Shape Changes in Hornbeam (*Carpinus betulus* L.) Lumber Induced by Spiral Grain

Peter Vilkovský,* Hugo Miroslav Uličný, Ivan Klement, and Tatiana Vilkovská

Hornbeam (*Carpinus betulus* L.) wood often has a spiral grain character, which contributes to shape instability in the resulting products. Spiral grain refers to the deviation of wood fibers from the longitudinal axis. This study identified and quantified specific shape changes caused by spiral grain in hornbeam samples. Differences between samples were analyzed with varying degrees of spiral grain and their impact on the shape stability of hornbeam lumber. Changes in the warp cup and the warp twist were monitored during three months of an air-drying process. Moisture loss was found to have a significant influence on the increase in the observed types of warps. An average rise in warp cup from 0 mm to 0.61 mm was recorded in specimens lacking spiral grain, whereas in specimens exhibiting spiral grain, it was raised from 0 mm to 0.92 mm over the same period. Warp twist was increased from a mean value of 7.2 mm in non-spiral-grain specimens to 19.6 mm in spiral-grain specimens. Moreover, the original position of the lumber pieces within the logs whether adjacent to the pith or the bark was determined to be a significant factor in the final type and size of the warp (curvature). This study highlights the critical role of spiral grain and log positioning in shaping the dimensional stability of hornbeam lumber during drying.

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Keywords: Hornbeam; Warp cup; Warp twist; Spiral grain; Shape stability

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INTRODUCTION

Hornbeam (*Carpinus betulus* L.), with an average density in the fresh state of 800 kg·m³, is typically grown to a height of 20 to 25 meters. It rarely exceeds 30 meters, with large, branching limbs. Hornbeam creates an impression of a stable, strong, and dense structure that can be influenced by spiral grain (Sikkema *et al*. 2016). As a result, shape instability can result, which distinguishes it from many other lumber species (Rouvinen and Kuuluvainen 1997; Skatter and Kucera 1998; Eklund 2000; Vilkovský *et al*. 2024).

Hornbeam wood is often avoided in construction because of its relatively high density, which increases the overall weight, along with its low resistance to biological degradation, and limited dimensional stability. Variations in shape and size, caused by changes in moisture content and temperature, can lead to complications both during processing and in the final application (Säll 2002; Aydemir *et al*. 2011). According to Aydemir *et al*. (2011), hornbeam is a high-density hardwood with limited dimensional stability. This combination of attributes has restricted its wider industrial application. To address this, thermal treatment under controlled oxygen-free conditions improved its shape stability by reducing moisture-related deformation. These findings support the potential of thermal modification as a method for enhancing the usability of hornbeam in various wood-based products.

One of the common defects occurring in hornbeam wood is spiral grain. This defect can be observed on the bark and extends inward to the center of the log. Spiral grain is characterized as a phenomenon in which wood fibers are arranged helically around the longitudinal axis of the stem, rather than being aligned in a straight axial direction. This deviation may be either right-handed or left-handed and is caused by genetic factors, growth conditions, or the tree's response to external influences, such as wind or terrain slope (Leelavanichkul and Cherkaev 2004; Schulgasser and Witztum 2007). According to Leelavanichkul and Cherkaev (2004), spiral grain formation is considered a compromise between water transport efficiency and mechanical stability.

Spiral grains are likely to be a primary cause of excessive warping in sawn timber after drying. This phenomenon may be exacerbated by increasing moisture changes (drying shrinkage) and is also influenced by the direction and angle of the fibers within the individual wood layers (Ekevad 2005). Ormarsson and Johansson (2006), Ormarsson *et al.* (2000), and Ormarsson (1999) found in their studies that spiral grain is a significant factor affecting the dimensional stability of lumber, particularly during drying. Ormarsson *et al.* (2000) also found that lumber with significant spiral grain has a greater tendency for twist deformation. The research also shows that a spiral grain angle of ±5° is acceptable and should not lead to significant deformations during drying. Angles between ±5° and ±10° may cause slight twisting. Angles over ±10° cause significant twisting, are unacceptable for construction lumber, and should only be used for non-structural parts. The study's results also recommend that the measurement of spiral grain should be performed on the log. These claims are confirmed by further research (Vilkovský *et al.* 2024), which focused on hornbeam lumber. The study compared the dimensional stability of hornbeam wood with and without the spiral grain. The results showed that spiral grain significantly affects the dimensional stability of lumber during drying.

