# Determination of the Bending Strength of Liquid Nitrogen-Treated Wood Using Two-Dimensional Digital Image Correlation

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The mechanical strengths of wood samples from three species were tested and compared – Uludağ fir (*Abies bornmüelleriana* Mattf.), oak (*Quercus robur* L.), and Oriental beech (*Fagus orientalis* L.) – after cryogenic treatment with liquid nitrogen (LN, −196 °C). Bending deformations were recorded by the ordinary method and two-dimensional digital image correlation (2D DIC) during bending tests. To apply the 2D DIC technique, a stochastic speckle pattern was sprayed onto the surface of each specimen and the displacement of these reference points was observed through non-contact during the bending tests. Deformation data obtained from the mechanical tests were compared with corresponding values determined *via* 2D DIC for the control samples and the samples treated with LN for 15 and 30 min, to evaluate the accuracy and reliability of the method. The results demonstrated that LN treatment influenced the mechanical behavior of the wood to varying degrees depending on the treatment duration. Furthermore, the deformation measurements obtained *via* 2D DIC showed excellent agreement with the results from conventional measurement methods. These findings indicate that the 2D DIC technique can be a reliable and effective non-contact measurement method for investigating the mechanical behavior of cryogenically treated wood materials.

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## INTRODUCTION

Wood is considered a renewable and strategic engineering material due to its favorable mechanical performance, renewable nature, and versatile functional properties (Burgert *et al.* 2015). Environmental temperature has a significant influence on the mechanical behavior of wood, and low-temperature conditions are known to substantially affect its mechanical properties (Gerhards 1982; Zhao *et al.* 2015a). Due to its naturally heterogeneous cellular structure, wood is highly sensitive to environmental conditions in terms of its mechanical performance. Temperature variations, in particular, can alter the integrity of the cell wall, thereby directly influencing the mechanical behavior of wood (Li and Wang 2020). Previous studies have quantitatively demonstrated that temperature has a substantial influence on the mechanical properties of wood. Gerhards (1982) reported that reductions in temperature generally increase both the stiffness and strength of wood, whereas elevated temperatures reduce these properties because of the softening of cell wall polymers. Similarly, Zhao *et al.* (2015a) observed that decreasing the testing temperature from room temperature to sub-zero conditions significantly increased the flexural strength and modulus of elasticity of wood, with improvements ranging from approximately 15% to 30%, depending on wood species and moisture content. Furthermore, Özkan (2021) reported that exposing Oriental beech wood to cryogenic temperature (−196 °C) increased several mechanical properties by approximately 24.2% to 60.9%. These findings demonstrate that the response of wood to low-temperature exposure is closely associated with changes in the mechanical behavior of the cell wall and provides a scientific basis for investigating cryogenic treatment under controlled conditions.

The impacts of temperature on the wood are usually arranged into two groups. The first group is associated with reversible or transient effects experienced while wood is either fast heated or cooled and subsequently tested at a defined temperature. The effects of temperature on wood can generally be classified into reversible and irreversible responses. Reversible changes occur when wood is exposed to moderate heating or cooling and subsequently returned to room temperature without permanent alteration of its microstructure. Under these conditions, mechanical properties are largely recovered. In contrast, severe thermal exposure, rapid drying, freezing under high moisture conditions, or prolonged exposure to extreme temperatures may induce irreversible changes, including cell wall damage, internal checking, collapse, moisture redistribution, and residual stresses, which can permanently affect the physical and mechanical properties of wood (Ateş *et al.* 1976; Green and Evans 2008; Ateş *et al.* 2017). Therefore, the mechanical response of wood depends not only on temperature level but also on exposure duration, moisture content, and the thermal history of the material.

Previous studies have investigated the mechanical response of wood either during exposure to cryogenic temperatures or after cryogenic treatment followed by testing under laboratory conditions. Therefore, the reported effects should be interpreted according to the specific thermal and testing conditions employed in each study. Özkan (2021) reported that exposure of wood to −196 °C resulted in increases of approximately 24.2% to 60.9% in the evaluated mechanical properties. These changes were associated with mechanisms such as freezing of free water within the wood structure, increased cell-wall stiffness, reduced intermolecular spacing, enhanced intermolecular bonding forces, and stabilization of the crystalline structure. Similarly, Kollman (1940) investigated the mechanical behavior of wood over a broad temperature range from −190 °C to 200 °C and reported an approximately 26% increase in the bending strength of wood exposed to −190 °C for 24 h. Other studies have investigated liquid-nitrogen treatment as a pretreatment and subsequently evaluated the properties of the treated wood under laboratory testing conditions. Accordingly, direct comparisons among published results should consider not only the cryogenic temperature and exposure duration but also the temperature at which the mechanical tests were performed.

Past studies also explored other aspects of cryogenic treatment on wood. Kendra and Cortez (2010) explored the combustion characteristics of liquid nitrogen-treated wood. Çalım (2013) evaluated the combustion behavior of liquid nitrogen-treated wood. It has been reported that cryogenic treatment may improve selected mechanical properties and increase the service life of wood materials under certain conditions (Yorur and Kayahan 2018; Özkan 2021). Additionally, Zhao *et al.* (2015b) investigated the influence of liquid nitrogen treatment on the modulus of elasticity of birch wood and reported that the modulus of elasticity increased by approximately 18 to 27%, depending on the treatment conditions. Similarly, Özkan (2021) reported improvements in several mechanical properties of Oriental beech ranging from approximately 24% to 61% following cryogenic treatment.

