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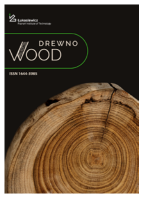

Investigation of the Effect of Perforations Applied to the Inner Layers of Cross-Laminated Timber (CLT) Panels on Thermal Insulation Performance by Experimental and Finite Element Methods

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In this study, perforations at rates of 10% and 20% were applied to the inner layers of cross-laminated timber (CLT) panels, manufactured from fir and oak wood, with thicknesses of 51 mm for three-layer panels and 85 mm for five-layer panels, in order to improve their thermal insulation properties. The thermal conductivity and thermal transmittance coefficients of both groups of CLT panels with perforations were determined using both experimental methods and the finite element method (FEM). According to the results obtained from the experiments, the perforation process applied to the inner layers of the CLT panels was found to cause reductions in both the thermal conductivity and thermal transmittance coefficients. The greatest decrease in the thermal conductivity coefficient was observed in the panels with 20% perforation, which exhibited a reduction of 10.8%, while the thermal transmittance coefficient decreased by 8.7% in the same panels. The results obtained from the FEM analyses were similar to those obtained through experimental methods. In conclusion, the study demonstrated that the use of different wood species and varying perforation rates in the production of CLT panels may have a positive and statistically significant effect on the thermal insulation properties of these panels. Therefore, the application of various perforation techniques can be recommended to improve the thermal insulation performance of CLT panels.

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Introduction

The increasing global population and the resulting rise in housing needs, along with the growing consumption of furniture and interior decoration products, have led to a higher demand for wood and wood-based materials. In order to meet this demand effectively, research and production efforts have focused on wood-based composite materials, leading to the development of engineered structural wood materials.

Types of engineered wood materials include glued laminated timber (glulam), layered veneer lumber (LVL), parallel strip lumber (PSL), layered strip lumber (LSL), and cross-laminated timber (Birinci, 2019). Cross-laminated timber (CLT) boards, one of the types of structural laminated timber materials,

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were developed in central Europe in the 1990s to meet requirements for load-bearing walls under horizontal loads, especially in multi-story buildings (Ceylan, 2021).

Cross-laminated timber (CLT) boards are produced by bonding three, five, seven, or more laminated timber boards on top of one another using glue applied to their broad surfaces, with the fiber directions perpendicular to one another (typically at 90°). The thicknesses of the solid sections used to construct cross-laminated timber boards range from 16 to 51 millimeters, while the widths can vary from 60 to 240 millimeters. CLT boards can have widths up to 3 meters, lengths up to 18 meters, and thicknesses up to 508 millimeters (Mohammad *et al.*, 2013). Structural wood glues containing phenol-resorption formaldehyde (PRF), emulsion polymer isocyanate (EPI), polyurethane (PUR), and melamine urea formaldehyde (MUF) are generally used in the production of CLT boards (Karacabeyli *et al.*, 2013).

Wood is a material that exhibits anisotropy: its rigidity and resistance values vary based on the orientation of its fibers. While the load-carrying capacity is excellent parallel to the fibers, it is lowest in a direction perpendicular to the fibers (Riyanto and Gupta, 1996). Wood is a natural material whose resistance and some characteristic properties vary depending on wood species, growth conditions, and moisture content (Keenan, 1986; Dickson and Parker, 2015). Consequently, the physical, mechanical, and technological properties of CLT boards made from wood vary based on these variables.

In addition to meeting the primary requirements of modern wooden buildings (strength and durability, lightness, sustainability, etc.), CLT panel building systems have greater thermal insulation values, acoustic performance, and fire resistance than steel and reinforced concrete building systems (Ceylan, 2021). Due to these benefits, CLT panels are utilized in the construction of a variety of structures, including both single-story and multi-story buildings (Wieruszewski and Mazela, 2017).

As a result of the rapid consumption of energy resources throughout the world, mainly developed nations have established efficient methods for meeting energy requirements in a controlled and sustainable manner. Thermal insulation facilitates the efficient utilization of energy. Due to its porous structure, wood has superior thermal insulation properties compared with other building materials. In addition, the thermal insulation capacity of wood materials varies by species, fiber orientation, density, and moisture content (Uysal *et al.*, 2011; Gu and Zink-Sharp, 2005; Demir, 2014). The thermal conductivity coefficient, one of the thermal insulation indicators, expresses the heat energy traveling through a unit thickness of the material depending on the temperature difference between the two opposite sides of the material (Örs and Keskin, 2008); its unit is W/m.K. In one-dimensional heat transfer where there is no time-dependent change in temperature, the temperature at any point of the plate is given by equation (1), the total amount of heat energy passing through the plate is given by (2), and the heat flux on the surface of the plate is given by (3) (Çengel and Ghajar, 2017).

$$\frac{d^2T}{dx^2} = 0, (C^{\circ}) \tag{1}$$

$$\dot{Q} = -kA\frac{dT}{dx}, (W) \tag{2}$$

$$\dot{q} = -k\frac{\partial T}{\partial x}, \left(\frac{W}{m^2}\right) \tag{3}$$

where T is temperature (K), k is the thermal conductivity coefficient (W/m.K), A is the vertical surface area through which heat energy passes (m^2), x is the plate thickness (m); $\dot{Q}$ is the heat energy passing through the plate (W), and $\dot{q}$ is the heat flux (W/m^2).

