laminated beech plywood. Grey bars mean values for S1 laminates, blue striped bars mean values for RS1 laminates,

error bars $\pm$ standard deviation, blue dots and bars mean specific value $\pm$ standard deviation, letters Tukey statistical test results

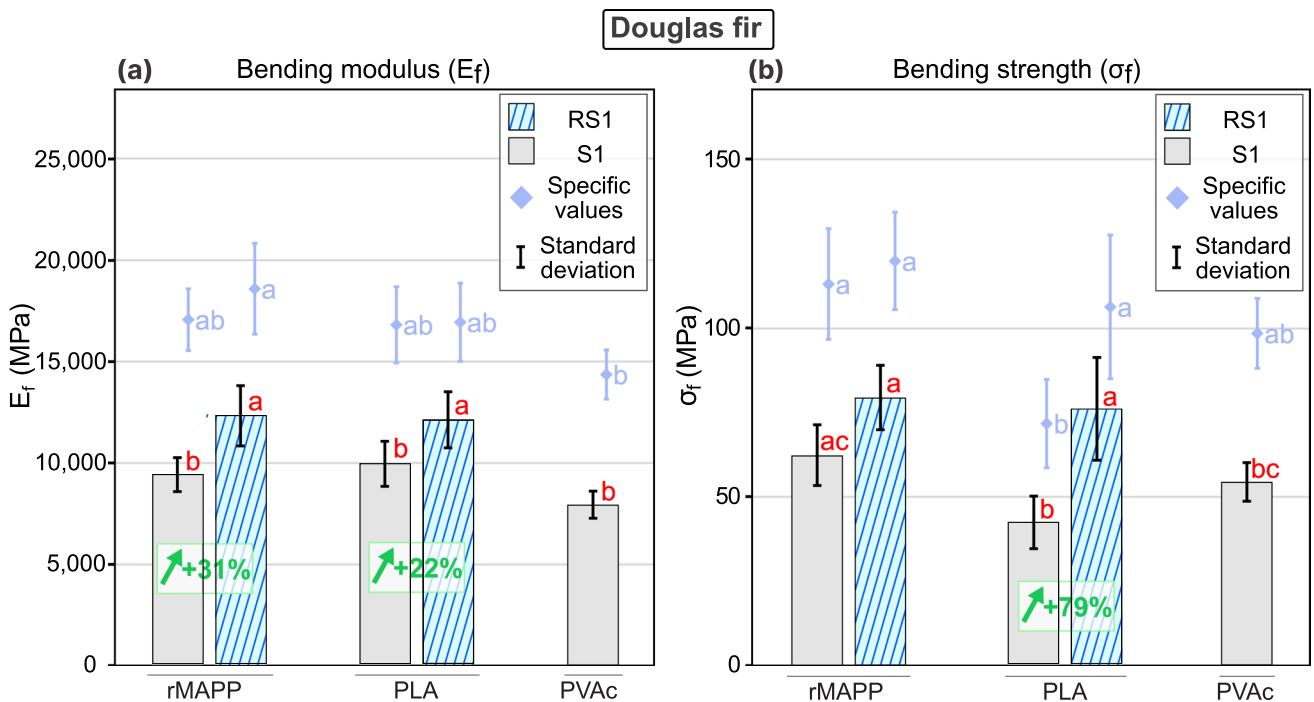


Fig. 5 Bending modulus (a) and bending strength b for S1 and RS1 laminated Douglas fir plywood. Grey bars mean values for S1 laminates, blue striped bars mean values for RS1 laminates,

error bars $\pm$ standard deviation, blue dots and bars mean specific value $\pm$ standard deviation, letters Tukey statistical test results

Table 4 Results of the 3-point bending tests

Adhesive	Lay-up	E_f (MPa)	E_f/d_e (MPa)	CoV (%)	σ_f (MPa)	σ_f/d_e (MPa)	CV (%)
<i>Beech</i>							
rMAPP	S1	12,632	16,114	3.5	113.6	144.9	5.0
	RS1	13,935	15,645	5.0	138.5	155.5	4.1
PLA	S1	14,317	16,766	1.7	131.9	154.5	2.9
	RS1	17,718	18,590	3.2	167.0	175.3	5.4
PVAc	S1	11,452	14,847	2.3	103.1	133.7	10.0
<i>Douglas fir</i>							
rMAPP	S1	9408	17,063	8.9	62.3	113.0	14.5
	RS1	12,317	18,589	12.1	79.4	119.8	12.0
PLA	S1	9955	16,822	11.2	42.4	71.6	18.3
	RS1	12,129	16,947	11.4	76.0	106.2	20.0
PVAc	S1	7936	14,366	8.5	54.3	98.3	10.5

Figure 4 presents the bending modulus and bending strength results for beech plywood, comparing S1 and RS1 laminations with different adhesives. The use of rMAPP and PLA adhesives significantly enhances the bending modulus compared to the reference PVAc adhesive, with p values of ($p < 3.4 \cdot 10^{-3}$) and ($p < 2 \cdot 10^{-9}$), respectively. However, regarding bending strength, only beech-PLA plywood exhibits a statistically significant increase compared to beech-PVAc plywood ($p < 4.9 \cdot 10^{-6}$). Additionally, beech-PLA plywood outperforms beech-rMAPP plywood in both bending modulus ($p < 4.4 \cdot 10^{-5}$) and bending strength ($p < 3.4 \cdot 10^{-3}$). The reference beech-PVAc plywood shows a bending modulus comparable to the 11,546 MPa reported by Jorda et al. [29] for beech-UF plywood. However, its bending strength is slightly lower, averaging 103.1 MPa, compared to 112.8 MPa in the study by Jorda et al. [29].

Figure 5 presents the bending modulus and bending strength values for Douglas fir plywood, comparing S1 and RS1 laminations.

Conversely, Douglas fir-PVAc plywood demonstrates bending properties in line with industrial references, reinforcing its consistency with existing data. The bending modulus values for Douglas fir-rMAPP and Douglas fir-PLA plywoods are also comparable to those reported by Biblis and Carino [30] for five-ply “southern pine” plywood bonded with PF resin, which has a bending modulus of 10,149 MPa, a value similar to Douglas fir plywoods, as noted by Bergman et al. [31]. However, the bending strength value of approximately 70 MPa reported by Biblis and Carino [30] exceeds the results obtained in this study for Douglas fir-rMAPP plywood and is significantly

higher than those recorded for Douglas fir-PLA and Douglas fir-PVAc plywoods. The bending modulus and strength values for Douglas fir-rMAPP and Douglas fir-PLA plywoods surpass those reported by Bergman et al. in the Wood Handbook [31] for industrial Douglas fir plywood, which lists values of 7450 and 41.37 MPa, respectively.

No significant differences are observed in bending modulus or strength between Douglas fir-rMAPP and Douglas fir-PVAc ($p > 0.69$, $p > 0.25$) or between Douglas fir-PLA and Douglas fir-PVAc ($p > 0.058$, $p > 0.31$). However, Douglas fir-rMAPP shows significantly higher bending strength than Douglas fir-PLA ($p < 0.035$).

The incorporation of fibre reinforcements in hybrids using RS1 lamination significantly enhances both elastic modulus and bending strength compared to their non-reinforced counterparts with the same adhesive (S1 lamination).