These findings indicate that the mechanical response of wood to cryogenic exposure is species-dependent and strongly influenced by treatment duration and moisture conditions. They suggested that cooling the wood from its freezing point transformed the water inside the cell lumina to ice. The volumetric expansion of the ice promoted the contraction of the cell walls, which contributed to improvement of the mechanical properties. Kurt (2022) explored the combined effects of liquid nitrogen pretreatment and the preservative retention on the mechanical properties of the wood. The study showed that the application of liquid nitrogen before the impregnation increased the preservative retention of the fir wood around 150 to 200% for all impregnation methods with respect to the untreated specimens. Even with this high increase in the retention value, no statistically important changes on the mechanical properties due to the liquid nitrogen treatment were observed. Yorur *et al.* (2017) explored the effect of liquid nitrogen treatment on the preservative retention of Oriental spruce (*Picea orientalis* (L.) Link) and Scots pine (*Pinus sylvestris* L.) wood. In their study, distilled water was used as the solvent for the preservative solution, and the vacuum–pressure method was employed for impregnation. The results showed that liquid nitrogen pretreatment significantly increased the preservative retention whereas, no important critical influences on the mechanical properties of wood were observed.

The measurement of surface deformation in materials and structural components subjected to various loading conditions is essential for understanding their mechanical behavior. In addition to conventional mechanical deformation measurement techniques, strain gauges and non-contact optical methods are widely used for deformation analysis (Rastogi 2000). Non-contact optical techniques can be broadly classified into three categories: interferometric techniques, moiré interferometric techniques, and non-interferometric techniques (Goldrein *et al.* 1995). Among the non-interferometric approaches, two-dimensional Digital Image Correlation (2D DIC) is based on capturing images of the specimen surface before and after deformation under diffuse illumination. The method enables non-contact monitoring of the displacement of surface points throughout the experiment. Surface deformation is quantified by tracking the movement of randomly distributed reference points (speckle pattern) and calculating the corresponding changes in the image field (Pan *et al.* 2009). Compared with conventional deformation measurement techniques, the 2D DIC method offers several important advantages, including (i) a simple experimental setup and straightforward specimen preparation, (ii) minimal environmental requirements for measurement, and (iii) the ability to perform full-field measurements with high spatial resolution over a relatively large observation area. Furthermore, the technique is applicable to a wide range of solid materials, including metals, composites, polymers, wood, and biological materials. Unlike conventional displacement transducers and strain gauges, which provide only localized measurements, 2D DIC can determine full-field displacement and strain distributions across the entire specimen surface during loading (Pan *et al.* 2009). Zink *et al.* (1997) employed the white-light speckle technique together with Digital Image Correlation to determine the Poisson's ratios of yellow poplar wood. The authors emphasized that the calculated values were derived from the deformation of the entire specimen under progressive loading rather than from measurements taken at discrete points. Similarly, del Rey Castillo *et al.* (2019) used the DIC method to evaluate strain fields in Fiber-Reinforced Polymer (FRP) composites commonly used in the construction industry. Their results demonstrated satisfactory agreement between DIC measurements and conventional measurement techniques. In addition, they concluded that the DIC method is an effective tool for identifying critical regions susceptible to damage before visible failure occurs.

In the present study, the bending strength and modulus of elasticity of liquid nitrogen-treated Uludağ fir (*Abies bornmüelleriana* Mattf.), Oriental beech (*Fagus orientalis* L.), and oak (*Quercus robur* L.) specimens were determined using a universal testing machine. During the bending tests, surface deformation was simultaneously monitored using the 2D DIC technique, and the measured deformation values were compared with those obtained from the universal testing machine to evaluate the accuracy and reliability of the optical method. Furthermore, the full-field strain maps generated from the post-test images were used to identify and analyze the stress concentration regions induced by liquid nitrogen treatment through the 2D DIC technique.

Recent studies have demonstrated that cryogenic treatment may influence not only the mechanical performance of wood but also preservative retention, moisture distribution, and cell-wall behavior. However, the reported responses vary considerably depending on wood species, moisture content, treatment duration, and testing conditions (Özkan 2021; Aytin et al. 2022; Kurt 2022). Therefore, additional investigations involving different wood species and advanced deformation analysis techniques are still required to better understand the mechanisms governing cryogenic treatment.

## EXPERIMENTAL

### Materials

*Wood species*

Beech (*Fagus orientalis* Lipsky), Uludağ fir (*Abies bornmüelleriana* Mattf.), and oak (*Quercus petraea* (Matt.) Liebl.) wood were obtained from approximately 45-year-old trees harvested in the Bartın region of Türkiye. The logs were processed into sawn timber with nominal dimensions of 100 mm × 100 mm × 1000 mm and supplied by a local sawmill. Defect-free specimens measuring 30 mm × 30 mm × 320 mm were prepared from the sawn timber. Prior to specimen preparation, all materials were visually inspected to exclude knots, checks, decay, reaction wood, and other visible defects. The specimens were then conditioned in a climate chamber at 20 ± 2 °C and 65 ± 5% relative humidity until they reached equilibrium moisture content before testing.

*Liquid nitrogen*

Liquid nitrogen is produced by cooling and liquefying nitrogen gas, which constitutes approximately 78% of the Earth’s atmosphere. It is a cryogenic fluid that is colorless, odorless, non-toxic, non-flammable, non-combustible, and non-explosive.