The air-dry thermal conductivity coefficient of Uludağ fir wood is 0.1128 W/m.K (Örs and Şenel, 1999). The thermal conductivity coefficient of oak wood is 0.14 W/m.K in the radial direction, 0.17 W/m.K in the tangential direction and 0.50 W/m.K in the longitudinal direction (Hrčka and Slováčková, 2021), which indicates that the thermal conductivity coefficient varies depending on the direction of the fibers.

As with other wood materials, the coefficient of thermal conductivity in laminated wood panels varies with panel density, fiber orientation, number of layers, type of solid wood used, relative humidity, and type of adhesive. At 12% moisture content, the value for softwoods used for structural purposes ranges from 0.10 to 0.14 W/m.K (Karacabeyli *et al.*, 2013). According to EN ISO 10456 (2007), the thermal conductivity of cross-laminated wood (CLT) panels is 0.13 W/m.K.

It has been reported that the thermal conductivity coefficient of CLT panels produced from spruce wood is higher than that of other laminated panels, with a value of 0.1161 W/m.K, the reason being that the moisture content of CLT boards is higher than that of laminated materials such as parallam (PSL) and microlam (LVL) (Öztürk *et al.*, 2017).

The coefficient of thermal transmittance, or U-value, is a crucial factor in thermal insulation. This is the quantity of heat passing through a unit area in unit time and unit area when there is a 1 °C temperature difference between two perpendicular faces of the building envelope. It has the unit W/m²K and is calculated using equation (4) (Ceylan, 2021). According to Öcal (2016), the thermal transmittance conductivity coefficient of solid pine and oak timbers is 5.70 W/m².K, but varies depending on material density and thickness.

$$U = k / d \tag{4}$$

where U is the thermal transmittance coefficient (W/m².K), k is the thermal conductivity coefficient (W/m.K), and d is the material thickness (m).

In this study, cross-laminated timber (CLT) panels with varying numbers of layers of oak and fir wood were produced, and their thermal insulation values were experimentally determined. The numerical data for thermal conductivity and thermal transmittance coefficients obtained experimentally were then compared with numerical data obtained through the finite element method. This comparison is important for determining whether experimental investigations will be necessary in future studies, based on the similarity of the numerical data to the actual results.

Current engineering applications of the finite element method (FEM) include stress analysis, fluid mechanics, static and dynamic elasticity, and heat conduction. This method has advantages that allow it to be used in the investigation of both isotropic and anisotropic substances (Şirin and Aydemir, 2016).

The aim of this study is to determine the effects of perforations applied at specific rates to the intermediate layers of cross-laminated timber (CLT) panels, which are wood-based composite panels, on the thermal conductivity and thermal transmittance coefficients of the panels, and to examine the degree of similarity between the experimental results and those obtained by the finite element method (FEM).

Material and method

Material

In this study, oak (*Quercus* L.), which occurs widely both globally and in Turkey, was used in view of the durability of its timber, which is known to be suitable for barrel making, furniture manufacturing, shipbuilding, underwater constructions, wood carving, parquet flooring, and coachbuilding (Kadem and Fakir, 2017). Fir (*Abies sp.* L.) wood, which is commonly used in structural applications (Bozkurt, 1979; Bozkurt and Erdin, 1997), was also used in the inner layers of cross-laminated timber (CLT) panels. The wood color is yellowish-grayish white, and among the softwood species that do not contain resin canals, it has low natural durability. The timbers used in the study were randomly selected, ensuring that they possessed first-class qualities such as silky fiber texture, absence of knots, absence of reaction wood, lack of decay, and freedom from insect or fungal damage. Some properties of the materials used in the production of the CLT panels are presented in Table 1.

The solid woods to be used in the production of CLT panels were initially cut to dimensions of 20 mm x 100 mm x 1000 mm before being cleaned on their surfaces and then reduced to a final net size of 17 mm x 80 mm x 310 mm. The solid wood sections were conditioned in a climate chamber at 20 °C and 65% relative humidity until they reached a constant weight. On the surfaces of the conditioned solid wood sections, PVAc adhesive with density 1.1 g/cm³, viscosity 16–20 cup and pH 5.5 was applied at a rate of 150 to 200 g per m². Subsequently, the sections were pressed using the press machine shown in Fig. 1(a) to produce cross-laminated timber (CLT) panels.

As shown in Fig. 1(b), the surface area of the laminated wood board to be used in the inner layer of the CLT boards was perforated at rates of 10% and 20%, using an SCM tech Z1 CNC woodworking machine in the machine workshop of the Department of Wood Products Industrial Engineering at Gazi University's Faculty of Technology.