For beech-rMAPP plywood, the addition of flax fibres leads to a notable increase in elastic modulus ($p < 1.2 \cdot 10^{-3}$), rising from 12,632 MPa to 13,935 MPa (+10.3%), and in bending strength ($p < 9 \cdot 10^{-5}$), increasing from 113.6 MPa to 138.5 MPa (+21.5%). A similar trend is observed for beech-PLA plywood, where the bending modulus ($p < 5.8 \cdot 10^{-11}$) increases from 14,317 MPa to 17,718 MPa (+23.8%), and bending strength ($p < 1.8 \cdot 10^{-7}$) rises from 131.9 MPa to 167 MPa (+26.6%). The bending modulus and bending strength values obtained for beech-rMAPP and beech-PLA plywood with RS1 lamination significantly exceed those reported by Jorda et al. [29] for beech-UF plywood reinforced with flax fibres in a similar configuration. Their study reported a

modulus of 11,734 MPa and a bending strength of 118.2 MPa, highlighting the superior mechanical performance of the RS1 hybrid laminates developed in this work. This difference can be attributed to the higher amount of fibrous reinforcements in the present work.

An examination of the specific property values reveals that the density increase resulting from flax fibre reinforcement, due to its higher density compared to wood, partially offsets the mechanical gains achieved through hybridisation. Notably, in beech-rMAPP plywood, the addition of flax fibres does not lead to a significant improvement in specific bending modulus or specific bending strength ($p > 0.6$ and $p > 0.3$, respectively).

However, hybridisation remains advantageous for beech-PLA plywood, where a significant increase is observed in specific bending modulus ($p < 4.5 \cdot 10^{-5}$), rising from 16,766 to 18,590 MPa (+10.9%), and in specific bending strength ($p < 3.7 \cdot 10^{-3}$), increasing from 154.5 to 175.3 MPa (+13.5%).

Hybridisation led to a significant enhancement in the bending modulus of Douglas fir-rMAPP plywood ($p < 0.032$), increasing from 9408 MPa to 12,317 MPa (+30.9%). However, no statistically significant effect was observed for the bending strength ($p > 0.069$).

For Douglas fir-PLA plywood, hybridisation also resulted in notable variations, with a significant increase in bending modulus ($p < 0.036$) from 9955 to 12,128 MPa (+21.8%), along with an improvement in bending strength ($p < 1.22 \times 10^{-4}$), rising from 42.4 to 76 MPa (+79.2%).

A comparison with the findings of Biblis and Carino [30] highlights similar trends. Their study demonstrated that reinforcing pine plywood with a glass fibre fabric of 610 g/m² on the outer surfaces increased its bending modulus to 12,340 MPa (+ 22%). Interestingly, despite the internal placement of reinforcements in the RS1 configuration, the bending modulus values obtained in this study for Douglas fir-rMAPP and Douglas fir-PLA hybrids closely match those reported by Biblis and Carino.

The bending strength value for reinforced plywood obtained by Biblis and Carino [30] is 94.3 MPa. This result surpasses the values obtained in our study for reinforced plywood, highlighting the strength performance gap between flax and glass fibres.

Comparison with classical laminate theory predictions

To evaluate the accuracy of the predictive calculations based on laminate theory, the values obtained experimentally are compared with theoretical predictions. This analysis focuses exclusively on the bending elastic modulus (E_f).

The diffusion of the adhesive into the veneers during the fabrication phase can affect the final mechanical properties of the laminate. To account for this phenomenon, Wei et al. [28] propose considering the region where the adhesive has diffused into the veneer as a new ply, whose mechanical properties are derived from those of the veneer and the adhesive. This approach improves the reliability of the predictions with respect to the experimental results. The methods used to determine the mechanical properties of this wood-adhesive layer are detailed in the Appendix A.1.

Figure 6 presents a comparison between experimental ($E_{f_{exp}}$, in red) and theoretical values ($E_{f_{LT}}$, in blue) for the bending modulus. The values obtained after considering the adhesive diffusion (or “corrected” classical laminate theory ($E_{f_{LT_c}}$)) are presented through the black striped bars.

First concerning the comparison with classical lamination theory: for beech plywood, the experimentally measured properties generally align closely with the predicted values, with deviations ranging from −1 to +15%. However, an exception is observed for beech-PLA plywood in both S1 and RS1 lay-ups, where the bending modulus exceeds the theoretical predictions by approximately 23%.

The comparison with the corrected lamination theory shows that considering the diffusion of adhesive into the veneer causes a very small increase in the bending modulus for most of the configurations, except for the beech-PLA samples, where the increase is more significant. This difference is due to the important diffusion depth of the PLA into the beech veneer.

Figures 7 and 8 present X-ray microtomography observations made around the 5 flax-polymer layers, including the external 0° veneer and the next 90° veneer. The diffusion ply thickness is determined thanks to these images. These observations reveal a significantly higher level of adhesive diffusion in beech-PLA specimens (Figure 8) compared to beech-rMAPP plywood (Figure 7). This phenomenon is likely due to the higher melt flow index (MFI) of PLA relative to rMAPP, which facilitates deeper penetration of the polymer into the wood porosities. The

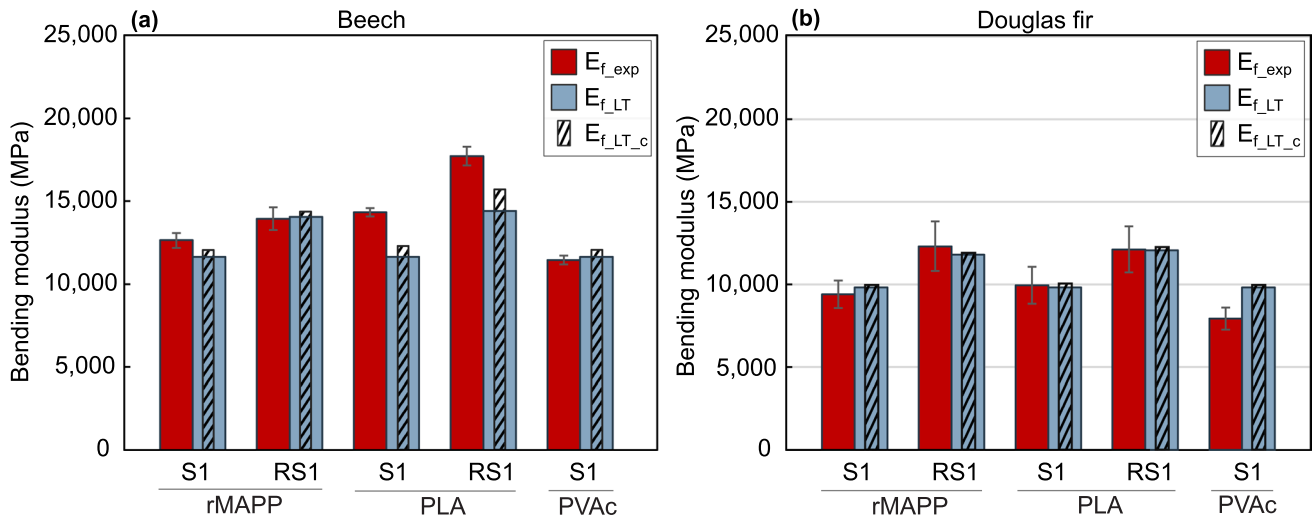


Fig. 6 Comparison of experimental results and values obtained from the classical laminate theory for **a** beech and **b** Douglas fir plywood. Red bars experimental values; blue bars values according to the classical laminate theory, black striped bars values according to the classical laminate theory with consideration of adhesive diffusion ($E_{f_LT_c}$)

ing to the classical laminate theory, black striped bars values according to the classical laminate theory with consideration of adhesive diffusion ($E_{f_LT_c}$)