*Preparation of experimental samples*

Prior to testing, all specimens were conditioned at 20 ± 2 °C and 65 ± 3% relative humidity until a constant mass was achieved. Test specimens measuring 20 mm × 20 mm × 320 mm (radial × tangential × longitudinal) were prepared from Uludağ fir, beech, and oak for the bending tests. Except for the control group, the samples were subjected to cryogenic treatment by being completely immersed in liquid nitrogen (−196 °C) for 15 or 30 minutes. The process was carried out using a rigid plastic container filled with liquid nitrogen. Following the designated treatment duration, the samples were carefully removed from the liquid nitrogen using insulated tongs and placed on a laboratory bench under ambient conditions (20 ± 2 °C). To prevent thermal shock that could result from immediate mechanical testing, all samples were allowed to equilibrate naturally under laboratory conditions for seven days protected from direct sunlight and humidity fluctuations before undergoing further testing. The same cryogenic treatment procedure was applied to all wood species and treatment groups. During the bending test, the support span was maintained at 200 mm. The bending strength (MOR) and modulus of elasticity (MOE) were determined using Eqs. 1 and 2, respectively,

$$\sigma_B = \frac{3.L_S}{2.b.h^2} \tag{1}$$

$$E = \frac{\Delta F.{L_S}^3}{4.\Delta\ell.b.h^3} \tag{2}$$

where $\sigma_B$ is the bending strength, $L_s$ is the distance between the supports, $b$ is the width, $h$ is the height, and $\Delta F$ is the force difference in the elastic region; $\Delta\ell$ shows the amount of elongation corresponding to the difference in force in the elastic region.

## Methods

*Density*

For each test condition, twenty-five specimens were prepared. Air-dry density was determined according to the procedures described in ISO 3131 (1975). Before testing, the specimens were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until they reached moisture equilibrium. The density of each specimen was then calculated from the ratio of its mass to its volume:

$$\delta_{12} = M_{12} / V_{12} \text{ (g/cm}^3\text{)} \tag{3}$$

*Digital image correlation*

Beech, oak, and Uludağ fir specimens were subjected to three treatment conditions: untreated (control), liquid nitrogen (LN) treatment for 15 min, and LN treatment for 30 min. All specimens were prepared in accordance with the standard dimensions, and their surfaces were coated with a randomly distributed black-and-white speckle pattern to facilitate Digital Image Correlation (DIC) analysis. The appearance of the liquid nitrogen-treated and speckle-patterned specimens is presented in Fig. 1.

The two-dimensional Digital Image Correlation (2D DIC) system was integrated with the universal testing machine throughout the bending tests. During loading, the deformation of each specimen at the maximum applied load ($F_{max}$) was continuously monitored using a high-resolution digital camera (ace acA1600-20gc, Basler AG, Ahrensburg, Germany), and the images were recorded in real time. The recorded images were processed using the NCORR software, which employs a dedicated DIC algorithm to calculate the full-field strain distribution. Normal strains in the XX and YY directions as well as the in-plane shear strain XY were determined, and the corresponding strain contour maps were generated. For each treatment condition, the maximum and minimum strain values were extracted. Consequently, the effects of wood species and liquid nitrogen treatment duration on the strain behavior were directly compared based on the strain distributions obtained at the maximum applied load $F_{max}$. The integration of the 2D DIC system with the universal testing machine requires several primary and auxiliary components to ensure synchronized image acquisition and mechanical loading. The experimental configuration of the integrated 2D DIC–universal testing machine system is illustrated in Fig. 2.

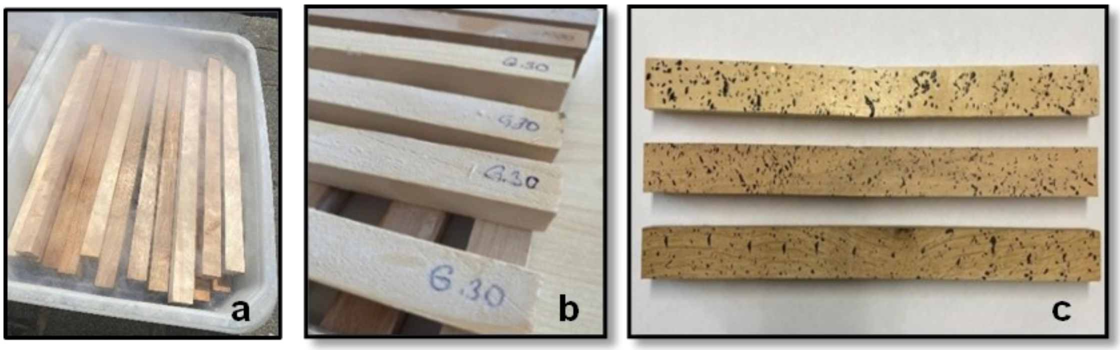


**Fig. 1.** Test samples: (a) Storage in liquid nitrogen; (b) View of LN–treated test samples; (c) View of patterned test samples