Following perforation at rates of 10% to 20% of the surface area of the laminated timber board to be used, the inner layer of the CLT boards was performed in a controlled manner on the CNC surface treatment machine, and then 100–120 g per m² of PVAc glue was applied on one surface of the outer layers and on both surfaces of the inner layers. Cross-laminated timber (CLT) boards were obtained with a press pressure of 80 kg per cm² in the press machine shown in Fig 2(b). The test samples of CLT boards were coded as shown in Table 2.

Table 1. Properties of materials used in the production of cross-laminated timber (CLT) boards

No.	Material name	Dimensions/Quantity	Density (g/cm³)	Moisture ratio (%)
1	Fir wood	17 x 80 x 310 mm	0.44	11.3%
2	Oak wood	17 x 80 x 310 mm	0.75	12.4%
3	PVAc glue	110–120 g/m²		

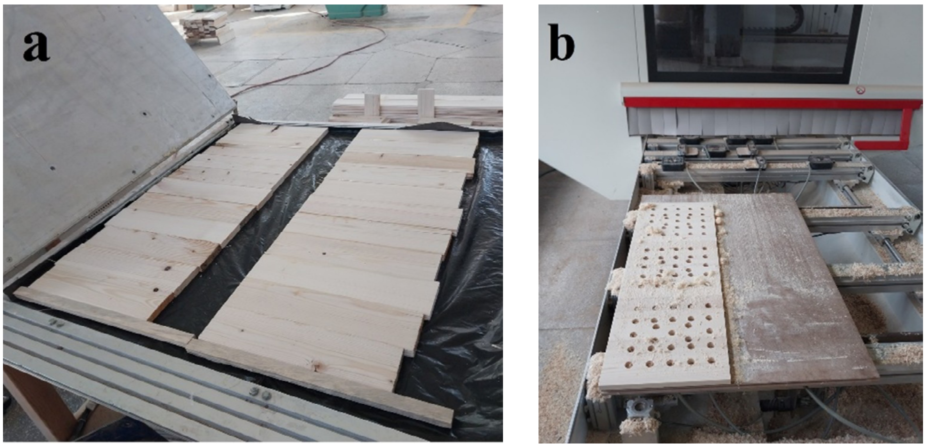


Fig. 1. (a) Formation of laminated timber boards, (b) surface perforation of laminated timber board to be used in inner layers

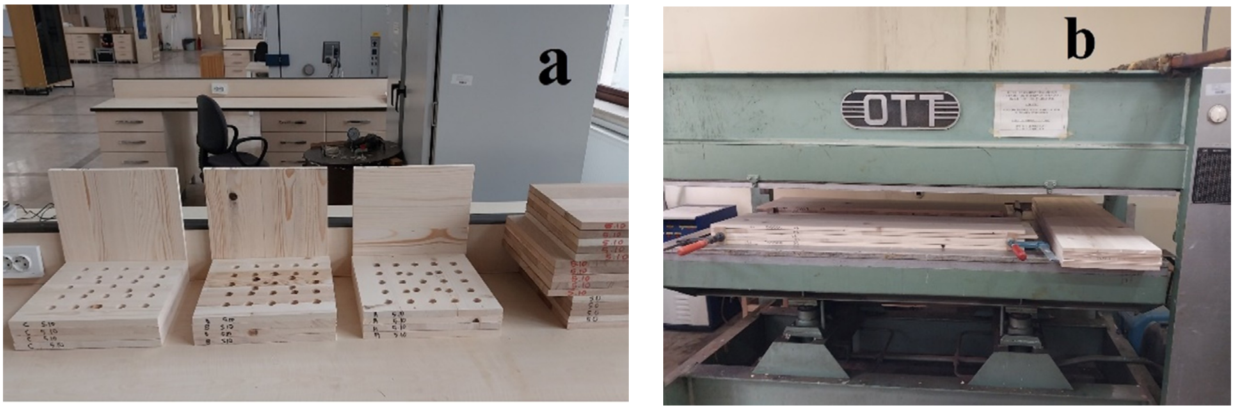


Fig. 2. (a) Perforation process in the inner layers, (b) pressing of laminated wood boards stacked with fiber directions mutually perpendicular to form cross-laminated (CLT) boards

Table 2. Coding of cross-laminated timber (CLT) boards

Code	CLT board	Code	CLT board
3G0	3-layer fir control CLT	5G0	5-layer fir control CLT
3G10	3-layer 10% perforated fir CLT	5G10	5-layer 10% perforated fir CLT
3G20	3-layer 20% perforated fir CLT	5G20	5-layer 20% perforated fir CLT
3M0	3-layer oak control CLT	5M0	5-layer oak control CLT
3M10	3-layer 10% perforated oak CLT	5M10	5-layer 10% perforated oak CLT
3M20	3-layer 20% perforated oak CLT	5M20	5-layer 20% perforated oak CLT

Method

To determine thermal conductivity and thermal transmittance coefficients, 36 specimens, three for each test group, 30 x 30 cm in size, were conditioned according to TS EN 12667 (2003) in an air conditioning cabinet at 20 °C temperature and 65% relative humidity until they reached constant weight. The specimens were then removed from the conditioning cabinet one by one, and their thermal conductivity and thermal transmittance coefficients were determined using a Linseis HFM 300 test device in the test laboratory of the Department of Wood Products Industrial Engineering, Faculty of Technology, Gazi University.