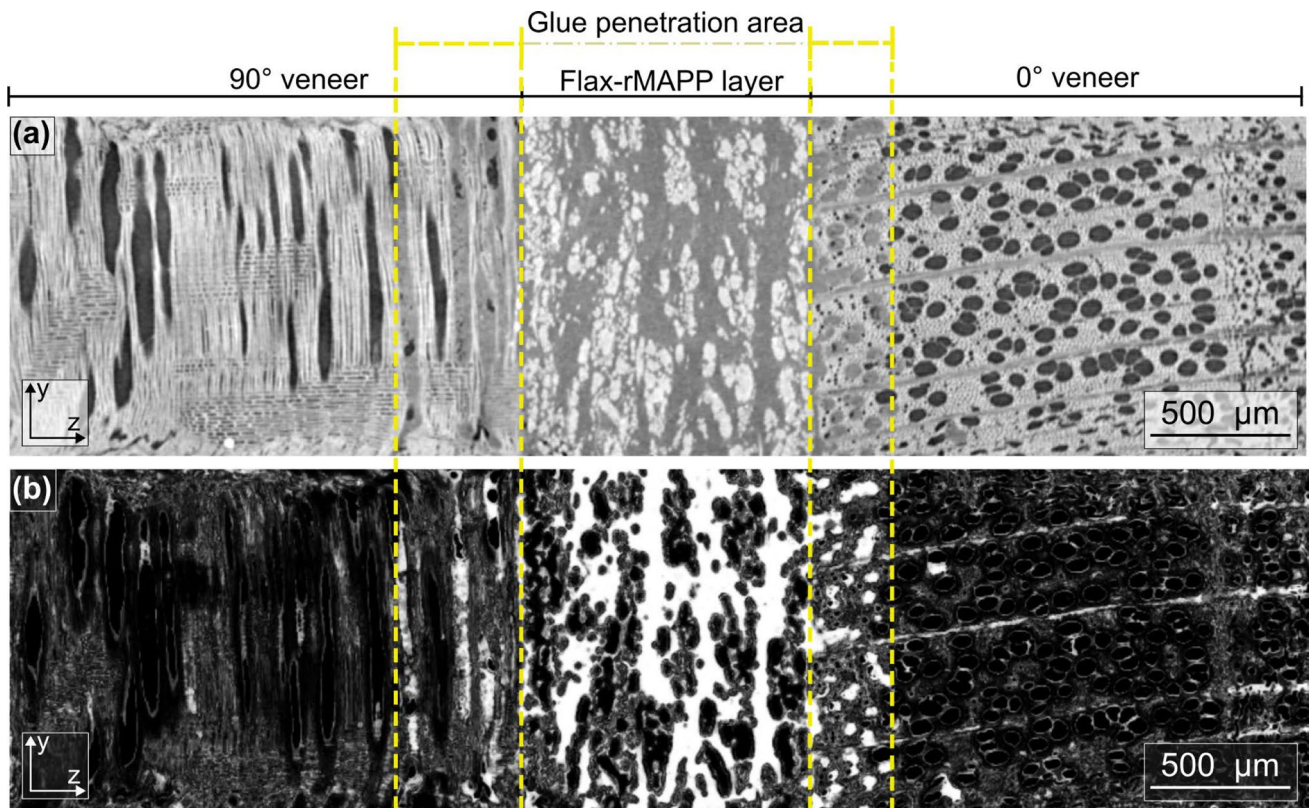


Fig. 7 X-ray microtomography of a RS1 beech-rMAPP sample. The image is shown before (a) and after (b) segmentation of the adhesive by machine learning

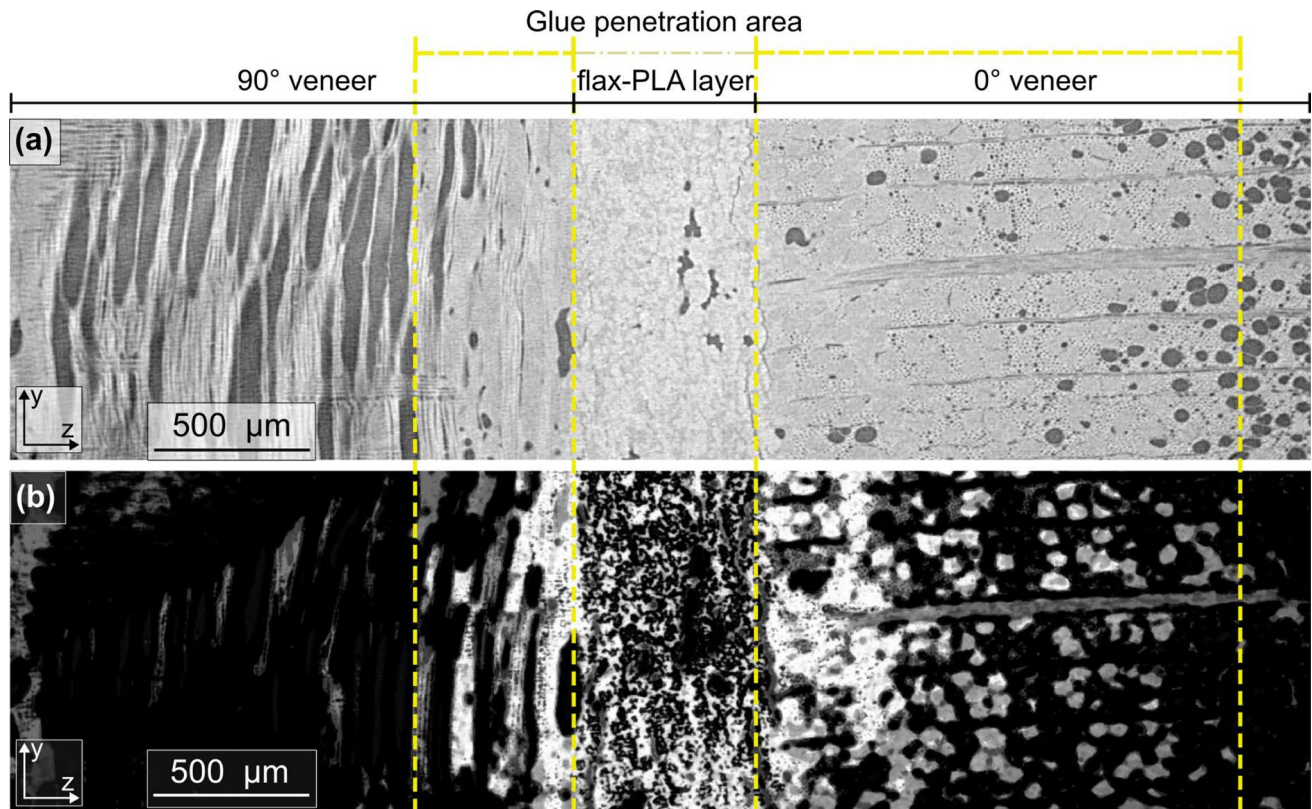


Fig. 8 X-ray microtomography of a RS1 beech-PLA sample. The image is shown before (a) and after (b) segmentation of the adhesive by machine learning

pronounced diffusion of PLA within beech veneers contributes to improving the veneer properties by filling internal voids. This partially explains the excellent flexural modulus and bending strength values observed in beech-PLA reinforced plywood. However, the calculations indicate that this phenomenon alone does not fully account for the higher values obtained for the beech-PLA samples, as these values remain above those predicted by the corrected laminate theory. Additionally, PLA-based plywood incorporating flax plies exhibits better fibre dispersion than rMAPP-based counterparts, potentially enhancing the mechanical performance of the reinforcing layer. The increased adhesive diffusion associated with PLA also leads to a higher fibre volume fraction, further contributing to the improved mechanical properties of the composite.

This diffusion phenomenon is considerably less pronounced in Douglas fir-PLA specimens. This difference can be attributed to the lower impregnability of Douglas fir, largely due to the partial closure of its bordered pits during latewood formation.

Mechanical behaviour

Figure 9 shows some representatives equivalent stress–equivalent strain curves for the different samples tested in 3-point bending experiments. The plotted strain corresponds to the equivalent strain of the external fibre beneath the loading point. Figures including all the test curves are presented in Appendix 6.