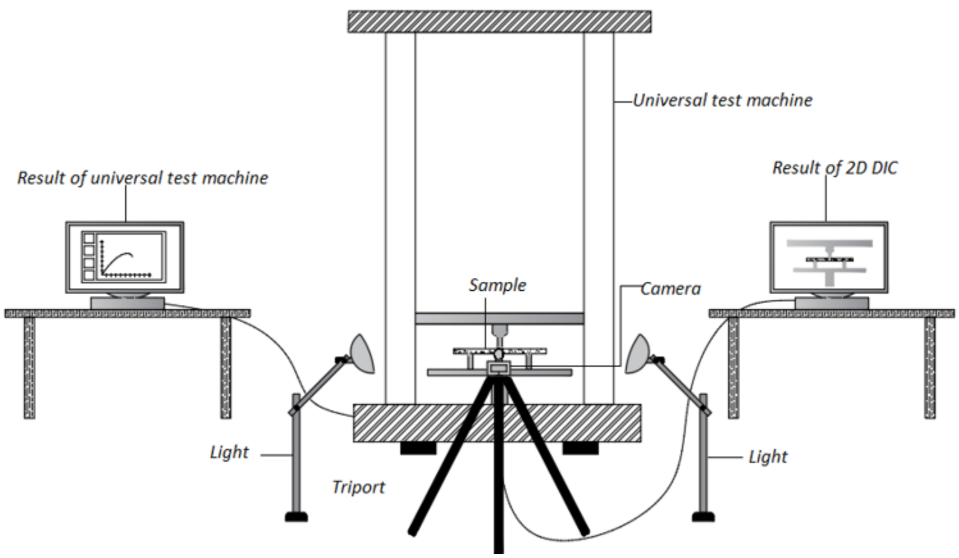


**Fig. 2.** Integration of 2D DIC method with universal testing machine (Sözen *et al.* 2021)

## RESULTS AND DISCUSSION

The main purpose of this study was to examine the effect of LN on the mechanical properties of tree species determined by using the 2D DIC method. The main findings are explained in detail according to density and mechanical property analysis.

### Density

The air-dried and oven-dried density values showed only limited variation among the control and cryogenically treated specimens. Although slight differences were observed after liquid nitrogen treatment, these changes remained relatively small and should be interpreted with caution because wood is a naturally heterogeneous material. The observed variations may be associated with normal biological variability, moisture redistribution during conditioning, or minor structural changes induced by cryogenic exposure. Since no chemical or microstructural analyses were performed in the present study, it is not possible to attribute these density differences to a specific mechanism. Similar observations have been reported in previous studies, where cryogenic treatment produced only minor changes in density while having a more pronounced influence on selected mechanical properties (Yorur *et al.* 2017; Kurt 2022). Therefore, the present results suggest that liquid nitrogen treatment has a limited effect on the density of wood under the experimental conditions employed in this study. The air-dried density values measured after the different treatment applications are summarized in Table 1.

**Table 1.** Densities of Uludag Fir, Oak, and Beech Wood (g/cm$^3$)

| | Air-dried | | | Oven-dried | | |
|---|---|---|---|---|---|---|
| | Non-treated | 15 min LN | 30 min LN | Non-treated | 15 min LN | 30 min LN |
| Uludag fir | 0.35 (0.012) | 0.36 (0.015) | 0.38 (0.008) | 0.34 (0.016) | 0.35 (0.014) | 0.37 (0.005) |
| Oak | 0.56 (0.018) | 0.49 (0.013) | 0.55 (0.011) | 0.49 (0.004) | 0.43 (0.001) | 0.48 (0.022) |
| Beech | 0.59 (0.022) | 0.52 (0.013) | 0.55 (0.012) | 0.52 (0.0030) | 0.46 (0.001) | 0.48 (0.018) |

The density changes observed after cryogenic treatment indicate that LN treatment may induce microstructural modifications in wood. Compared with the control specimens, the LN-treated specimens exhibited lower density values. This reduction may be attributed to the partial removal or redistribution of extractive substances associated with the cell walls or stored within the cell lumina during cryogenic treatment. Extractives are known to reduce wood permeability while contributing to its overall density. It has been reported that water, cold water, and alcohol are effective solvents for removing extractive compounds from wood (Erdin and Bozkurt 2013). Therefore, the density reduction observed following LN treatment may be associated with changes in the amount and distribution of extractive substances within the wood structure.

## Mechanical Test Results

Results of statistical analysis for the mechanical tests are listed in Table 2. When using $p < 0.05$ as the criterion for significance, all but one of the considered effects was found to be significant. The exception was the modulus of elasticity in the case of oak.

**Table 2.** Analysis of Variance (ANOVA) Results of the Effect of Liquid Nitrogen Treatment on Mechanical Properties

| Wood Type | Mechanical Properties | F Account | p-value | Levene Statistic | Homogeneity of Variance |
|---|---|---|---|---|---|
| Uludag Fir | Bending strength (N/mm$^2$) | 8.45 | 0.005 | 0.427 | Homogeneous |
| | Modulus of elasticity (N/mm$^2$) | 6.92 | 0.010 | 0.013 | Homogeneous |
| Beech | Bending strength (N/mm$^2$) | 14.21 | 0.001 | 0.007 | Homogeneous |
| | Modulus of elasticity (N/mm$^2$) | 4.85 | 0.029 | 0.473 | Homogeneous |
| Oak | Bending strength (N/mm$^2$) | 6.11 | 0.015 | 2.069 | Homogeneous |
| | Modulus of elasticity (N/mm$^2$) | 3.02 | 0.085 | 0.580 | Homogeneous |

In summary, the one-way ANOVA results showed that the effect of cryogenic treatment on mechanical properties varied among wood species. Levene's test confirmed the homogeneity of variances for all mechanical property datasets. Based on the ANOVA results ($p < 0.05$), liquid nitrogen treatment affected the bending strength and modulus of elasticity of Uludağ fir and beech, as well as the bending strength of oak. In contrast, the effect of liquid nitrogen treatment on the modulus of elasticity of oak was not statistically significant ($p = 0.085$). These findings demonstrate that the mechanical response to cryogenic treatment is species- and property-dependent.