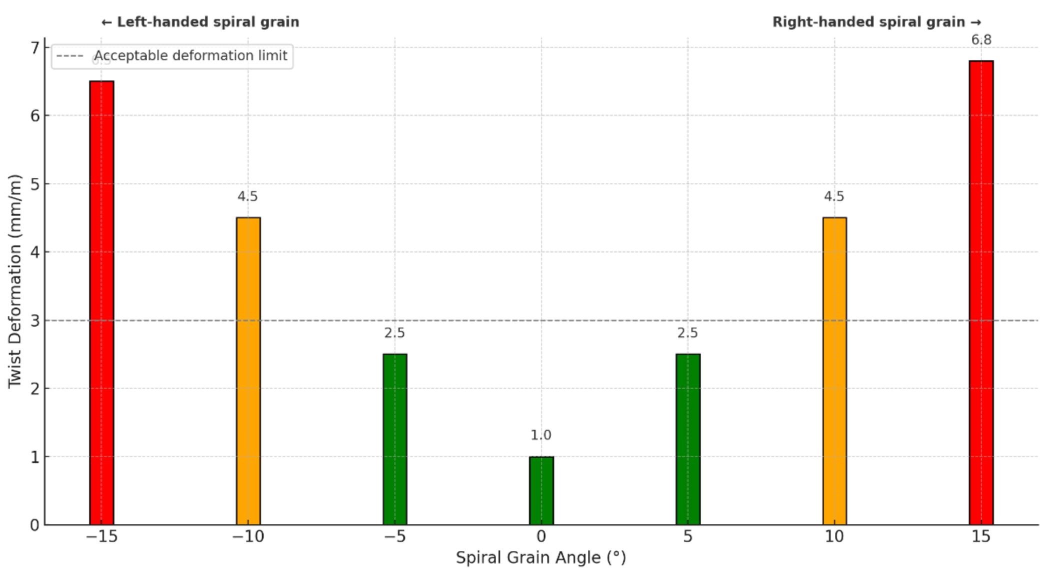

Fig. 1. Effect of spiral grain angle on dimensional stability (twist). The green bars represent spiral grain angles within ±5°, where the lumber is considered stable; orange bars indicate angles between ±5° and ±10°, showing slight deformation and conditional usability; red bars correspond to angles above ±10°, where significant deformation occurs, making the lumber unsuitable for precise applications (Ormarsson *et al.* 2000).

Cown *et al.* (1996) found that the diameter of the logs may also be another significant factor affecting shape stability. The study also confirmed that drying distortions of the lumber are exacerbated by the presence of spiral grain. It was discovered that small log diameters and temperature during drying affected up to 80% of the lumber, resulting in its classification as rejected due to distortions. In contrast, for large-diameter logs, approximately 5% of the boards were rejected. Over 90% of the distortion issues were related to twist, with the remaining 10% attributed to crook or bow. The study by Zhan and Avramidis (2007) revealed additional causes of dimensional instability. The results indicate that another factor influencing shape changes may be the width of the lumber. Data showed that by increasing the width of the lumber from 100 to 150 mm and then to 200 mm, the warp of samples with thicknesses of 25 and 40 mm significantly increased, both for samples dried in the kiln and those subjected to additional heat treatment. For example, for samples with a thickness of 40 mm, the warp of the 150 mm wide samples increased by 71.7%, and for the 200 mm wide samples, it increased by 211.7% compared to the 100 mm wide samples. After thermal treatment, the warp increased by an additional 47.5% for the 100 mm wide samples, 7.2% for the 150 mm wide samples, and 5% for the 200 mm wide samples with a thickness of 25 mm.

Another significant factor was identified by Straze *et al.* (2011) during research the warp of spruce lumber (*Picea abies* (L.) H. Karst.). It was determined that the original position of the lumber within the log may be a critical determinant of shape stability. The greatest twist warp was observed in lumber located near the pith, particularly within the innermost ten annual rings, at a moisture content of 31.5%. In contrast, lumber obtained from the outer sections of the log were found to exhibit greater dimensional stability, with warp occurring primarily at moisture levels below 23.8%. Regression analysis confirmed that twist warp is influenced by the initial position of the lumber in the log, with the most pronounced deformations occurring at the final stages of the drying process. Lumbers situated closer to the pith displayed a rotation angle of approximately 17°, which was reduced to 1° and 3° as the distance from the pith increased. Similarly, Knight (1961) emphasized in his work that deformations such as cupping, twisting, and bowing arise due to the natural structure of wood—particularly due to differential shrinkage in the tangential and radial directions. These deformations can be influenced by the lumber original position within the log, the presence of spiral grain, and moisture conditions during drying. As their causes are internal and biologically determined, they cannot be eliminated. However, a thorough understanding of these factors is essential for minimizing lumber degradation during processing. Also, according to Wengert and Meyer (1993), all types of warp in lumber namely cup, bow, and crook are caused by differential shrinkage in various anatomical directions of wood during the drying process. The authors explain that bow and crook are associated with longitudinal shrinkage, particularly in juvenile wood near the center of the tree. The severity of these deformations is further influenced by the original location of the board within the log, the grain orientation, and drying practices.

The primary focus of this study was to provide a general assessment of the dimensional stability of hornbeam timber during three months of the air-drying process. Primarily, the influence of moisture reduction on the selected types of warps was evaluated. In addition, an analysis of the influence of spiral grain on selected types of warps (warp cup and warp twist) was conducted. Finally, the effect of the original position of the timber within the log on its dimensional stability was also evaluated. This study is essential for advancing the understanding of how spiral grain and initial log positioning affect shape changes in hornbeam lumber during natural drying, providing valuable insights for improving the dimensional stability and quality control of this increasingly utilized hardwood species.

EXPERIMENTAL

Selection of Samples

The hornbeam was harvested in Hronská Dúbrava in the Žiar nad Hronom (Slovakia) district at approximately 457 m above sea level. The collection was conducted in collaboration with the Technical University of Zvolen Forestry Enterprise. The forests in this area are predominantly deciduous, with European beech (*Fagus sylvatica* L.) and hornbeam being the main species. Two types of samples were obtained for research. The first had deviations without the spiral grain (Fig. 2A) while the second exhibited significant deviations with the spiral grain (Fig. 2B).