Data analysis

MSTAT-C software was used for the analysis of the data obtained through experimental methods. Multivariate analysis of variance (MANOVA) and multiple comparisons were performed based on a 95% confidence level using this software.

Results and discussion

Thermal conductivity coefficients of cross-laminated timber (CLT) boards

Statistical data on the thermal conductivity and thermal transmittance coefficients of cross-laminated timber (CLT) boards determined according to TS EN 12667 (2003) are given in Table 3.

The panels' thermal conductivity and thermal transmittance coefficients varied due to the application of perforation at varying rates in the inner layers, as shown by the experimental results in Table 3. A multi-way analysis of variance was conducted to determine whether the variables affect these differences, and the results are given in Table 4.

As shown in Table 4, it was found that the single effects of the variables of wood species, number of layers, and perforation process applied in the inner layer on the thermal conductivity and thermal transmittance coefficients of cross-laminated timber boards are statistically significant. The binary interaction of the number of layers and perforation rate was also found to have a significant effect ($p < 0.05$) on the thermal conductivity coefficient of the boards. In turn, the interaction of wood species and number of layers

Table 3. Statistical data on thermal conductivity and thermal transmittance coefficients of cross-laminated timber (CLT) boards

	Panel code	**N**				**Std. sp.**	**V(%)**
Thermal conductivity coefficient (W/m.K)	3G0	3	0.085	0.098	0.093	0.002	2.40
	3G10	3	0.082	0.095	0.088	0.003	3.74
	3G20	3	0.083	0.095	0.090	0.001	0.22
	5G0	3	0.101	0.114	0.107	0.004	4.11
	5G10	3	0.089	0.102	0.096	0.001	0.52
	5G20	3	0.084	0.096	0.090	0.003	2.89
	3M0	3	0.147	0.160	0.153	0.006	4.05
	3M10	3	0.145	0.158	0.151	0.009	5.96
	3M20	3	0.134	0.147	0.140	0.004	2.78
	5M0	3	0.163	0.176	0.170	0.007	3.89
	5M10	3	0.156	0.169	0.162	0.011	6.78
	5M20	3	0.140	0.153	0.147	0.001	0.75
	Panel code	**N**				**Std. sp.**	**V(%)**
Thermal transmittance coefficient (W/m².K)	3G0	3	1.809	1.885	1.849	0.038	2.06
	3G10	3	1.745	1.853	1.805	0.055	3.05
	3G20	3	1.847	1.862	1.855	0.008	0.43
	5G0	3	1.258	1.358	1.296	0.054	4.17
	5G10	3	1.158	1.183	1.171	0.013	1.11
	5G20	3	1.053	1.076	1.065	0.012	1.13
	3M0	3	2.920	3.194	3.034	0.143	4.71
	3M10	3	2.888	3.246	3.042	0.184	6.05
	3M20	3	2.711	2.887	2.796	0.088	3.15
	5M0	3	1.962	2.118	2.040	0.078	3.82
	5M10	3	1.828	2.085	1.981	0.135	6.81
	5M20	3	1.784	1.798	1.793	0.008	0.45

Table 4. Multiple variance analysis results for coefficient of thermal conductivity (k) and coefficient of thermal transmittance (U) values for cross-laminated timber boards

	Variables	Squares total	df	Mean squares	F	Level of significance ($p < 0.05$)
Thermal conductivity coefficients (W/m.K)	Wood species (A)	0.033	1	0.033	1149.240	**0.000**
	Number of layers (B)	0.001	1	0.001	29.096	**0.000**
	Perforation rate (C)	0.001	2	0.001	20.912	**0.000**
	A x B	2.272E-5	1	2.272E-5	0.797	0.381
	A x C	0.000	2	9.551E-5	3.350	0.052
	B x C	0.000	2	0.000	3.827	**0.036**
	A x B x C	9.024E-6	2	4.512E-6	0.158	0.854
	Error	0.001	24	2.851E-5		
	Total	0.588	36			
	Adjusted error	0.036	35			
	Variables	**Squares total**	**df**	**Mean squares**	**F**	**Level of significance ($p < 0.05$)**
Thermal transmittance coefficient ($W/m^2.K$)	Wood species (A)	7.968	1	7.968	1015.807	**0.000**
	Number of layers (B)	6.341	1	6.341	808.369	**0.000**
	Perforation rate (C)	0.198	2	0.099	12.634	**0.000**
	A x B	0.292	1	0.292	37.242	**0.000**
	A x C	0.056	2	0.028	3.574	**0.044**
	B x C	0.023	2	0.012	1.487	0.246
	A x B x C	0.025	2	0.012	1.568	0.229
	Error	0.188	24	0.008		
	Total	155.843	36			
	Adjusted error	15.092	35			