This plot highlights the similar mechanical behaviour exhibited by the samples within each lamination configuration. The stress evolution reveals an initial linear phase, with a slightly steeper slope for RS1 laminate samples. This linear response extends up to an equivalent strain of approximately 0.75% for both lay-ups. Beyond this point, the slope decreases, likely due to the damageable nature of wood, particularly under compressive loading. For non-reinforced laminates (S1), failure occurs distinctly after this progressive damage phase, likely due to tensile failure of the lower veneer. In contrast, reinforced laminates exhibit a more gradual failure process, possibly due to load

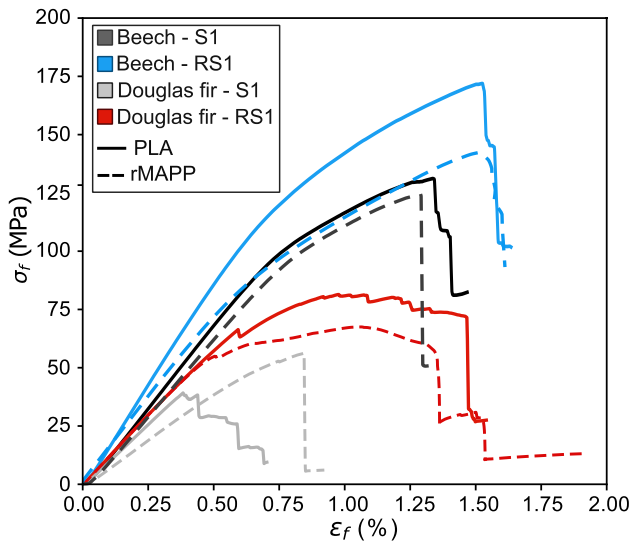


Fig. 9 Stress–strain curves for 3-point bending tests on beech and Douglas fir samples, with PLA and rMAPP adhesives in S1 and RS1 lay-ups

redistribution to the flax composite ply after the failure of the outer veneers.

For Douglas fir samples, the representation highlights the significant variability in both bending modulus and stress at break for these laminates.

The test curves for S1 laminate samples exhibit an almost purely elastic behaviour, with a much less pronounced inflection point compared to beech samples. Some samples fail abruptly at the end of the elastic phase, while others display a more gradual decrease in slope, indicative of progressive damage.

For reinforced samples (RS1), the curves also exhibit an initial elastic phase, followed by a distinct damage zone characterised by sudden drops and a significant reduction in slope. Unlike S1 laminates, the apparition of damage does not immediately lead to sample failure; instead, the equivalent stress continues to rise after this initial damage. This behaviour suggests a redistribution of stress to the flax ply, which possesses a much higher rupture stress than Douglas fir, thereby enhancing the laminate's resistance to failure.

Failure behaviour

Failure facies

The study of failure facies focuses on the S1 and RS1 lay-up. Figure 10 illustrates the different failure modes observed in the study, through different samples.

Observation of the failure modes reveals that tensile failure of the wood veneer is predominant in most beech samples. This failure mode is particularly prevalent in configurations without reinforcement (S1).

For reinforced beech-rMAPP samples (RS1), veneer failure is followed by tensile failure of the composite ply, as well as delamination. In contrast, for RS1 laminated beech-PLA plywood, failure of the composite ply is observed less frequently. As illustrated in Figure 10b, after veneer failure, the crack propagates along the interface between the veneer and the composite ply. This difference in behaviour between beech-rMAPP and beech-PLA plywood in RS1 lamination can be attributed to the brittle nature of PLA, causing interfacial fracture propagation, whereas rMAPP, being more flexible, mitigates this effect.

For Douglas fir plywood, S1 laminated samples frequently exhibit tensile failure of the lower veneer. In Douglas fir-rMAPP and Douglas fir-PVAc samples, this failure is often followed by shear failure in one of the wood veneers, mostly in a 90°-oriented ply. In contrast, for Douglas fir-PLA samples, veneer failure is typically followed by delamination. In the presence of reinforcements (RS1 laminates), tensile failure of the outer veneer is rarely observed. Instead, the predominant failure mode differs by adhesive type: Douglas fir-rMAPP plywood primarily exhibits shear failure in the 90° plies, whereas Douglas fir-PLA plywood mainly fails through delamination.

The observed failure modes are consistent with those reported for solid wood by Bodig et al. [32]. Beech plywood predominantly exhibits a tensile failure of the outer (lower) veneer, which then transitions into a shear failure upon reaching a mechanically weaker region, here, the interlaminar interface. This behaviour is similar to failure propagation between growth rings in solid wood subjected to bending solicitations with the span oriented parallel to the grain.

In Douglas fir specimens, mostly shear failure is observed, in agreement with failure mechanisms commonly reported in solid wood for species with abrupt changes in the growth zones [32].

Failure kinetics

Wood and plant fibre composites exhibit complex mechanical behaviour, characterised by a damageable behaviour and differences in tensile and compressive properties. These factors can influence the bending