**Table 3.** Mean and Standard Deviation Table (Bending Strength and Modulus of Elasticity)

| Wood Species | Treatment | Bending Strength (MPa) Mean ± SD | Modulus of Elasticity (MPa) Mean ± SD |
|---|---|---|---|
| Uludag Fir | Control | 57.81 ± 4.17[a] | 5876.58 ± 511.00[a] |
| | 15 min | 59.87 ± 3.93[a] | 6325.30 ± 513.53[a] |
| | 30 min | 60.49 ± 3.22[a] | 6550.31 ± 306.89[a] |
| Beech | Control | 90.78 ± 3.81[a] | 7488.54 ± 369.71[a] |
| | 15 min | 80.27 ± 1.72[b] | 7082.58 ± 160.40[a] |
| | 30 min | 84.03 ± 4.79[ab] | 7078.28 ± 406.45[a] |
| Oak | Control | 77.03 ± 3.07[a] | 5911.46 ± 119.81[a] |
| | 15 min | 75.17 ± 9.02[a] | 5927.49 ± 786.95[a] |
| | 30 min | 70.91 ± 8.65[a] | 5974.05 ± 644.42[a] |

## 2D DIC Analysis

The strain component contour maps for $\varepsilon_{xx}$ (Fig. 2), $\varepsilon_{xy}$ (Fig. 3) and $\varepsilon_{yy}$ (Fig. 4), calculated by means of the DIC technique, are shown, and the associated maximum and minimum values of strain are tabulated in Table 1. Results were considered in terms of wood species and duration of treatment with LN. The results indicate that the liquid nitrogen treatment time (15 min, 30 min) and wood species were critical parameters determining the deformation behavior of the test samples, as the strain response of wood to deformation was markedly affected by treatment time. Cryogenic treatment with liquid nitrogen resulted in a stiffer mechanical response in beech and oak, as evidenced by the reduced strain values, particularly in the XX and YY directions. In contrast, localized increases in strain were observed in Uludağ fir. Furthermore, this study is the first to comprehensively visualize and evaluate the effects of liquid nitrogen treatment on wood by employing the Digital Image Correlation (DIC) technique to obtain full-field strain distributions. The results indicate that improving the mechanical performance of wood through liquid nitrogen treatment requires careful optimization of treatment parameters for each wood species. The present findings are also consistent with previous studies employing Digital Image Correlation for deformation analysis. Pan *et al.* (2009) emphasized that DIC provides reliable full-field strain information that cannot be obtained using conventional point-based measurement techniques. Similarly, Sözen *et al.* (2021) demonstrated that the DIC method successfully characterized strain localization and deformation behavior in laminated veneer lumber subjected to bending loads. Likewise, del Rey Castillo *et al.* (2019) reported that full-field strain measurements obtained by DIC enable the identification of localized deformation zones before visible failure occurs. In agreement with these studies, the present work confirms that DIC is an effective and reliable technique for evaluating the deformation behavior of cryogenically treated wood materials and provides substantially more comprehensive information than conventional displacement measurements.

