Article citation info:
Ahmed M.Z., Sikora K.S. 2024. Mechanical Properties of Cross-Laminated Panels Made from Date Palm Leaves. *Drewno. Prace naukowe. Doniesienia. Komunikaty* 67 (213): 00022. https://doi.org/10.53502/wood-190123

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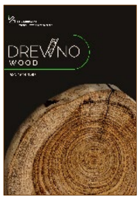
Journal website: https://drewno-wood.pl/



Mechanical Properties of Cross-Laminated Panels Made from Date Palm Leaves

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Article info
Received: 8 June 2023
Accepted: 10 June 2024
Published online:
21 June 2024

Keywords
cross-laminated
timber
bending strength
date palm leaves
rolling shear strength
mechanical properties

An experimental investigation was carried out to determine the bending and shear performance of cross-laminated (CL) panels made from date palm leaves. A four-point bending test was performed on 3-layer, 5-layer, and 7-layer cross-laminated panels to determine maximum bending strength and rolling shear strength for the specimens. The mean maximum bending strength for the 3-layer samples was 2.79 MPa. The values of maximum rolling shear for 3-layer, 5-layer, and 7-layer samples were 1.59 MPa, 0.76 MPa, and 1.57 MPa respectively. The results suggest that cross-laminated panels made from date palm may not be a viable structural material.

DOI: 10.53502/wood-190123
Published by Łukasiewicz Research Network – Poznań Institute of Technology.

Introduction

Concrete is considered to be an ideal construction material, and is the second most widely used substance after water [Scrivener et al. 2018]. Despite its high performance as a construction material, reinforced concrete has significant environmental drawbacks. Its production and use contribute to environmental degradation, raising concerns about its sustainability. In 2019 the construction industry accounted for 38% of global carbon dioxide production [UNEP.org 2021], and cement alone contributes around 8% of carbon dioxide emissions every year [Rodgers 2021]. In addition to the carbon dioxide emissions associated with concrete production, the manufacture of cement also releases toxic gases such as sulfur dioxide, nitrogen oxide, and carbon monoxide [Helepciuc 2017]. These gases contribute to air pollution and can cause serious health problems. Given these environmental and health concerns, there is a pressing need to identify alternative construction materials. In light of the urgent need to reduce carbon emissions and achieve a carbon-neutral footprint, the construction industry must explore more sustainable solutions. Timber is one of the oldest construction materials and is rising in popularity amid the need for more sustainable construction [Bradner et al. 2016].

Timber is a natural material that has orthogonal properties: it is much stronger in the direction of the trunk (parallel to the grain) than in the tangential or radial direction [Khatib 2012]. Recent research [Kuzmanovska et al. 2018] has led to the development of several engineered wood products (EWPs), including

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glue-laminated timber (glulam), cross-laminated timber (CLT), and laminated veneer lumber (LVL). These materials have the potential to be used in multi-story buildings. CLT, in particular, has an orthogonal laminar structure that allows it to be used for walls, floor elements, and linear timber members capable of carrying loads both in and out of plane [Bradner et al. 2016].

CLT panels are prefabricated and typically have an odd-numbered configuration that is symmetric about the middle layer. The panels are usually stacked in three, five, or seven layers, with the grain direction oriented orthogonally in adjacent layers [Sikora et al. 2016]. The orthogonal orientation of consecutive layers in CLT provides high strength and stiffness in both the longitudinal and transverse directions. CLT also offers several additional benefits, including increased robustness, high axial load capacity for walls due to large bearing stresses, and high thermal and fire performance [Porteous and Kermani 2013]. Buildings constructed using CLT can be built using either platform or balloon construction methods, with walls and floors connected using angular metal brackets in combination with screws or nails [O'Ceallaigh et al. 2018].

Timber-based construction is less common in the UAE than in North America and Europe. However, date palm trees, which are abundant in the UAE, have the potential to be used as a construction material. Unlike traditional softwoods and hardwoods, palm trees have continuous fibrous strands similar to grass. The Middle East is home to 70% of the world's date palm trees, with over 40 million trees [UAEU.ac.ae 2021]. Date trees are an important part of the heritage of the UAE, and their fruit (dates) is a major export, making them a significant contributor to the economy [Datepalmdubai 2021, Gardenine 2021]. Utilizing date palm trees as a construction material could provide an opportunity to reduce the country's carbon footprint.