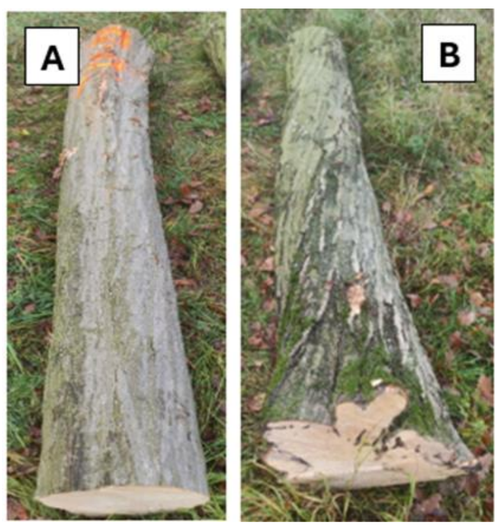

Fig. 2. Examples of samples without spiral grain (A) and with spiral grain – right-handed (B)

Production of Squared-Edged Lumber

The selected samples were cut to 3 meters and transported to the Development Workshops and Laboratories of the Technical University of Zvolen, where they were sawn into lumber. The logs were harvested at breast height (approx. 1.3 m), with diameters ranging from 37 to 41 cm. The lumber was produced using the through-and-through sawing pattern. For this sawing pattern, tangential lumber (where the growth rings are parallel to the edges of the lumber) and radial lumber (where the growth rings are perpendicular to the surface of the lumber) are primarily produced. Before sawing, the grain's deviation in spiral grain samples was measured according to the STN EN 1309-3 (2018) standard. The lumber was carefully sorted into radial and tangential categories. Lumber of dimensions 0.025 × 0.095 m (height × width) was selected from each sample and then cut to 2 meters. From each log, 10 to 14 boards were produced. See Fig. 10 for the visual of lumber cutting. Each produced lumber was marked. The marking included: lumber quality (S - center lumber or B - side lumber), order of produced layer (1), order of produced lumber by layer width (1), spiral grain content (N - without or To - with), lumber type (R - radial or T - tangential). The resulting marking was, for example, S/1-1/To/R. Two drying stacks (Fig.

3) were prepared in the storage. One was designated for lumber from samples without spiral grain, and the other for lumber with spiral grain. The stacks were placed on four concrete pedestals, each 0.435 m high, and spaced 1.80 m apart on an asphalt surface.

The lumbers in the stacks were arranged alternately: tangential, radial, tangential, radial, and tangential (fig.3). In the center of each stack, one lumber was replaced by a drying sample to monitor moisture loss (weight). The sample had the same cross-section as the lumber, only its length was shortened to 0.3 m.

Air-drying Conditions

Air drying conditions were monitored using a Data Logger, with hourly intervals for tracking ambient temperature in °C and relative humidity in %.

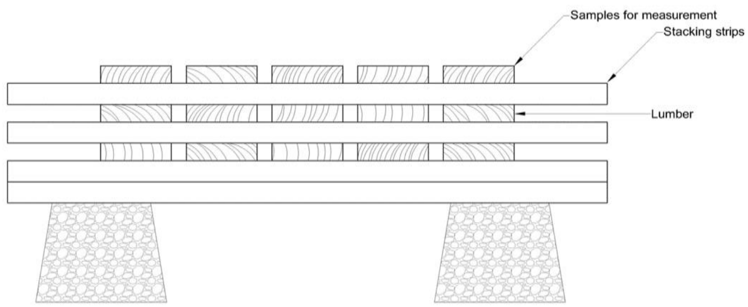

Fig. 3. Schematic of the drying stack

Measurement of Angles in the Sample

The grain deviation angles from the trunk's longitudinal axis were measured on the bark of samples with spiral grain. The angles on the lumber were measured both before and after air drying. All measurements, whether on the samples or the lumber, were carried out by STN EN 1309-3 (2018) standard (Fig.4).

Measured Shape Changes in Lumber

The study was focused on shape changes in hornbeam lumber during air drying. Two types of warps were examined: twist and cup. A warp cup is defined as a transverse deformation of wood, in which the board is bent across its width, resulting in a concave or convex shape. This deformation is measured as the maximum distance between the highest point of curvature and the flat surface on which the board is placed. A warp twist is described as a torsional deformation, in which the ends of the board are rotated around its longitudinal axis, causing a twist. It is measured as the difference in height between diagonally opposite corners of the board when it is laid on a flat surface.

The measurements were carried out using a digital caliper at the Development Workshops and Laboratories of the Technical University of Zvolen, by the STN EN 1309-3 (2018) standard (Fig. 4).

Classification of Lumber According to DIN 4074-5 (2008)

The DIN 4074-5 (2008) standard was applied to evaluate the warp values and to determine the expected quality of the lumber.