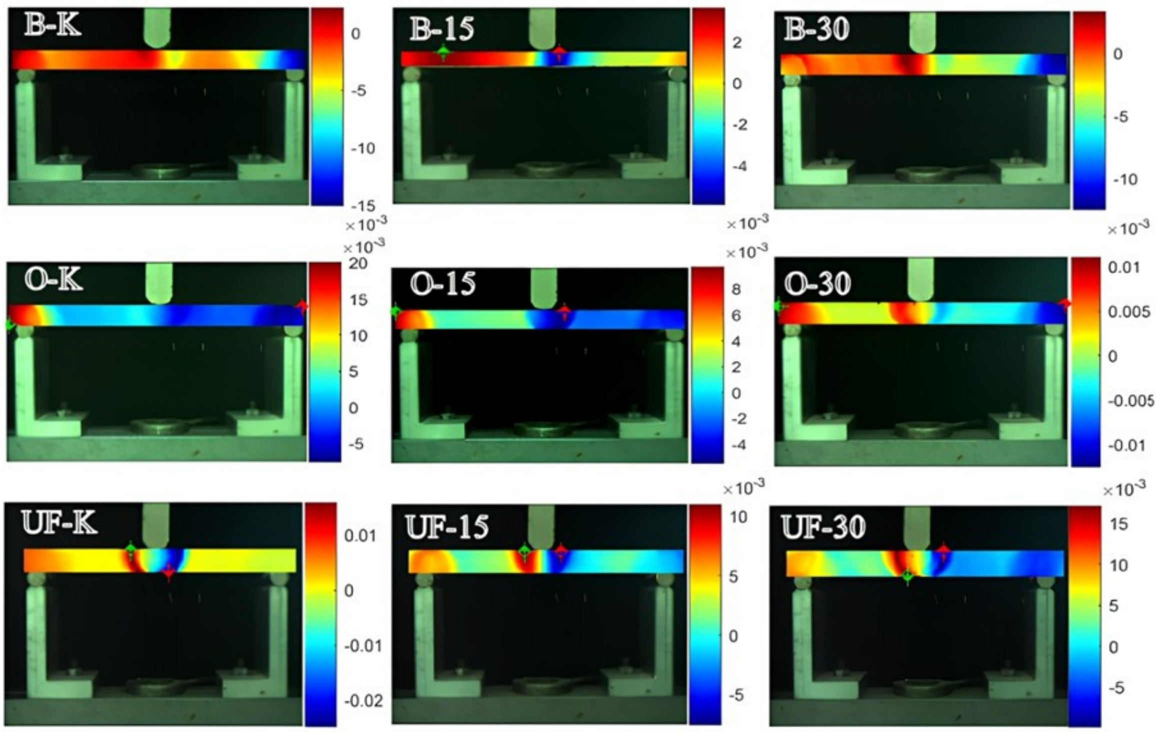


**Fig. 3.** Strain distributions in $\varepsilon_{xx}$ in the heat treatment (UF: Uludag fir, B: Beech, O: Oak)

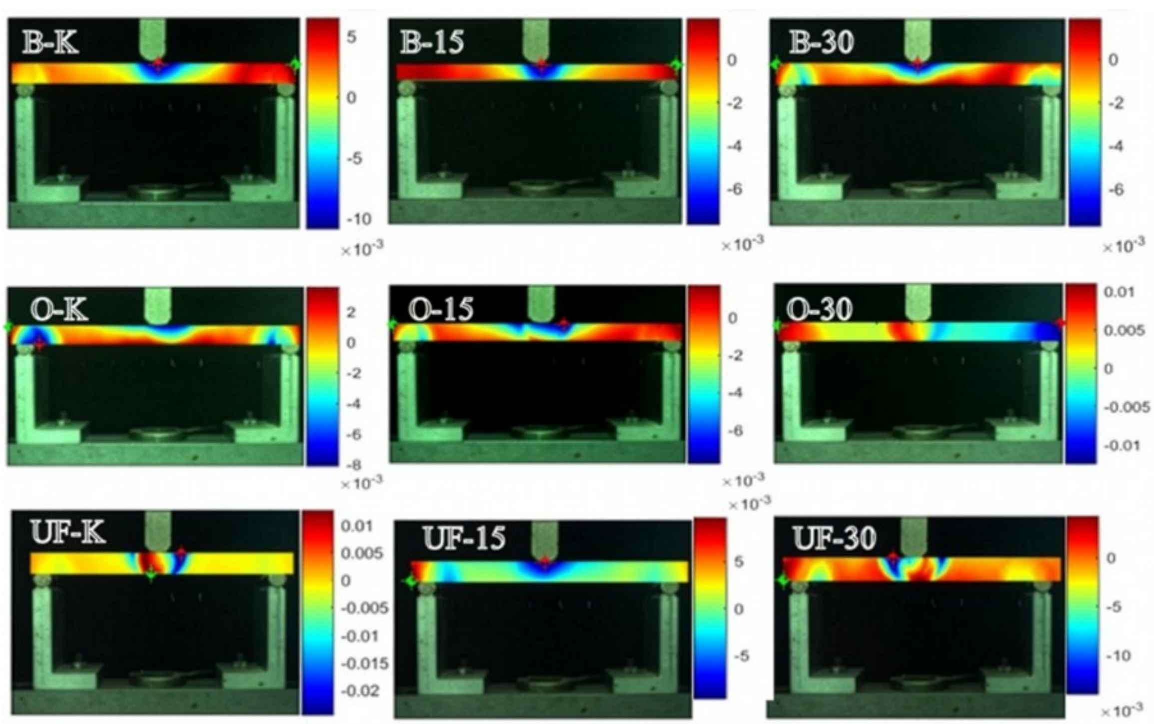


**Fig. 4.** Strain distributions in $\varepsilon_{xy}$ in the heat treatment (UF: Uludag fir, B: Beech, O: Oak)

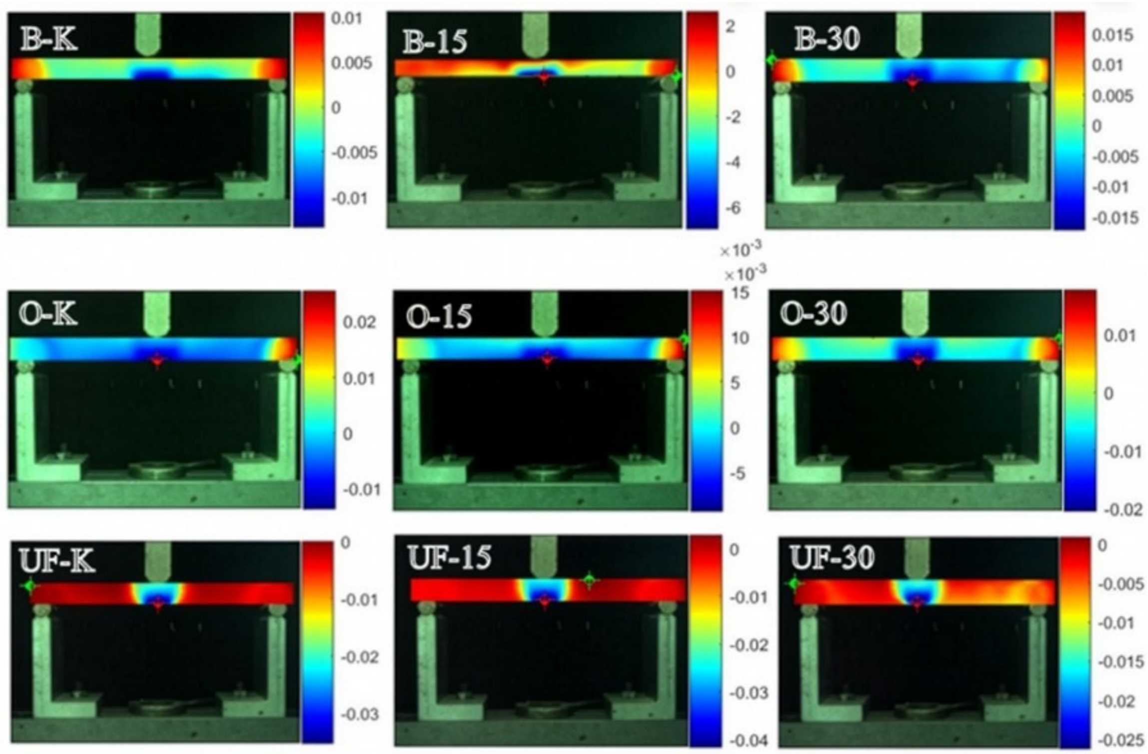


**Fig. 5.** Strain distributions in $\varepsilon_{yy}$ in the heat treatment (UF: Uludag fir, B: Beech, O: Oak)

When the results obtained for the $\varepsilon_{xx}$, $\varepsilon_{xy}$ and $\varepsilon_{yy}$ strain components are evaluated collectively, it is evident that LN treatment affected the deformation behavior of wood in a direction-dependent, species-specific, and treatment duration-dependent manner. The $\varepsilon_{xx}$ component represents the normal strain parallel to the grain and is particularly sensitive to changes in material stiffness under bending loading. Accordingly, the maximum $\varepsilon_{xx}$ strain values generally decreased in beech and oak following LN treatment, indicating increased stiffness. In contrast, Uludağ fir exhibited an increasing trend in $\varepsilon_{xx}$ under certain LN treatment conditions. These findings suggest that the anatomical differences between hardwood and softwood species play a significant role in determining their mechanical response to cryogenic treatment.

The $\varepsilon_{xy}$ strain part corresponds to an in-plane shear strain and the LN treatment influence on this strain field was more related to point defects effects than to those seen in the $\varepsilon_{xx}$ and $\varepsilon_{yy}$ strain fields. In beech and oak, the 15 min LN exposure decreased the shear strain and enhanced strain uniformity. In some specimens, however, a 30 min LN treatment again produced an increase in $\varepsilon_{xy}$ values. In contrast, in Uludağ fir, the $\varepsilon_{xy}$ strain component showed a more unpredictable behavior with respect to the LN treatment. This phenomena can be attributed to the influence of rapid cryogenic cooling on the fibrous composite tissue of wood and the resin canal arrangement of softwood species. The $\varepsilon_{yy}$ strain component corresponds to the tensile and compressive strain that is induced during bending and was found to be stronger and more consistent in its response to the LN treatment. In beech and oak, LN treatment decreased both the maximum and minimum $\varepsilon_{yy}$ strain values, thus reducing strain concentrations and leading to a more uniform deformation over the specimen. Conversely, the absolute value of $\varepsilon_{yy}$ strain increased, particularly after 30 min of LN treatment, in Uludağ fir, indicating that cryogenic treatment may increase the susceptibility to brittle behaviour in softwods and maybe in general in wood.