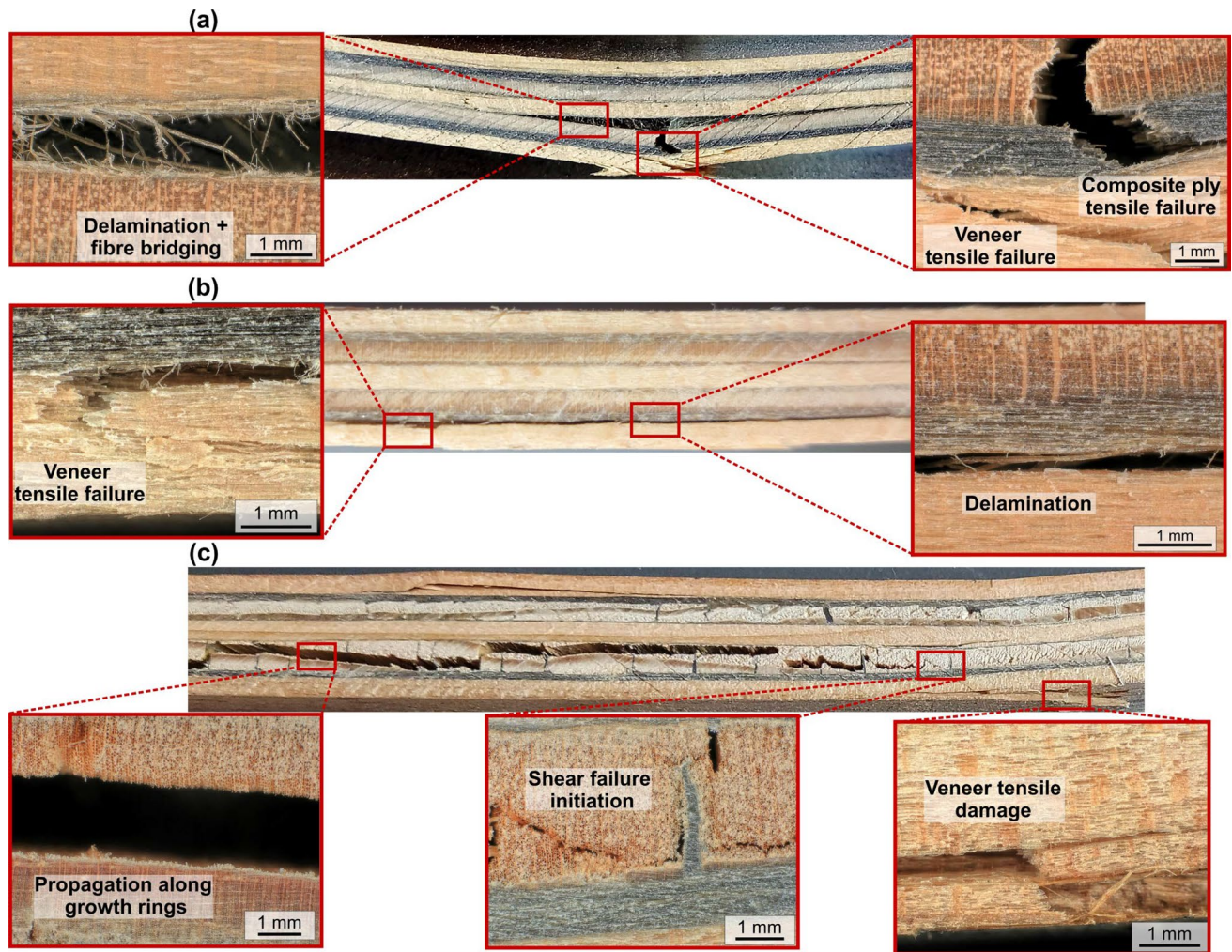


Fig. 10 Illustration of the different damage modes observed during bending tests, using three representative samples: **a** beech-rMAPP; **b** beech-PLA; **c** Douglas fir-rMAPP; and each with RS1

lay-up. Samples photographs are accompanied by micrographs of interesting failure areas

performance of plywood and its damage evolution. Predicting the impact of hybridisation on the damage progression of such materials is highly challenging. This section aims to address this question by presenting the damage kinetics of samples representing each configuration, supported by image correlation analysis to monitor the strain field during bending tests.

Figure 11 illustrates the failure kinetics of beech-rMAPP and Douglas fir-rMAPP samples, in S1 and RS1 configurations. For each examined configuration, a representative test curve is illustrated in Fig. 11a, f, and annotated with numbers that indicates interest points in the evolution of the specimen damage. The strain fields in the directions relevant for understanding the damage are shown for each points in Fig. 11b,

e, g and i, with strain levels in key areas indicated by dots and described below each image. The x-axis corresponds to the longitudinal direction of the specimen, while the z-axis represents the through-thickness direction. Additionally, Fig. 11c, d, h, j presents the stress distribution across the laminate's thickness for the load level corresponding to each interest point, based on classical laminate theory calculations. For RS1 laminate samples, and to capture load transfer between the veneers and composite plies, stress distribution is also depicted for damaged veneers, represented in dark blue. (The curve number is marked with a '.'). In this case, the stresses are computed by modelling the damaged ply with reduced mechanical properties (by factor of 100). Since accurately

determining the extent of damage is not possible, a stress distribution for the same load level without damaged plies is also provided in light blue, serving as a comparison for the stress distribution.

Regarding beech-rMAPP samples, Figure 11a shows a similar behaviour between the S1 and RS1 lay-up, until the apparition of important damage in the bottom veneer, which corresponds to points 2 and 3. At that point, the stress estimated in the bottom veneer for the S1 lay-up is 130 MPa (Figure 11c), which exceeds the average bending strength of beech of 107 MPa reported in the literature, and therefore initiates failure through damage propagation in the outer veneer. It rapidly spreads through the 90° veneer and reaches the central 0° veneer.

For the RS1 laminates, the stress at point 3 is 117 MPa in the outer veneer, causing the initiation of its tensile failure. This causes a load transfer within the composite ply (represented in dark blue in the stress distribution graph, Figure 11b). After this transfer, the maximum axial stress in the composite ply reaches 251 MPa, corresponding to its mechanical strength. The composite ply then fails immediately under tension, followed by the failure of the 90° veneer in tension and the interface between the 90° and central veneers in shear.

In both cases, the lower veneer appears to be the limiting factor. For reinforced laminates, the load transfer after the appearance of damage in the lower veneer is too important for the composite ply, which instantly breaks in tension.

For the Douglas fir-rMAPP samples, the test curves (Figure 11f) show a more complex failure kinetics for RS1 laminates compared to S1 laminates. In both cases, the observation of the shear strain field shows an important amount of shear strain within the 90° veneer. This phenomenon can be attributed to the very low shear modulus of Douglas fir in the LR direction, which ranges between 80 and 114 MPa [31, 33]. For the S1 lay-up, splintering damage appears in the lower veneer at the point 1 (Figure 11g.1 (ϵ_x)), for an estimated tensile stress of 65 MPa in the veneer, causing the initiation of its failure, which quickly propagates through the whole sample causing complete failure of the sample.

For the RS1 laminate, damage starts appearing near the same equivalent stress level (point 2), through buckling phenomena in the top veneer, and splintering in the bottom one (Figure 11g.1 (ϵ_x)). The damage observed in the outer veneers leads to a redistribution

of the load towards the composite layer, which does not exceeds its tensile strength, making it able to support the entire load. At point 3, the increased shear stress in the 90° wood layer, resulting from the stiffness degradation of the damaged external veneers, triggers shear failure of the specimen. No tensile failure is observed in the composite ply, as the estimated stress in this layer is approximately 220 MPa (Figure 11j, left), remaining below its estimated tensile strength of 250 MPa.

It is interesting to note that here, the composite ply does not appear to reach failure. It does, however, maintain the structural integrity of the sample after damage to the outer veneers. The continuous increase in axial stresses and the low shear stiffness of the 90° veneer make it the limiting element, with failure initiated in shear in this veneer.

The presence of reinforcements in plywood has shown to allow load transfer when damage occurs in the outer veneers, helping to increase the sample bending strength.

Fatigue

This fatigue study focuses on Douglas fir-rMAPP samples with S1 or RS1 lay-up, and Douglas fir-PVAc samples with S1 lay-up. Figure 12 shows the number of cycles achieved by each sample, plotted as a function of the percentage of their quasi-static strength σ_{QS} (a) and the maximum stress applied (b). Samples that did not fail before 1 million cycles are marked with an arrow. The multiplier next to the arrows indicates the number of samples that survived up to 1 million cycles at that particular stress level. The results of the preliminary quasi-static tests used to obtain the maximum stress value are marked with a cross on the y-axis. The fatigue test results for the Douglas fir-PVAc samples were fitted with a power law model, shown in red on the graphs. The correlation coefficient “R” is also indicated in red on the figure. The estimated fatigue strength values for 1 million cycles are presented in Table 5.

The fatigue test results illustrate the significant variability between samples of the same material. This variability is attributed to the significant differences in mechanical properties observed under quasi-static loading conditions, which in turn affect the fatigue life of the samples.

For Douglas fir-PVAc plywood, the estimated fatigue strength at 1 million cycles is approximately