Table 5. Homogeneity groups of mean values of coefficient of thermal conductivity and coefficient of thermal transmittance differing depending on the wood species used in cross-laminated timber boards

Thermal conductivity coefficient				**Thermal transmittance coefficient**			
Wood species	**N**	**$\bar{X}$ (W/m.K)**	**HG**	**Wood species**	**N**	**$\bar{X}$ ($W/m^2.K$)**	**HG**
Fir	18	0.094	B	Fir	18	1.507	B
Oak	18	0.154	A	Oak	18	2.448	A
LSD: 0.0007 W/m.K				LSD: 0.061 $W/m^2.K$			

and the interaction of wood species and perforation rate were found to have significant effects ($p < 0.05$) on the thermal transmittance coefficients. The Duncan test was performed to determine the differences between the groups of variables whose effects were statistically significant according to the multiple variance analysis. The homogeneity groups of mean values of the coefficients of thermal conductivity and thermal transmittance, which differ depending on the wood species used in the CLT boards, are given in Table 5.

Table 5 reveals that the thermal conductivity and thermal transmittance coefficients differ statistically significantly between the wood species. This variation can be attributed to the anatomical structure and density values of the wood material.

In studies reported in the literature, the thermal conductivity coefficient of fir wood has been determined to range between 0.090 and 0.1128 W/m·K (Tokuc, 1997; Örs and Şenel, 1999), while the thermal conductivity coefficient of oak wood was found to be

Table 6. Homogeneity groups of the mean values of coefficient of thermal conductivity and coefficient of thermal transmittance differing depending on the number of layers used in cross-laminated timber boards

Thermal conductivity coefficient				**Thermal transmittance coefficient**			
Number of layers	**N**	**$\bar{X}$ (W/m.K)**	**HG**	**Number of layers**	**N**	**$\bar{X}$ (W/m².K)**	**HG**
3 layers	18	0.1190	B	3 layers	18	2.397	A
5 layers	18	0.1286	A	5 layers	18	1.558	B
LSD: 0.0007 W/m.K				LSD: 0.061 W/m².K			

Table 7. Homogeneity groups of mean values of coefficients of thermal conductivity and coefficient of thermal transmittance differing depending on the perforation rates used in cross-laminated timber (CLT) boards

Thermal conductivity coefficient				**Thermal transmittance coefficient**			
Perforation rate	**N**	**$\bar{X}$ (W/m.K)**	**HG**	**Perforation Rate**	**N**	**$\bar{X}$ (W/m².K)**	**HG**
0%	12	0.1306	A	0%	12	2.055	A
10%	12	0.1243	B	10%	12	2.000	A
20%	12	0.1165	C	20%	12	1.877	B
LSD: 0.0008 W/m.K				LSD: 0.074 W/m².K			

0.18 W/m·K (Bozkurt and Göker, 1987). Similarly, it is reported that the thermal conductivity coefficient of willow wood, which is similar to low-density fir wood, ranges between 0.090 and 0.103 W/m·K (Kaya *et al.*, 2025).The thermal conductivity of wood depends on many factors, including the species of wood, density, moisture content, heat flow direction (anisotropy), and fiber orientation (Suleiman *et al.*, 1999), and a positive correlation has been found between softwood and hardwood density and thermal conductivity (Mauranen *et al.*, 2015). The fact that these properties differ between the wood materials used in this study explains why the thermal conductivity and transmittance coefficients take distinct values. Table 6 presents the homogeneity groups of mean values of the coefficients of thermal conductivity and thermal transmittance differing depending on the number of layers used in cross-laminated timber boards.

Table 6 shows statistically significant differences in the thermal conductivity and thermal transmittance coefficients of cross-laminated timber (CLT) panels. According to equation (1), there is a linear relationship between the thickness of the panel and the thermal transmittance coefficient. According to the study design, panel thickness increased as the number of layers increased. Consequently, it was determined that the thermal conductivity coefficient also increased. Moreover, as the thickness increased, the thermal transmittance coefficient decreased.

When the thermal transmittance coefficient and the thickness of a material are evaluated together, the insulation performance of the material can be determined. Consequently, no matter how low the thermal conductivity coefficient of a material is, if it lacks sufficient thickness, its thermal transmittance will be high, and it cannot be considered to provide adequate thermal insulation (Ünal, n.d.; Zach *et al.*, 2012; Asdrubali *et al.*, 2015). This is because the thermal transmittance coefficient, which is a key parameter for thermal insulation, is inversely proportional to the thickness of the insulation material (Zhang & Yang, 2018). Therefore, it can be stated that there is a relationship between the thermal conductivity coefficient and the thermal transmittance coefficient in terms of thermal insulation (Kaya *et al.*, 2025). In wood-based composite materials, both the thickness of the material and the direction of heat flow within the material affect its thermal conductivity (Demirkır and Aydın, 2015). According to equation (2), an inverse relationship exists between panel thickness and the thermal transmittance coefficient: as the thickness of the panel increases, a decrease in the thermal transmittance coefficient is observed. The homogeneity groups of the mean values of the thermal conductivity and thermal transmittance coefficients for groups differentiated by perforation rates used in cross-laminated timber panels are presented in Table 7.