In summary, the analysis of all $\varepsilon_{xx}$, $\varepsilon_{xy}$, and $\varepsilon_{yy}$ strain components confirms that LN treatment cannot enhance the deformation behavior of wood-based materials in a uniform manner. Rather, the magnitude of its impact differs with wood type, treatment time, and strain direction, due to the different anatomical features and deformation mechanisms of the species. These results suggest that the enhancement of engineering performance of wood-based materials through optimized cryogenic treatment is a species- and loading direction-specific issue. In addition, the full-field strain information from the DIC technique was much more detailed than the traditional point-based measuring methods, which allowed for a more precise and dependable description of the deformation process and mechanical behavior of wood-based materials treated cryogenically.

**Table 4.** Strain Values of Control and Liquid Nitrogen–treated Test Specimens (15 min and 30 min)

| Wood Species | Treatment | XX Max | XX Min | XY Max | XY Min | YY Max | YY Min |
|---|---|---|---|---|---|---|---|
| Beech | Control | 0.0075 | -0.0216 | 0.0046 | -0.0160 | 0.0127 | -0.0159 |
| | 15 min LN | 0.0022 | -0.0084 | 0.0037 | -0.0062 | 0.0031 | -0.0081 |
| | 30 min LN | 0.0031 | -0.0092 | 0.0041 | -0.0151 | 0.0241 | -0.0208 |
| Oak | Control | 0.0057 | -0.0109 | 0.0221 | -0.0091 | 0.0328 | -0.0162 |
| | 15 min LN | 0.0047 | -0.0090 | 0.0117 | -0.0057 | 0.0191 | -0.0108 |
| | 30 min LN | 0.0052 | -0.0091 | 0.0130 | -0.0181 | 0.0250 | -0.0240 |
| Uludağ Fir | Control | 0.0150 | -0.0333 | 0.0190 | -0.0294 | 0.0010 | -0.0421 |
| | 15 min LN | 0.0140 | -0.0118 | 0.0129 | -0.0093 | 0.0035 | -0.0497 |
| | 30 min LN | 0.0075 | -0.0216 | 0.0203 | -0.0136 | 0.0023 | -0.0328 |

Table 4 presents the minimum and maximum strain values in the $\varepsilon_{xx}$, $\varepsilon_{xy}$, and $\varepsilon_{yy}$ directions for the control specimens and those treated with LN for 15 and 30 min. The results demonstrate that liquid nitrogen treatment exerts species- and treatment duration-dependent effects on the deformation behavior of wood.