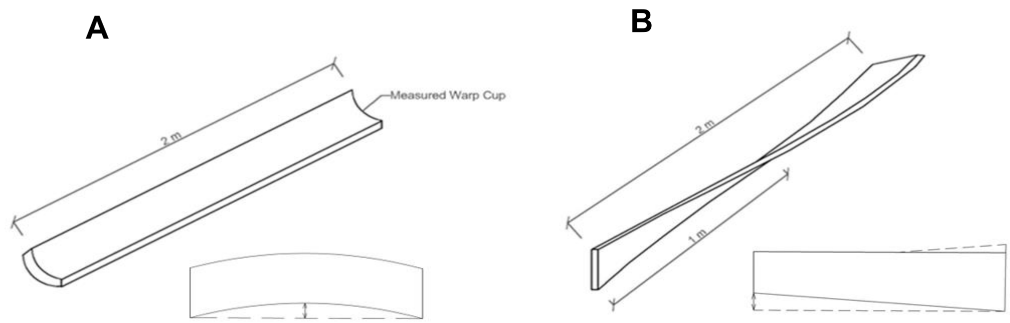

Fig. 4. Measurement of warp cup (A) and warp twist (B) according to STN EN 1309-3 (2018)

RESULTS AND DISCUSSION

Changes in Spiral Grain

Spiral grain was measured on the examined lumber both before and after three months of air drying (Table 1). The results were compared and evaluated based on the study by Ormarsson *et al.* (2000). After taking their findings into account, it was concluded that three out of five lumber samples were classified into the orange category, where only slight deformation was observed, and conditional usability was indicated. The remaining samples were reassigned to the red category, where significant deformation was detected, making the lumber unsuitable for further use. This deterioration was also reflected in the measured warp twist values after drying, where a notable increase, from 25% to 160%, was recorded in all samples (see Table 1). The results showed that spiral grain can influence the dimensional stability of hornbeam lumber to a lesser or greater extent. Similar findings were reported by Cown *et al.* (1996), where lumber with pronounced spiral grain was found to exhibit a higher tendency toward deformation, which corresponds with the present findings. This trend may significantly affect even the mechanical properties of the lumber.

Evaluation of a Warp Cup in Hornbeam Lumber

As illustrated in Fig. 5, the development of values during the measurement process showed a consistent increase in warp cup in all observed pieces, except for one specimen labeled S/5-1/To/R. For this piece, a disproportionately high increase in warp cup was recorded, up to 245%. This result was likely caused by the presence of the pith within the lumber, which led to reduced shape stability. From this, it can be concluded that the original position of the lumber within the log, as well as the presence of the pith, significantly affects the dimensional stability of hornbeam lumber. A comparative view of both sides of the lumber (5-1/To/R) after the drying process is shown below the graph in Fig. 4. The presence of pith is observed to contribute significantly to the increase of dimensional instability in the lumber. Similar conclusions were drawn by Straze *et al.* (2011), who noted that the warp cup is strongly influenced by their distance from the pith. They agree that this factor plays a key role in evaluating and preventing shape deformation during the drying and processing of lumber. Furthermore, Harald Säll (2002) stated that warp cup constitutes a specific form of distortion caused primarily by moisture variations.

Figure 6 presents the warp cup values of lumber without spiral grain that resulted from the air-drying process.

Table 1. Difference in Spiral Grain Angle Before and After the Air-Drying Process

Lumber no. →		**S/4-1/To/R**	**Ormarsson *et al.* 2000 (Fig. 1)**	**S/5-1/To/R**	**Ormarsson *et al.* 2000 (Fig. 1)**	**S/10-1/To/T**	**Ormarsson *et al.* 2000 (Fig. 1)**	**S/3-2/To/T**	**Ormarsson *et al.* 2000 (Fig. 1)**	**S/2-1/To/T**	**Ormarsson *et al.* 2000 (Fig. 1)**
Before air-drying		5		5		8		5		6	
After air-drying		13		9		10		9		12	
The Warp twist [mm] >	*Before air-drying*	0		0		0		0		0	
	After air-drying	23.96		21.2		16.83		14.49		21.37	
	The green bars represent spiral grain angles within ±5°, where the lumber is considered stable										
	The orange bars indicate angles between ±5° and ±10°, showing slight deformation and conditional usability										
	The red bars correspond to angles above ±10°, where significant deformation occurs, making the lumber unsuitable for precise applications										