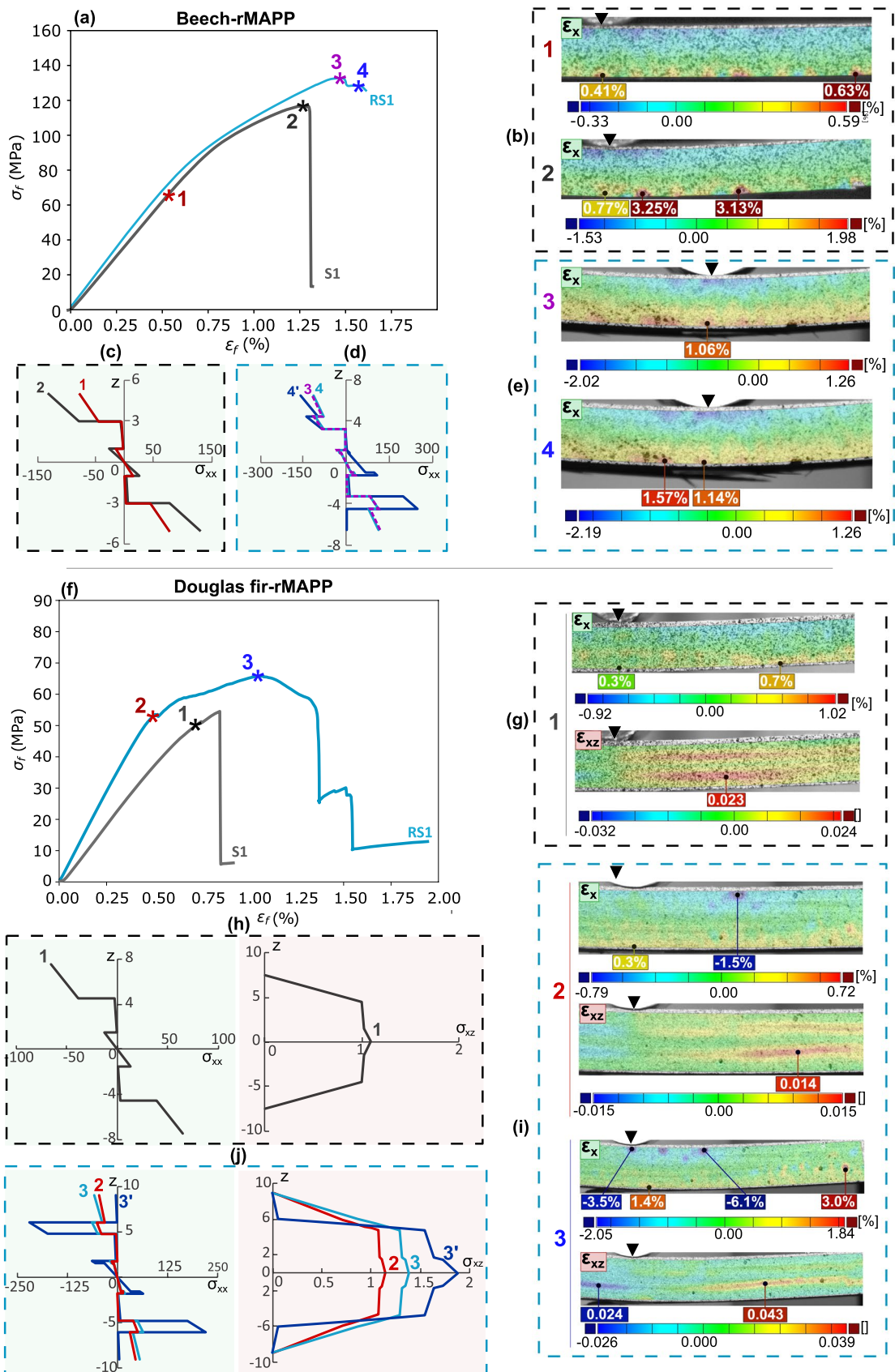


Fig. 11 Failure kinetics of beech-rMAPP and Douglas fir-rMAPP samples. **a** and **f** illustrate stress–strain curves of selected bending tests on non-reinforced (S1) (in grey) and reinforced (RS1) samples (in blue). Different points of interest are marked on the curves by coloured numbers. **b**, **e**, **g** and **i** illustrate the strain fields observed by DIC in the sample for each interest point. The strain direction presented depends on its relevance. **c**, **d**, **h** and **j** indicate the stress distribution in the sample thickness at the different interest points

45% of its quasi-static strength, consistent with values reported by Kommers et al. for Douglas fir planks [5]. However, the results for the S1 and RS1 stacking sequences exhibit substantial variability, making it difficult to represent these samples accurately with a simple analytical model.

For the S1 configuration, all samples that failed before reaching 1 million cycles were subjected to stress levels of 50% or higher. Notably, three out of four samples at this level successfully reached 1 million cycles. Based on these observations, the fatigue strength at 1 million cycles is estimated at around 40% of the quasi-static bending failure stress.

RS1 samples demonstrated greater fatigue resistance, with three out of four samples enduring 1 million cycles under a load of 70% of their quasi-static strength, suggesting a fatigue strength exceeding 60% of their quasi-static bending strength.

Figure 12b presents the fatigue life as a function of the applied bending stress, highlighting the superior fatigue resistance of RS1 samples. The estimated fatigue strength at 1 million cycles for RS1 laminated Douglas fir-rMAPP hybrids is approximately 48 MPa—twice that of Douglas fir-PVAc and unreinforced Douglas fir-rMAPP plywood, which are estimated at 24 MPa and 25 MPa, respectively. These results demonstrate the significant impact of hybridisation on the fatigue strength of plywood.

Despite the substantial variability in results, this study demonstrates that plywood bonded with rMAPP adhesive exhibits fatigue resistance comparable to that of PVAc-bonded plywood, confirming rMAPP as a viable alternative to traditional adhesives. Additionally, plywood hybridisation resulted in a twofold increase in fatigue resistance compared to non-reinforced plywood, which highlights its considerable advantage for applications involving cyclic loading.

Conclusion

The aim of the study was to assess the effect of hybridising wood veneers with plant fibre and thermoplastic composites on the properties of the resulting plywood.

A mechanical characterisation campaign in bending confirmed the significant effect of hybridisation on the mechanical properties of plywood, particularly in terms of mechanical strength. Its results are summarised in Figure 13.

- The introduction of plant fibres combined with thermoplastic adhesives led to substantial improvements in beech plywood, achieving a flexural modulus and ultimate strength of 13.9 and 138 MPa with rMAPP adhesive, and 17.7 and 167 MPa with PLA, compared to 11.5 and 103 MPa for unreinforced PVAc-bonded plywood. Similarly, for Douglas fir, flexural modulus and strength reached 12.3 and 79.4 MPa with rMAPP, and 12.1 and 76 MPa with PLA, significantly outperforming the 7.9 and 54 MPa recorded for non-hybridised PVAc plywood.
- Comparison with classical laminate theory demonstrated that this approach is an effective tool for predicting the mechanical properties of hybridised plywood. The difference between the beech-PLA experimental and theoretical results shows that this approach could be improved by taking into account the diffusion of the adhesive into the wood cells.
- The analysis of damage mechanisms and their kinetics revealed that the presence of composite plies helps mitigate the degradation of overall material properties by facilitating a progressive load transfer to the composite layer when damage initially appears in the outer veneers.
- To further investigate the effect of hybridisation on fatigue performance, tests were conducted on Douglas fir-rMAPP plywood, selected based on previous findings. The results demonstrated a significant improvement in fatigue resistance, with hybridised plywood retaining approximately 60% of its quasi-static bending strength after 1 million cycles, compared to only 40% for unreinforced plywood bonded with rMAPP or PVAc. This corresponds to a fatigue strength of approximately 48 MPa for reinforced Douglas fir-rMAPP plywood, which is twice the 24 MPa recorded for non-reinforced Douglas fir-PVAc reference plywood.