Experiments conducted by Shamsi [Shamsi and Mazloumzadeh 2021] have shown that the leaves (fronds) of palm trees have higher compressive strength in the radial direction than palm trunks. This makes palm leaves a more suitable choice for cross-laminated panels than palm trunks. The selection of appropriate adhesives for cross-laminated panels is critical, as a study by Xing et al. [2019] found that different glues had a significant effect on shear performance. PUR (polyurethane) and PRF (phenol-resorcinol-formaldehyde) are the most common types of glues used in CLT, and a study by Sikora et al. [2015] confirmed that both meet the requirements for CLT shear strength. In addition, an experiment by Gharbi and Sikora [2022] on the shear strengths of adhesive bonds in laminated elements made from palm fibers found that PUR achieved higher consistency than other adhesives such as DAP (diallyl phthalate). Given its availability and performance, PUR is an appropriate adhesive for this experiment.

While date palm leaves have the potential to be used as a construction material, there is currently a knowledge gap regarding their use in construction. To determine their potential, several mechanical properties and parameters, such as rolling and bending stress, stiffness, and strength, must be established. This study aims to investigate the bending stress and rolling shear strength of cross-laminated panels made from palm tree leaves in three, five, and seven layers. The goal is to address the knowledge gap and determine the potential application of palm leaves in the Middle East. The results will be analyzed to assess whether date palm trees, a locally sourced material, could be used to make construction more sustainable in that region.

Materials and methodology

Experiments to determine the mechanical properties of the cross-laminated panels were carried out according to EN 16351:2015. Five different configurations were used in the experiments, and three specimens were tested for most of those configurations.

The date palm fronds used to make the panels were carefully selected, with rejection of any leaves with defects or disease. The palm fronds were then sliced into 2 mm thin strips, as shown in Figure 1, and then cut further to the required dimensions necessary for the five configurations. Table 1 specifies the nomenclature, dimensions and the number of specimens for each configuration. The rolling shear specimen and the bending strength specimens had a width equivalent to four times the total thickness to comply with EN 16351:2015.

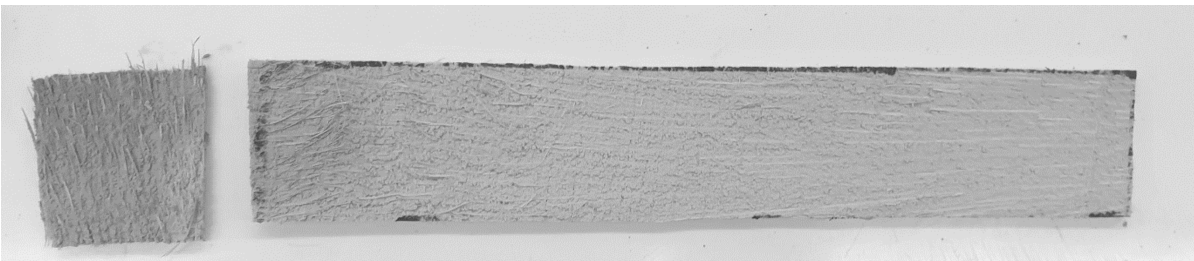

Fig. 1. 2 mm sliced date frond cut to the dimensions of B-5 ply

Once the samples were cut into specific dimensions and assembled according to their configuration, the specimens were then glued together using polyurethane (PUR) at room temperature. While gluing, it was ensured that the specimens were only face bonded, and that the glue layer was as thin as possible. Once the specimens were glued, a clamping pressure of 0.6 N/mm^2 was applied using a Universal Testing Machine (UTM) as shown in Figure 2. Furthermore, the force applied was increased by 25% to account for the drop in compression pressure that occurs in the UTM machine, and the specimens were kept under the clamping pressure for twenty minutes.

A four-point bending test was used for loading and testing the strength and stiffness of the panels as specified by EN 16351:2015 for Cross Laminated Timber panels. The span was 24 times the thickness for the bending strength specimen, and 12 times the thickness for the determination of rolling shear strength and stiffness. For both types of samples, the width-to-thickness ratio was kept at 4, and the distance between the two load points was six times the thickness. Figure 3 shows the setup used for the bending stress specimens, where *h* represents the thickness of each specimen and *F* is the force applied. The load was applied using a UTM machine at a constant rate of 0.06 mm/s, to ensure that failure occurred within 180 to 420 seconds.