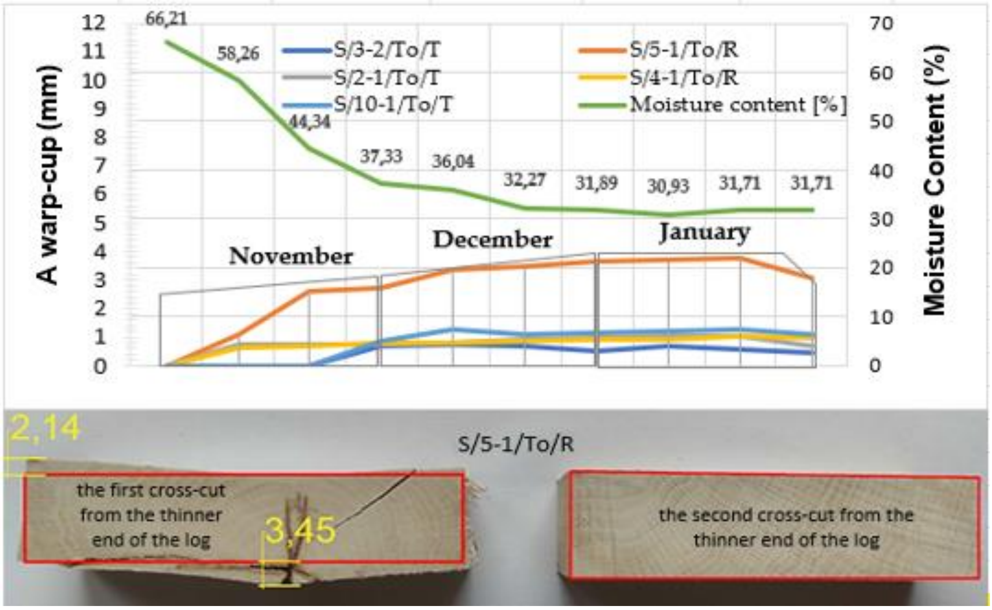

Fig. 5. A warp cup of hornbeam lumber with spiral grain

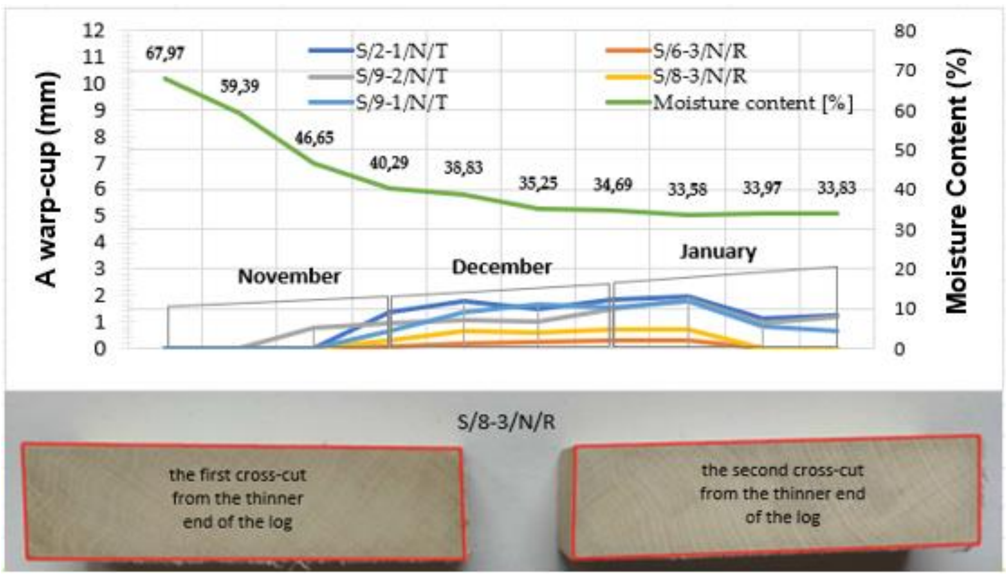

Fig. 6. A warp cup of hornbeam lumber with no spiral grain

A warp cup during or after the drying of lumber was hardly observable in lumber with no spiral grain. The maximum measured final average values ranged from 0.64 to 1.25 mm, almost the same as those measured in lumber with spiral grain. This indicates that the size of the warp cup is not affected by spiral grain to the extent that was expected. It has also been confirmed that a drop in moisture content below the fiber saturation point (<30%) significantly contributes to an increase in warp cup, which can be seen from December (Fig. 5 and 6). A similar observation was made by Ormarsson and Johansson (2006). Zhan and Avramidis (2007) state that, among other factors, the width of the lumber can significantly affect the final size of a warp cup. Additionally, it is claimed that a warp cup is very effective for monitoring stresses during drying.

All cup warp values were analyzed using inductive statistical methods. The analysis of variance (ANOVA) was applied to these data, and the results were subsequently visualized in a two-dimensional box plot, with the significance level set at $p < 0.05$. Based on the statistical evaluation, no statistically significant difference was found ($p = 0.9599$) between timber containing spiral grain and timber without it (see Fig. 7). This indicates that spiral grain does not have a statistically significant effect on this type of deformation (cup warp).

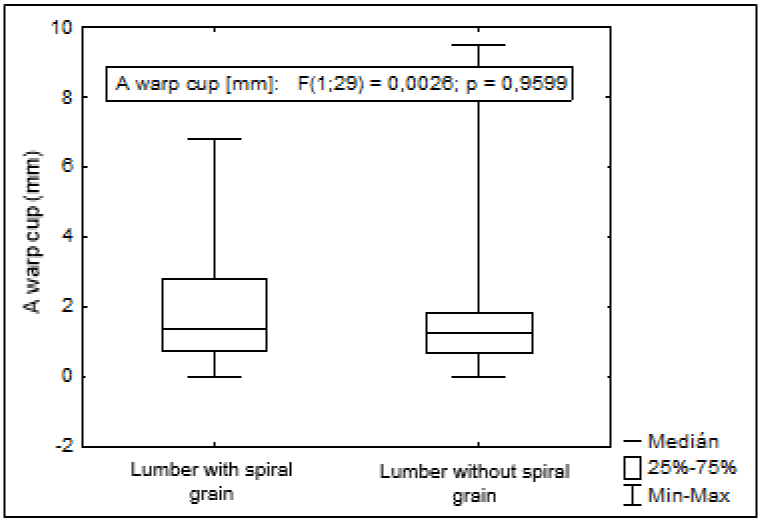

Fig. 7. Impact of spiral grain on warp cup (ANOVA evaluation)