According to the results of the experimental tests carried out to determine the effects of perforation

Table 8. Homogeneity groups of the mean values of the coefficient of thermal conductivity and coefficient of thermal transmittance of cross-laminated timber (CLT) panels depending on the interactions of number of layers x perforation ratio and wood species x perforation ratio

Thermal conductivity coefficient					Thermal transmittance coefficient				
Number of layers	**Perforation rate**	**N**	**$\bar{X}$ (W/m.K)**	**HG**	**Wood species**	**Perforation rate**	**N**	**$\bar{X}$ (W/m².K)**	**HG**
3 layers	0%	6	0.123	C	Fir	0%	6	1.573	C
	10%	6	0.120	D		10%	6	1.488	CD
	20%	6	0.115	F		20%	6	1.460	D
5 layers	0%	6	0.139	A	Oak	0%	6	2.537	A
	10%	6	0.129	B		10%	6	2.512	A
	20%	6	0.118	E		20%	6	2.295	B
LSD: 0.0012 W/m.K					LSD: 0.105 W/m².K				

rates applied to the inner layers of cross-laminated timber (CLT) boards on the thermal insulation values of those boards, which is the main objective of this study, it was seen that the effects of the perforation process on the thermal conductivity coefficients of the boards were statistically significant. For thermal transmittance coefficients, no statistically significant difference was found between 0% and 10% perforation in the inner layers, whereas the use of 20% perforation had a statistically significant effect on the thermal transmittance of the panels.

Owing to its porous structure, wood has a low thermal conductivity coefficient, and as a result of its unique structure it offers superior thermal insulation properties compared with many other construction materials (Uysal *et al*., 2008; Aytin *et al*., 2016). In the present study, the perforation process applied to the inner layers of CLT panels led to a reduction in the overall density of the panels, which in turn contributed to decreases in both thermal conductivity and thermal transmittance coefficients. Notably, the thermal conductivity coefficient of the air present in the perforated cavities is reported as 0.026 W/m.K (Pehlivanli, 2009, Bülbül and Keskin, 2023; Bülbül et al., 2025), which further explains this reduction. Table 8 presents the homogeneity groups of mean values of the thermal conductivity and thermal transmittance coefficients of CLT panels, differentiated by the interactions of number of layers × perforation ratio and wood species × perforation ratio.

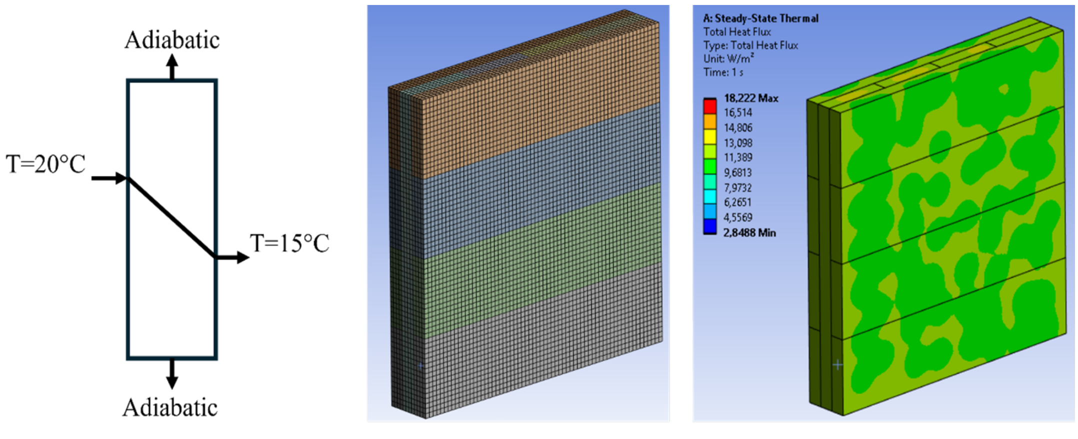
An analysis of the effect of the interaction between the number of layers and the perforation rate on the thermal conductivity coefficients of the boards, as presented in Table 8, indicates statistically significant differences between all groups. However, when evaluating the effect of the interaction between wood species and perforation rate on the thermal transmittance coefficient, no statistically significant difference is observed between the 0% and 10% perforation rates for either wood type.

According to previous studies, geometrically shaped modifications applied to the inner layers of wood-based composite panels lead to reductions in both heat conduction and thermal conductivity coefficients (Kaya and İmirzi, 2023). Similarly, the perforation process implemented in the inner layers of the panels lowers their density, which in turn results in density-dependent decreases in the thermal conductivity and thermal transmittance coefficients of the boards.