Fig. 2. Applying clamping pressure on a 5 layer specimen using a UTM

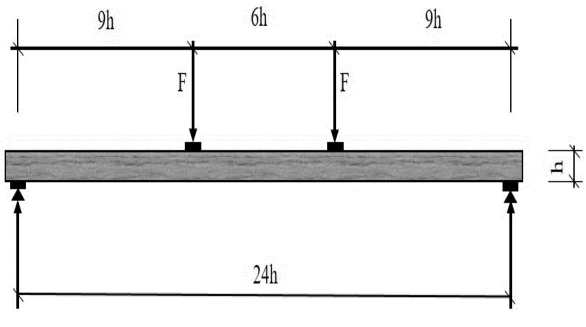

Fig. 3. 4 point bending test to determine bending stress

Table 1. Dimension and Configuration of different panel lay ups

Specimen	Tested for	No. of layers	Dimension (thickness*width*length) (mm*mm*mm)
R-3	Rolling Shear	3	6*24*72
R-5	Rolling Shear	5	10*40*120
R-7	Rolling Shear	7	14*56*168
B-3	Bending Strength	3	6*24*180
B-5	Bending Strength	5	10*40*300

A Linear Variable Differential Transformer (LVDT) was used to measure the global displacement from the centre of the specimen, and each specimen was loaded until failure. Only specimens with the desired failure were used for calculations of maximum bending moment and shear force. Timoshenko's transversal-flexible-in shear beams technique [Bogensperger et al. 2012] was used as a verification method for calculating maximum rolling shear and bending strength.

The maximum rolling shear (τ_{max}) was calculated using equation (1) below, as given by Bogensperger et al. [2012]. The maximum internal shear force (V_{max}) was calculated using equilibrium equations, while bending stiffness (K_{CLT}) was computed using equations (2), (3) and (4) for the relevant configuration.

$$\tau_{max} = \frac{V_{max}}{K_{clt} * b} \sum E A_i e_{s,i} \tag{1}$$

where

E is the modulus of elasticity of the specimen
V_{max} is the maximum internal shear force
A_i is the area of lamina i
$e_{s,i}$ is the distance between the centre of a ply and the centroid of lamina i
b is the width of the specimen

$$K_{CLT,3\ layers} = \sum \frac{13}{6} * E * b * {t_i}^3 \tag{2}$$

$$K_{CLT,5\ layers} = \sum \frac{33}{4} * E * b * {t_i}^3 \tag{3}$$

$$K_{CLT,7layers} = \sum \frac{61}{3} * E * b * {t_i}^3 \tag{4}$$

where

E is the modulus of elasticity of the specimen
b is the width of the specimen
t_i is the thickness of lamina i

Similarly to the rolling shear strength, the maximum bending strength was evaluated using the revised Timoshenko method as given by Bogensperger et al. [2012]. The maximum bending strength was evaluated using equation (5), where M_{max} was calculated from equilibrium equations, while bending stiffness (K_{CLT}) was computed using equations (2), (3) and (4) for the relevant configuration.

$$\sigma_{max} = \frac{M_{max} * t_{clt} * E}{K_{clt} * 2} \tag{5}$$

where

E is the modulus of elasticity of the specimen
M_{max} is the maximum internal moment
t_{clt} is the average thickness of a lamina
$K_{clt}$is the bending stiffness

The global modulus of elasticity was calculated using equation (6) [EN 408:2010+A1:2012], where the force and deflection values at 10% and 40% of the maximum force value were evaluated.

$$E = \frac{a l^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \tag{6}$$

where

a is the distance between the support and the loading point
I is the second moment of inertia
L is the span length
F_2 is 40% of the ultimate load
F_1 is 10% of the ultimate load
w_2 is the deflection corresponding to F_2
w_1 is the deflection corresponding to F_1

Results and discussion

1. Bending stress

The detailed results for all specimens are presented in Table 2. The two results obtained for maximum bending strength are both for 3-layer samples, with values of 2.36 MPa and 3.3 MPa. The remaining four specimens (one 3-layer sample and three 5-layer samples) failed due to delamination. There is a disparity in bending strength at failure between specimens failing in bending and those failing due to delamination, as shown in Figure 4. The lower strength observed in delamination signifies the failure of the adhesive rather than inherent failure of the material. This underscores the critical necessity of maintaining rigorous standards in the production of CL panels. The bending strength values of date palm leaves are very low compared with typical values of CLT used in construction. The lowest strength class of timber used for making CLT as per EN 338:2009 is a softwood species (C14) with a bending strength of 14 MPa. The low strength value indicates that date palm may not be a suitable structural material.