Evaluation of a Warp Twist in Hornbeam Lumber

The values of warp twist in lumber with spiral grain during the three-month air-drying period are presented in Fig. 8. A pronounced increase in twist values was observed in November, ranging from 13.52 to 22.51 mm. During December and January, the twist values changed only minimally. The graph also illustrates the progressive decrease in moisture content over the three months. Based on these results, it can be inferred that the reduction in moisture content directly influences the increase in warp twist. This is likely due to the wood reaching fiber saturation point (around 28 to 30%), where free water loss ends and shrinkage intensifies. These findings are consistent with the general understanding that moisture loss intensifies deformation in lumber with spiral grain. Therefore, careful control of drying conditions is recommended to minimize the risk of twist formation, particularly in materials where spiral grain is present. Schulgasser and Witztum (2007) found that even a slight deviation in grain orientation (*e.g.*, 10°) from the longitudinal axis can significantly reduce bending strength and increase deformation, making such lumber unsuitable for construction. When wood is dried, uneven shrinkage in different directions (radial and tangential), combined with spiral grain, causes lumber to twist, resulting in so-called twist deformation. Their results also showed that a constant tendency of cells to change their inclination during maturation leads to spiral grain formation, which is a direct precondition for the development of twist deformation during drying or exposure to moisture. Similarly, authors Leelavanichkul and Cherkaev (2004) also found that the size of the change in spiral grain plays a key role in the formation of warp twist.

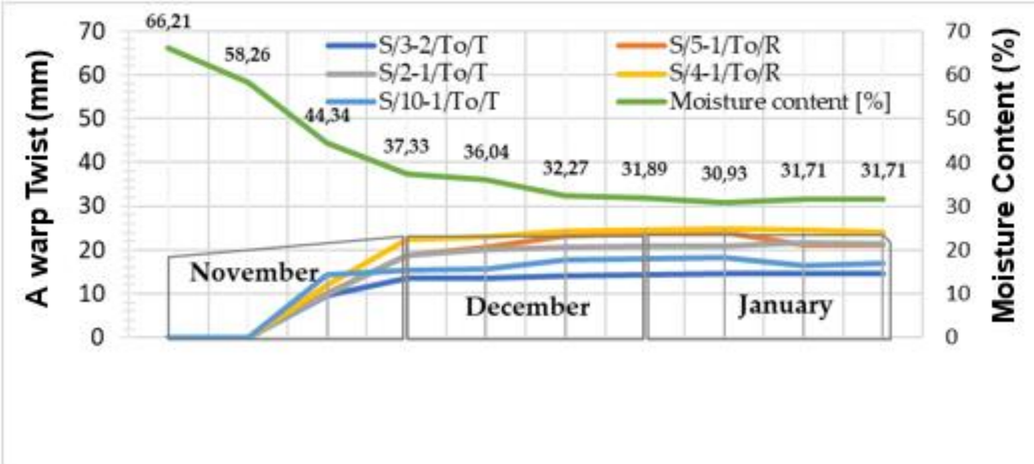

Fig. 8. A warp twist of Hornbeam lumber with spiral grain

After the air-drying process, changes in the angle of spiral grains were also observed. An increase was detected in all pieces of lumber. This change may also be caused by high values in warp twist. It was found by Ormarsson *et al.* (1999) that the size or change in the angle of spiral grains is an important parameter significantly affecting shape changes, such as warp twist.

The analysis of variance (ANOVA) was also conducted on the data concerning the development of warp twist. A statistically significant difference in warp twist was identified between sections with and without spiral grain. The p-value obtained for this type of warp was p = 0.00002, confirming that the warp twist is significantly influenced by the occurrence of spiral grain (Fig. 9).

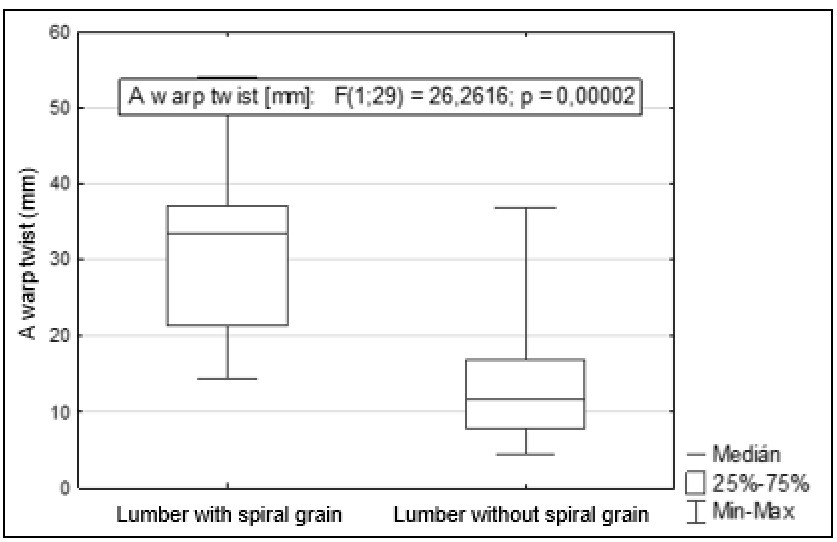

Fig. 9. Impact of spiral grain on warp twist (ANOVA evaluation)

Impact of the Original Position of Lumber in the Log on Warp Cup and a Warp Twist

In this study, attention was also directed towards the hypothesis that the original position within the log might influence the dimensional stability of hornbeam timber. For this purpose, a through-and-through sawing pattern was selected (Fig. 10).