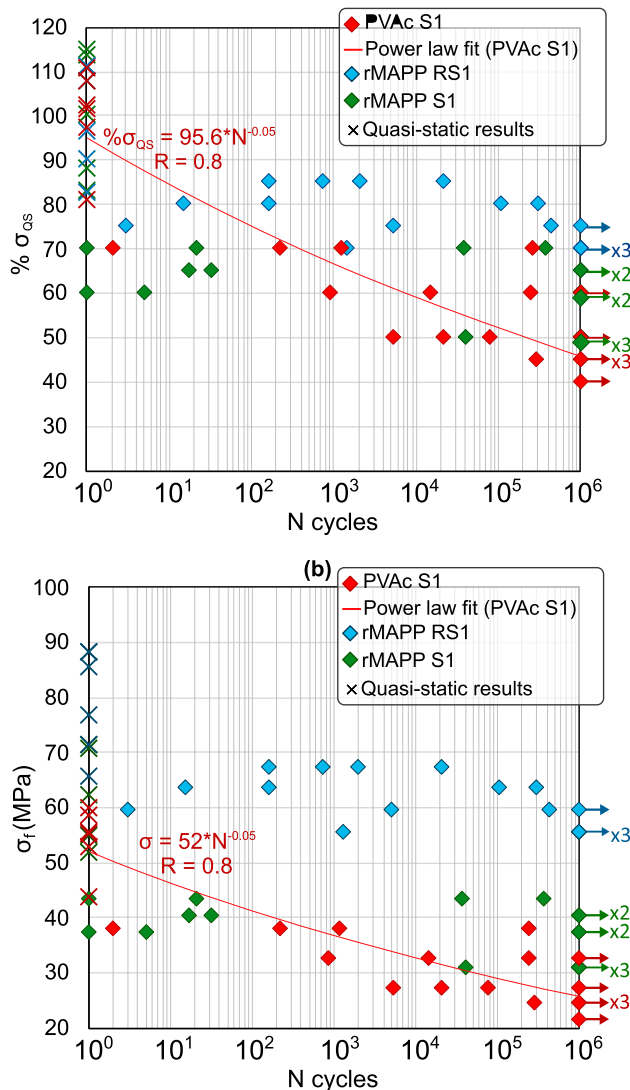


Fig. 12 Wöhler curve indicating the number of cycles reached relatively to the stress level as **a** a percentage of the quasi-static strength and **b** as a stress value. Points marked by arrows indicate the samples that did not reach failure

Table 5 Fatigue strength values at 1 million cycles for Douglas fir plywood, based on percentage of quasi-static bending strength (σ_{QS}) and applied stress (σ_f)

Adhesive	Lay-up	Fatigue strength for 1 million cycles	
		% σ_{QS}	σ_f (MPa)
rMAPP	S1	40	25
	RS1	60	48
PVAc	S1	45	24

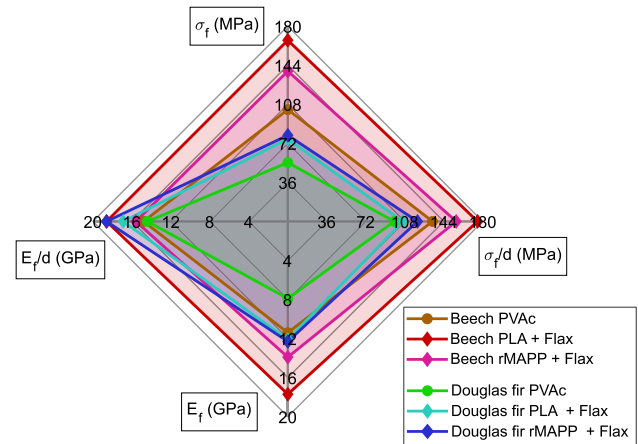


Fig. 13 Summary of the measured mechanical properties for hybrid and non-hybrid laminates

In conclusion, this study demonstrates that hybridisation is an effective strategy for enhancing both the quasi-static and fatigue properties of wood veneer laminates. By significantly improving flexural strength and durability under cyclic loading, this approach opens new possibilities for structural applications where repeated mechanical stresses are a critical consideration.

It is important to also consider that hybridisation significantly increases the manufacturing costs of the material, primarily due to the higher cost of flax compared to wood, as well as the longer processing time and higher temperatures required. Optimising the lay-up by incorporating more cost-effective materials, strategically oriented according to the mechanical requirements of the application, could help reduce production costs while promoting more efficient resource use. Furthermore, investigating the fatigue failure behaviour of these hybrid materials could provide valuable insights into how hybridisation affects failure mechanisms under cyclic loading conditions.

These findings suggest that hybrid plywood could be a viable alternative for industries requiring high-performance and more sustainable materials, particularly in the transport sector.

Acknowledgements

This work was supported by the “Investissements d’Avenir” programme, ISITE-BFC project (ANR-15IDEX-0003 contract), as part of the WooFHi project and by EIPHI Graduate School under ANR-17EURE-0002. Authors are grateful to MIFHySTO technological

platform (FEMTO-ST, France) for the use of X-ray nanotomography and to the AMETISTE technological platform (FEMTO-ST, France) for the use of mechanical testing equipment. We also sincerely wish to thank Louis Denaud, Guillaume Pot, Jean-Claude Butaud, Stéphane Girardon, and Leyne Demoulin from the WMM (Wood Material and Machining) team at LaBoMaP research laboratory (Cluny, France) for providing the veneers and for the insightful discussions conducted within the framework of the WooFHi project on veneer peeling and the properties of wood veneers.

Funding

Open access funding provided by Université Marie et Louis Pasteur. This work was supported by the “Investissements d’Avenir” programme, ISITE-BFC project (ANR-15IDEX-0003 contract), as part of the WooFHi project and by EIPHI Graduate School under ANR-17EURE-0002.

Data Availability

The datasets analysed during the current study will be made available upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

Appendix A Details about the lamination theory calculus

A.1 Classical lamination theory

The values used are presented in Table 6. As the properties are calculated only in the longitudinal

and tangential directions, the elastic properties in the radial direction are not presented, with the exception of the shear moduli G_{RT} and G_{RL} of the veneers, needed to calculate the shear stress in the thickness.

The properties of the wood species were defined on the basis of the properties for solid wood provided in the “Guide des essences” by Benoit [35] and the book “Mécanique du matériau bois et composites” by Guitard [33].

The properties of flax-rMAPP plies were characterised in the thesis by Agnès Mattlet [24]. The longitudinal modulus is 28.7 GPa for a composite with a fibre volume content of 38.4%. In our case, the fibre content of the composite plies used here can be estimated from the density and mass per unit area of the flax layers and thermoplastic films used as adhesive and matrix, according equation

$$V_f\% = \frac{\frac{Ms_f}{\rho_f}}{\frac{Ms_f}{\rho_f} + \frac{Ms_m}{\rho_m}}, \quad (A1)$$

with Ms_f the mass per unit area of the flax sheets, ρ_f the density of the flax, with Ms_m the mass per unit area of the matrix films, ρ_m the density of the matrix. The volumetric ratio of fibres $V_f\%$ is therefore estimated at 26%. According to the law of mixtures, it can therefore be estimated that the longitudinal modulus of the flax-rMAPP composite ply is approximately 19,960 MPa and 21,560 MPa for flax-PLA. The thickness of the composite plies was estimated at 0.25 mm based on the thickness of the thermoplastic films and the flax sheets.

The shear modulus of flax-PLA composites is taken from the Ref. [36] for which it was measured for flax-PLA composites with a manufacturing method close to that used in this work. To estimate the shear modulus of flax-rMAPP plies, we use the fibre shear modulus, given in the literature as equal to 2500 MPa [34].

The ply shear modulus of flax-rMAPP composites is estimated using the law of mixtures:

Table 6 Mechanical properties of the materials used for the classic lamination theory calculus [24, 33–37]

	E_L (MPa)	E_T (MPa)	G_{LT} (MPa)	G_{RT} (MPa)	G_{RL} (MPa)	ν_{LT}	ν_{TL}	ρ (kg/m ³)
Beech	14,300	1,160	2,280	470	1,640	0.46	0.033	700
Douglas fir	[12,100–16,800]	[846–1,320]	[812–930]	[80–114]	[711–1,200]	0.42	0.021	540
Flax-rMAPP	19,960	2,740	775	–	–	0.43	–	1,320
Flax-PLA	21,560	4,130	2,308	–	–	0.43	–	1,070

$$\frac{1}{G_c} = \frac{V_f}{G_f} + \frac{V_m}{G_m}. \quad (\text{A2})$$

with G_c , G_f and G_m , respectively, the shear moduli of the composite, fibres and matrix and V_m the matrix volume. The shear modulus of the matrix can be estimated using the relationship between shear modulus and elastic modulus for an isotropic material:

$$G = \frac{E}{2(1 + \nu)}. \quad (\text{A3})$$

The shear modulus of flax fibres, measured by Bailey et al. [34], is considered equal to 2500 MPa. The Poisson coefficients for flax fibres, PLA and rMAPP are taken from the literature and are estimated at 0.498, 0.4 and 0.4, respectively [37, 38]. The Poisson's ratio of the composite can be estimated using the law of mixtures [37]:

$$\nu_c = V_f \nu_f + V_m \nu_m, \quad (\text{A4})$$

where ν_c , ν_f and ν_m represent the Poisson coefficients of the composite, fibres and matrix, respectively.