Table 2. Bending strength results

Specimen Label	Total number of plies	Displacement Rate (mm/s)	Type of Failure	Modulus of Elasticity (MPa)	Bending Stress at failure (MPa)	Shear Strength at failure (MPa)	Maximum Bending Stress (MPa)
B-3-1	3	0,06	Bending	N.A.	3,31	0,82	3,31
B-3-2	3	0,06	Bending	612,71	2,36	0,63	2,36
B-3-3	3	0,06	Support	N.A.	N.A.	N.A	N.A.
B-5-1	5	0,07	Delamination	N.A.	0,91	0,29	N.A.
B-5-2	5	0,07	Delamination	440,45	0,76	0,23	N.A.
B-5-3	5	0,07	Delamination	546,86	1,13	0,34	N.A.

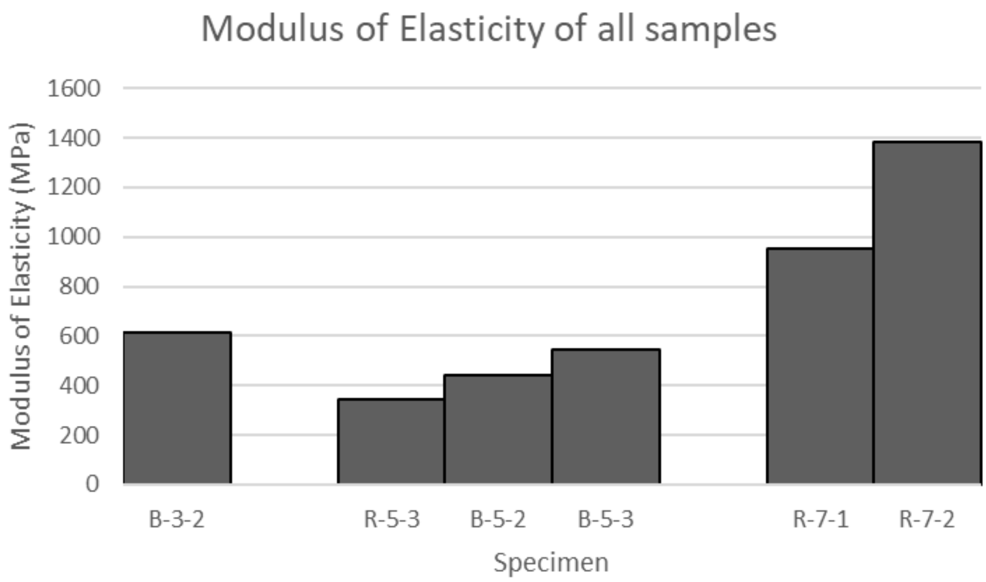

Fig. 4. Modulus of Elasticity of 3, 5 and 7 layer specimens

2. Maximum rolling shear strength

Table 3 shows detailed results for all rolling shear specimens. Eight specimens with three different configurations were tested for shear failure, but only three of them failed in rolling shear. One of each of the 3-layer, 5-layer and 7-layer configurations had the desired failure. The 3-layered specimen failed at a shear of 1.54 MPa, a similar value to that obtained for a 7-layer structure, which failed at 1.57 MPa. However, the 5-layer specimen failed in rolling shear at 0.76 MPa, which is significantly lower than the other results. The variation in the results is displayed in Figure 5, where the results for the 5-layered specimen can be considered an anomaly. The early failure may be due to internal cracks and delamination rather than visible or natural defects. However, a rolling shear of around 1.5 MPa is considered too low for structural elements, as the minimum shear strength of timber used for CLT is between 3 and 5 MPa [EN-338:2009]. However, there was a slight increase in rolling shear strength with an increase in thickness.