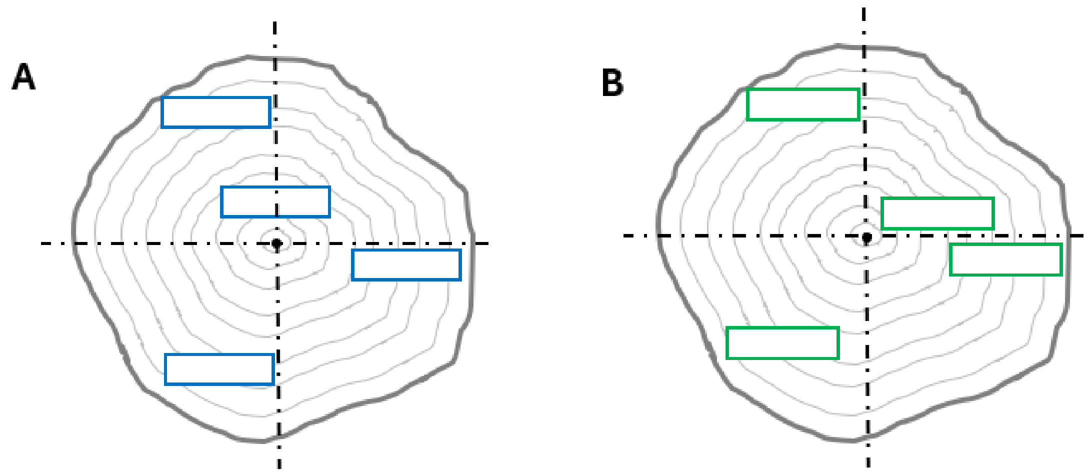

Fig. 10. Schematic representation of the location selection of timber for evaluating the impact of the original position of the lumber in the log on the shape stability of the hornbeam timber: A - Log with spiral grain, B - Log without spiral grain

For comparison, timber samples were chosen either from the near of the pith or near the bark, in both types of logs (with and without spiral grain). The development of warp cup and warp twist was monitored in the selected specimens. To verify this hypothesis, an inductive statistical method was used, the analysis of variance (ANOVA). The results indicated that the original position within the log did not have a statistically significant effect on either warp twist or warp cup. The closest result was obtained in the case of the log containing spiral grain (Fig. 11), where warp cup was evaluated ($p=0.0687$). Based on this outcome, it may be assumed that, in the case of hornbeam wood, the original position within the log could potentially influence this type of deformation (warp cup). It should also be emphasized that, in this measurement, higher values of warp cup were measured in the near of the pith (increase more than 150%) rather than near the bark (Fig. 11). Greater warp cup near the pith could be likely due to also unbalanced tangential shrinkage and presence of juvenile wood. A similar reserch was addressed by Wengert and Meyer (1993), who found that warp cup can be described as a transverse deformation across the width of a lumber, caused by unequal tangential and radial shrinkage. They emphasized that lumber sawn from areas closer to the pith tends to exhibit greater tangential shrinkage on the bark side, resulting in cupping away from the pith and toward the bark (*i.e.*, increased warp cup values). Furthermore, they highlighted that the most significant factor affecting the dimensional stability of lumber is its original position within the log. Knight (1961), who investigated the causes of deformation during lumber drying, emphasized that boards sawn closer to the pith had greater warp cup. He also noted that, although the differences in shrinkage between sapwood and heartwood are minimal, the key influencing factor is the original position within the log. Additionally, it was found that boards containing spiral grain were more susceptible to longitudinal shrinkage, which resulted in twist deformation.

This behavior was attributed to the transposition of tangential shrinkage into a longitudinal effect, which is more pronounced in wood with spiral grain orientation.

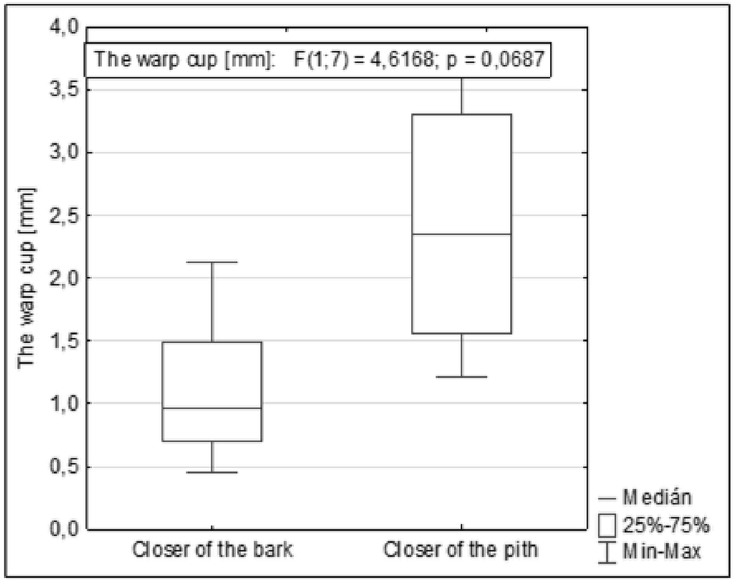

Fig. 11. Statistical evaluation – Impact of the original position of lumber for the warp cup in the log with spiral grain

Classification of Lumber into Strength Classes

Based on the DIN 4074-5 (2008) standard, lumber was classified into strength classes as defined by German regulations based on visual grading criteria. The lumber was sorted into three primary strength classes (LS_7, LS_{10}, LS_{13}). According to this DIN 4074-5 (2008), LS7–LS13 classes define structural timber based on visual grading, including maximum allowable warps (*e.g.*, warp twist max. 6 mm/m for LS10).