Using these parameters, the laminates mechanical properties and the stress distribution in their thickness are calculated using the equations given in [39].

A.2 Corrected lamination theory

The “corrected” lamination theory acknowledge the diffusion phenomenon of the adhesive in the veneers

by considering it as a new ply. The properties of this new ply are determined through the law of mixture. As indicated by Wei et al. [28], the modulus of the “diffusion ply” can be estimated *via*:

$$E_d = \frac{\rho_0}{\rho_w} E_w + \left(1 - \frac{\rho_0}{\rho_w}\right) E_g, \quad (\text{A5})$$

where E_d , E_w and E_g are, respectively, the modulus of the diffusion ply, the wood cell wall and the adhesive, and ρ_0 and ρ_w are, respectively, the density of the wood veneer and the wood cell wall. The wood cell wall density is considered equal to 1.5, as estimated in the literature [28] [31]. Contrary to what is presented by [28], the final laminate properties cannot be calculated through a simple mixture law, as the solicitation mode here is bending. Therefore, the estimated properties obtained for the diffusion ply are used to calculate its reduced stiffness matrix, and ultimately the new ABD matrix of the laminate, as described in [39].

Appendix B Detailed 3-point bending curves

Figures 14 and 15 illustrate the stress–strain curves obtained for the 3-point bending tests, as discussed in the Sect. 3.1.3.

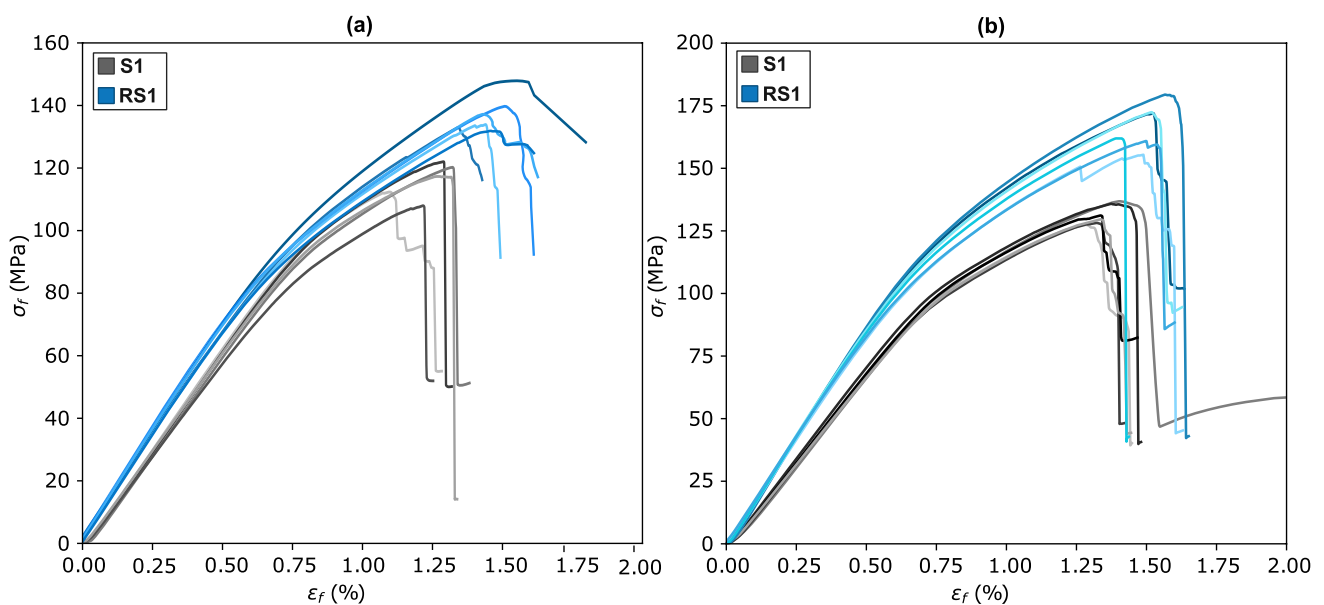


Fig. 14 Stress–strain curves for 3-point bending tests on beech-rMAPP (a) and beech-PLA (b) samples, in S1 and RS1 laminations

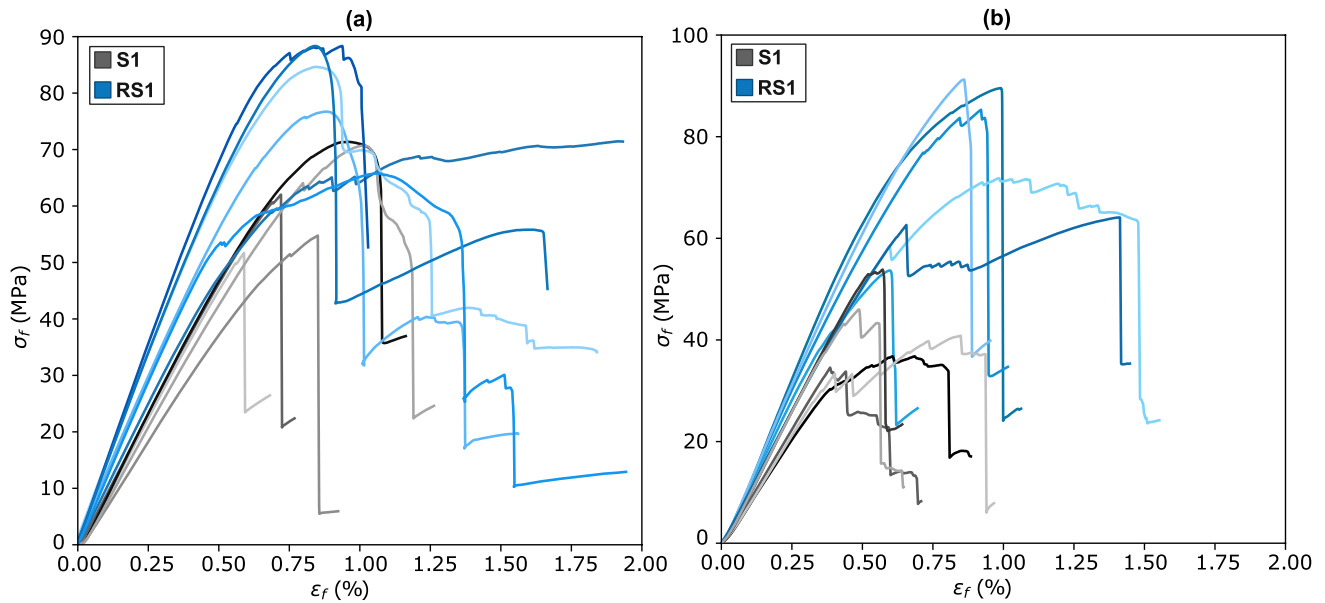


Fig. 15 Stress–strain curves for 3-point bending tests on Douglas fir-rMAPP (a) and Douglas fir-PLA (b) samples, in S1 and RS1 laminations

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