In beech wood, the maximum strain values were significantly decreased by LN treatment, especially for the XX and YY directions, and the absolute values of the minimum (compressive) strain were also reduced. These results suggest that the stiffness of the cell walls was improved by cryogenic cooling, leading to less bending-induced deformation in the stiffer material. It is worth mentioning that the 15 min LN treatment led to a more uniform strain distribution, while the 30 min treatment seemed to show an increase in strain values along some orientations. This behavior can be explained by thermally induced microstructural damage of the cellular structure due to long-term or overcryogenic treatment, as known from literature (Özkan 2021; Aytin *et al.* 2022). The pattern of LN treatment on oak was similar to that of beech, but the absolute strain values were still relatively high, especially for the XY and YY strain components. This can be explained by the fact that oak has a more compact and variable anatomical structure and thus reacts differently to the cryogenic treatment. Results from previous investigations indicate that cryogenic treatment-induced changes may be restricted or directionally dependent in high density wood species with developed vessels (Özkan 2021). However, in general the strain values in the 15 min LN treatment were lower than in the control along almost all directions, although the strain value in the 30 min treatment was higher in some directions.

Beech and oak were completely different from Uludag fir (*Abies bornmüelleriana* Mattf.) with respect to responding to LN treatment. In particular, the absolute value of the minimum strain in the radial–tangential (RT) direction increased, and in some samples, the absolute value of the maximum strain also increased. These observations indicate that rapid cryogenic cooling might have a more heterogeneous impact on fiber morphology, resin canal structure, and moisture distribution of softwood species such as Uludağ fir. Contrastingly, it was also reported that rapid cryogenic cooling can facilitate the development of microcracks for wood species with relatively lower density and a more uniform fiber structure (Özkan 2021). Overall, the results show that the LN treatment cannot generally or universally be expected to enhance the deformation properties of wood-based materials. Rather, its impact depends on the wood species, duration of the treatment, and the strain component analyzed. In this respect, the generic statement on the enhancement of the mechanical properties of wood by cryogenic treatment available in the literature has been challenged with a more advanced and species-specific interpretation acquired from full-field strain maps using DIC technique. The results demonstrate that the improvement in mechanical performance of wood by liquid nitrogen treatment is feasible though a precise control of both the treatment time and species-specific processing parameters is necessary.

Although no further hypothesis testing (*e.g.*, ANOVA) was conducted on the strain data in this study, the DIC results were interpreted through quantitative evaluations of full-field strain measurements. Compared to traditional point measurement techniques, the DIC method delivers not only mean strain values, but also strain distribution information over the full surface of the specimen. The magnitude of the differences in the maximum and minimum strains between the control and LN-treated samples showed regular and directional patterns for each wood species. In addition, the strain response was studied as a function of the duration of treatment, anatomical direction, and to some extent, stochastic variations. This is in line with the approach typically followed in studies based on DIC, focusing on physically meaningful trends or deformation mechanisms that are material specific, rather than purely on statistical significance. Hence, the results were discussed in terms of statistically significant and mechanically meaningful, reproducible variations in deformation behaviour.

The present study focused primarily on the mechanical response and full-field strain behavior of cryogenically treated wood. Physical characteristics such as dimensional stability, mass change, and color variation, as well as microstructural observations using microscopy techniques, were beyond the scope of the present investigation. These properties may provide valuable insight into the mechanisms responsible for the observed mechanical behavior and should therefore be considered in future studies combining mechanical testing with microscopic characterization of the wood cell wall.

## CONCLUSIONS

1. The results indicate that LN treatment's effect on the mechanical performance of wood-based materials is highly species-specific. In Oriental beech (*Fagus orientalis* L.) and oak (*Quercus* spp.), LN application for 15 and 30 min decreased strain values at XX and YY directions, implying that the stiffness of the materials was increased. In contrast, local peaks of strain seen in *Abies bornmuelleriana*, suggest a different reaction of this softwood species to the cryogenic process. These results imply that

optimizing the treatment parameters of liquid nitrogen for improving the engineering properties of wood-based materials should be conducted meticulously with respect to wood species.

2. The two-dimensional Digital Image Correlation (2D-DIC) technique successfully characterized the effects of LN treatment on the deformation behavior of wood by providing full-field strain maps. The results demonstrated that the mechanical response to cryogenic treatment is strongly dependent on wood species, emphasizing the importance of species-specific optimization of cryogenic treatment parameters to maximize the engineering performance of wood materials.
3. In the future, a systematical optimization of the cryogenic treatment parameters should be investigated, to further exploit the effect of LN treatment on wood-based materials performance. In particular, the optimal treatment parameters (liquid nitrogen treatment time, cooling rate, moisture content, and so on) should be determined individually for every species of wood. Such a species-specific optimization approach would allow for a controlled application of cryotreatment and the success of subsequent engineering wood-based solutions.

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