Data obtained by finite element method

To verify the experimental results, virtual models of the test specimens were created and the heat fluxes of the specimens were found by ANSYS steady-state thermal analysis. The thermal conductivity coefficients of the specimens were obtained by equation (3). The boundary conditions determined in the finite element analysis (FEM) are shown in Fig. 3(a), the mesh structure of the model is shown in Fig. 3(b), and the result of the analysis is shown in Fig. 3(c). The thermal conductivity coefficients required for the FEM analysis were obtained from the thermal conductivity coefficients obtained experimentally for each test specimen. Numbers of points and elements of the FEM models are given in Table 9. The gaps formed by the holes in the models are defined as air.

Based on this study's determinations of heat transfer coefficients of CLT boards, the FEM analyses revealed that the heat flux is concentrated around the perforations in the boards (Fig. 4). Table 10 contains the findings of a comparison of the thermal conductivity



(a) (b) (c)

Fig. 3. a) FEM analysis boundary conditions, b) mesh structure of the FEM model, c) FEM heat flux result

coefficients determined using the FEM and experimental methods.

Table 10 demonstrates that as the perforation rate of CLT boards increases, so does the proportional difference between the FEM and experimental results. Despite these differences, it is evident that the thermal conductivity coefficients derived by FEM analysis and the experimental method are compatible. However, the largest percentage difference was obtained for 5M20 panels, and the smallest for 5G0 and 3M0 panels.

As the porosity ratio, which expresses the amount of air and void space in the material, increases, the thermal conductivity decreases (Pehlivanli, 2010). Fig. 5 depicts the differences between the FEM and experimental measurement results for the thermal conductivity coefficient.

As Figure 5 confirms, the results obtained by the finite element method are quite similar to those obtained by the experimental method.

It has been reported that the thermal conductivity coefficients of various epoxy-based composite materials obtained by experimental and finite element methods are also quite similar (Nayak *et al.*, 2010). Similarly, it has been reported that the thermal conductivity values of structural timber, such as CLT, determined by experimental and numerical methods are in good agreement (Zitouni *et al.*, 2025; Díaz *et al.*, 2019; Pal and Malek, 2025; Li *et al.*, 2025). Therefore, based on the results obtained from this study, it can be stated that

Table 9. Numbers of points and elements of FEM models

Sample code	Number of points	Number of elements
3G0	856476	183600
3G10	1688575	372130
3G20	2419778	535150
3M0	856476	183600
3M10	1688575	372130
3M20	2418452	534838
5G0	687680	142500
5G10	1314022	278372
5G20	1917144	406996
5M0	687680	142500
5M10	1290659	272755
5M20	1921546	408065

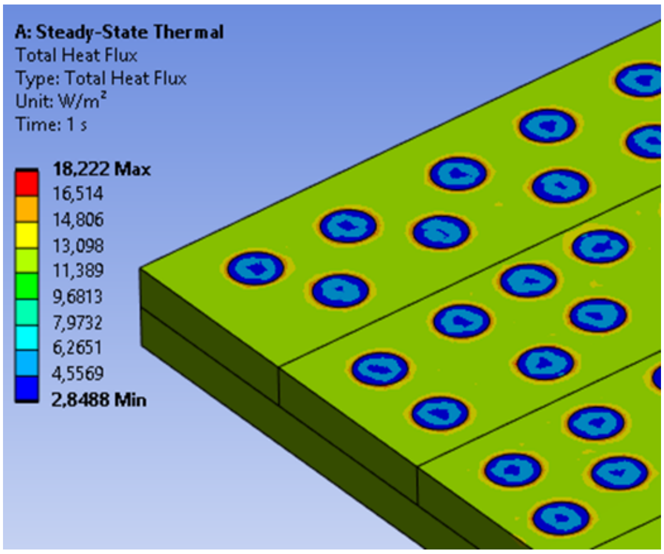


Fig. 4. Results of FEM analysis of air gaps

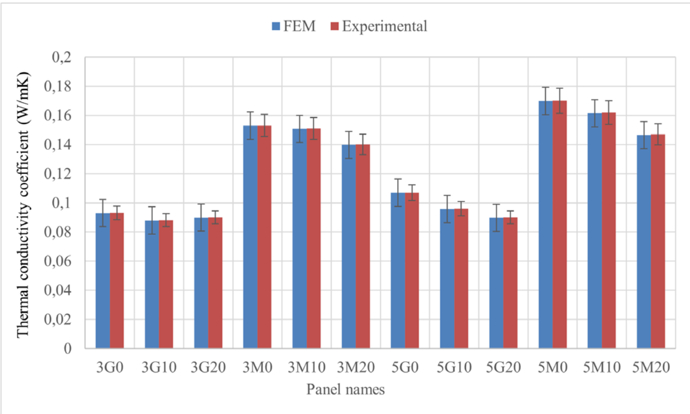
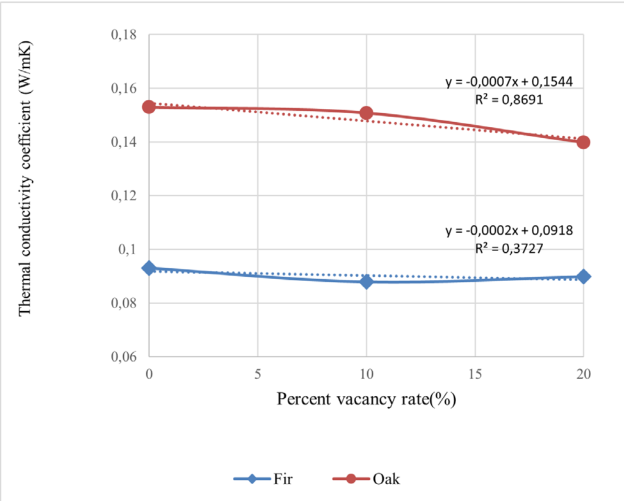