Lumber that failed to meet the minimum requirements of the standard strength classes, including the LS_7 category, was assigned to a newly defined group referred to as Reclaimed Wood. This classification was introduced to ensure clearer differentiation and to support further evaluation or potential alternative utilization of such material in non-structural or recycled wood applications. The categorization was carried out based on the log origin, specifically focusing on the presence or absence of spiral grain, to assess its suitability for use in structural timber applications. In the case of lumber exhibiting spiral grain, only four specimens were assigned to the higher strength classes LS_{10} and LS_{13} (Table 2). This outcome suggests that the presence of twisted fibers can, to a certain extent, negatively affect the mechanical performance and structural applicability of the lumber. A comparable classification was conducted by Vilkovský *et al.* (2024), where it was observed that only one piece of lumber exhibiting longitudinal surface warp met the criteria for the LS_7 strength class. The same procedure was applied to lumber without spiral grain. It was determined that lumber free of spiral grain exhibited superior strength properties. Based on the degree of warp twist and warp cup, up to seven specimens were classified into the higher strength classes LS_{10} and LS_{13} (Table 3). Based on the research by Vilkovský *et al.* (2024), in the evaluation of longitudinal warp, eight samples without spiral grain were classified into strength classes LS10 and LS13, while four were placed in class LS7. This research same confirms that timber without spiral grain could be more stable and stronger than timber containing spiral grain.

Table 2. Classification of Lumber with Spiral Grain into Classes according to the DIN 4074-5 (2008) Standard (R = classification due to twist, W = classification due to cup)

Sample	Twist (mm) – W	Cup (mm) – R	LS_7	LS_{10}	LS_{13}	Reclaimed Wood
S/3-2/To/T	14.49	0.00			R	W
S/5-1/To/R	21.20	2.81				R, W
S/2-1/To/T	21.37	6.80				R, W
S/4-1/To/R	23.96	1.49				R, W
S/10-1/To/T	16.83	2.13				R, W
S/7-1/To/R	36.98	1.67				R, W
S/6-1/To/R	54.13	3.81				R, W
S/6-2/To/T	36.51	1.22	R			W
S/8-2/To/T	35.90	0.00			R	W
S/3-1/To/T	23.81	0.45			R	W
S/9-1/To/T	37.17	3.90				R, W
S/7-2/To/T	30.82	0.70		R		W
S/8-1/To/R	43.79	0.96	R			W
S/5-1/To/R	44.67	1.90	R			W

Table 3. Classification of Lumber without Spiral Grain into Classes According to the DIN 4074-5 (2008) Standard*.* Standard (R = classification due to twist, W = classification due to cup)

Sample	Twist (mm) – W	Cup (mm) – R	LS_7	LS_{10}	LS_{13}	Reclaimed Wood
S/1-1/N/R	10.11	0.00			R	W
S/8-2/N/T	19.91	3.20				R, W
S/8-1/N/R	16.54	0.00			R	W
S/10-2/N/T	20.57	1.81				R, W
S/7-1/N/R	11.38	1.35				R, W
S/3-3/N/R-T	18.45	1.51				R, W
S/2-2/N/T	11.41	1.79				R, W
S/11-1/N/T	6.66	0.65		R		W
S/3-2/N/R	11.74	3.22				R, W
S/10-1/N/T	13.00	0.69		R		W
S/5-2/N/T	36.88	9.49				R, W
S/6-1/N/R	16.90	5.75				R, W
S/2-1/N/T	7.87	1.25	R			W
S/6-3/N/R	11.96	0.00			R	W
S/9-2/N/T	4.36	1.17	R			W
S/8-3/N/T	6.38	0.00			R	W
S/9-1/N/T	5.36	0.64		R		W

CONCLUSIONS

These findings have direct implications for primary wood processing. Early identification of spiral grains can reduce the size of warps and finally the loss of lumber.

1. A significant influence of spiral grain on warp twist was identified.
2. No statistically significant effect of spiral grain on warp cup was observed.
3. Variations or reductions in moisture content were found to substantially affect shape stability, contributing to increased warp. Moisture content variations, especially during the critical drying phase below fiber saturation point, significantly affect warp twist and warp cup.
4. It was concluded that the original position of lumber within the log may be a critical factor influencing mainly warp cup.
5. According to the DIN 4074-5 (2008) standard, the presence of spiral grain may result in shape deformations that could lead to the exclusion of lumber from further structural processing.
6. Finally, it should be emphasized that, to obtain dimensionally stable lumber, the original position of the lumber within the log must be carefully monitored, and the moisture content must be controlled both during the drying process and throughout storage. Furthermore, the identification and exclusion of lumber containing spiral grain and the pith can significantly reduce the risk of dimensional instability of lumber.

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