Fig. 5. Proportional differences between FEM and experimental measurement results

Table 10. Data and proportional comparisons of thermal conductivity coefficients (W/m.K) of cross-laminated timber (CLT) boards obtained experimentally and by the finite element method

Sample code	FEM (W/m.K)	Experimental measurement (W/m.K)	Similarity ratio (%)
3G0	0.09295	0.093	0.05
3G10	0.08787	0.088	0.15
3G20	0.08983	0.090	0.19
3M0	0.15292	0.153	0.05
3M10	0.15076	0.151	0.16
3M20	0.13972	0.140	0.20
5G0	0.10692	0.107	0.07
5G10	0.09571	0.096	0.30
5G20	0.08969	0.090	0.34
5M0	0.16987	0.170	0.08
5M10	0.16148	0.162	0.32
5M20	0.14645	0.147	0.37

Note: The similarity ratio is calculated based on the experimental measurement



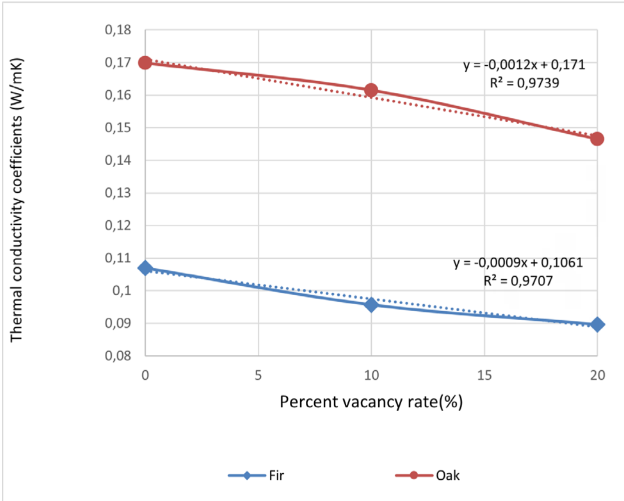


Fig. 6. Thermal conductivity coefficients obtained by FEM analysis: a) three-layer boards, b) five-layer boards

the use of the finite element method is appropriate in terms of reliability.

As shown in Fig. 6, the R^2 values of the five-layer boards' thermal conductivity coefficients are more significant than 0.97 and their behavior is very close to linear. Consequently, the thermal conductivity coefficients of five-layer boards can be reliably calculated for void ratios ranging from 0% to 20%. In contrast, when three-layer boards are considered, it is found that fir has an R^2 value of 0.3727, and the derived thermal conductivity coefficients are unreliable. This is because the thermal conductivity coefficient of the boards with a 20% void ratio is greater than that of the board with a 10% void ratio. With R^2 = 0.8691, the calculated values for three-layer oak boards were found to be reliable.

Conclusion

Based on the study's results, it was determined that the inner layer perforation procedure reduced the panels' thermal transmittance and thermal conductivity coefficients.

A 20% perforation rate caused the greatest reduction in the thermal conductivity and thermal transmittance coefficients of the panels. The reduction in the thermal conductivity coefficient was 10.8%, while the reduction in the thermal transmittance coefficient was 8.7%.

It was determined that as the number of layers in cross-laminated timber (CLT) boards increased, the thermal conductivity coefficient increased, while the thermal transmittance coefficient decreased.

Depending on the wood species, the thermal conductivity coefficient and thermal transmittance coefficient of cross-laminated timber (CLT) panels made from fir wood were found to be lower than those of the panels made from oak wood.

As determined by the experimental study, perforation processes applied at different rates to the inner layers of cross-laminated timber (CLT) panels were found to increase the thermal insulation values of the panels.

However, the perforation process applied to the middle layers resulted in a reduction in the density values of the cross-laminated timber (CLT) panels. Nevertheless, due to the presence of air, which has a lower thermal conductivity coefficient, in the perforation cavities, the panels' thermal conductivity and thermal transmittance coefficients decreased.

According to the results obtained in this study, it can be stated that applying a perforation rate of 20% or more to the inner layers of such cross-laminated timber (CLT) panels leads to a reduction in the thermal conductivity and thermal transmittance coefficients. It has also been observed that the thermal conductivity and thermal transmittance coefficients obtained by experimental measurement and by the finite element method (FEM) are similar; therefore, the finite element method (FEM) can be preferred for determining the thermal conductivity coefficients of anisotropic materials such as wood. Moreover, it is recommended to investigate different perforation rates and perforation diameters in future studies.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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