3. Effect of number of layers on modulus of elasticity (MOE)

The results are given in Table 4, and show that the MOE values ranged from 346 MPa to 1386 MPa. Figure 6 illustrates the relationship between the number of layers and MOE. There was a sharp increase in MOE from a 5-layer sample to a 7-layer sample, indicating that increasing the number of layers may increase the bending stiffness of the material. There is a slight decrease in MOE from a 3-layer sample to the 5-layer samples. This may be attributed to variations in the local modulus of elasticity of each specimen, especially if low-stiffness defects are located within the central span of the panel [Ridley-Ellis et al. 2009].

The results show some of the key properties required to understand the load bearing capacity of CL panels made from date palm leaves. The maximum bending strength and rolling shear strength are low when compared with the values for wood used for CLT manufacturing. However, as a pilot study, the experiment was limited by the size and number of samples that were tested. Different configurations and larger panels may have yielded more positive results. Furthermore, delamination was the most common type of failure in CL, indicating that the effect of the adhesive type cannot be overlooked. In addition to the mechanical properties obtained for date palm, other factors such as the availability of wood, the cost of acquiring raw materials, and the operational costs of CLT manufacturing facilities must also be evaluated [Nicał and Sikora 2022].

Table 3. Rolling shear results

Specimen Label	Total number of plies	Displacement Rate (mm/s)	Type of Failure	Modulus of Elasticity (MPa)	Bending Stress at failure (MPa)	Shear Strength at failure (MPa)	Maximum Rolling Strength (MPa)
R-3-1	3	0,06	Rolling	N.A.	1,723	1,549	1,549
R-3-2	3	0,06	Support	N.A.	N.A	N.A.	N.A.
R-3-3	3	0,06	Support	N.A.	N.A	N.A.	N.A.
R-5-1	5	0,06	Delamination	N.A.	0,462	0,451	N.A.
R-5-2	5	0,06	Rolling	N.A.	0,838	0,761	0,761
R-5-3	5	0,06	Delamination	346,41	0,691	0,551	N.A.
R-7-1	7	0,06	Delamination	951,27	0,937	1,19	N.A.
R-7-2	7	0,06	Rolling	1385,95	1,24	1,57	1,57

Table 4. Experimental results of the modulus of elasticity

Specimen Label	Total number of plies	I (mm^4)	F_2 (N)	w_2 (mm)	F_1 (N)	w_1 (mm)	Modulus of Elasticity (MPa)
R-5-3	5	6091,75	96,9	1,82	31	0,35	346,4
R-7-1	7	14165,76	194,6	1,57	74,2	0,4	951,3
R-7-2	7	14191,75	260,3	1,4	61,6	0,07	1386
B-3-2	3	1210,32	37,9	1,85	6,5	0,19	612,7
B-5-2	5	9317,53	49,6	1,98	13,4	0,37	440,4
B-5-3	5	9827,44	64,3	2	13,4	0,28	546,9

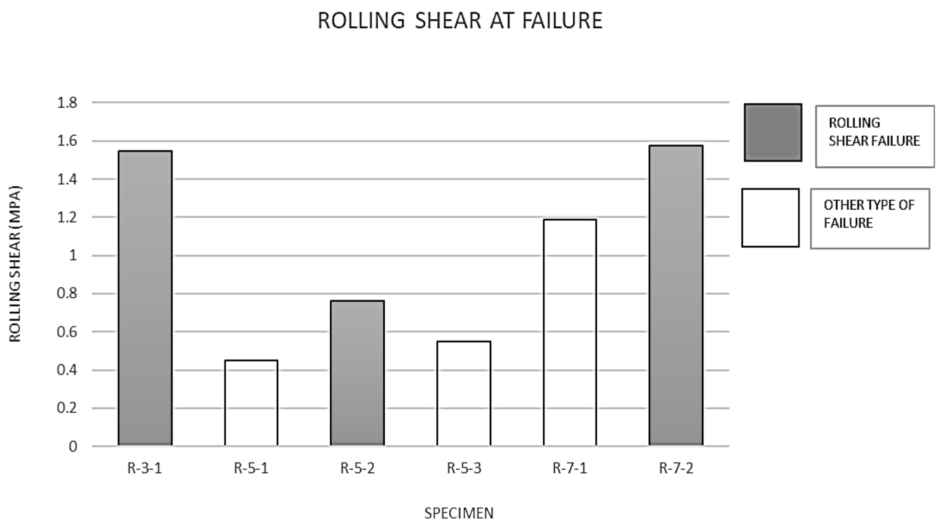

Fig. 5. Rolling shear at failure

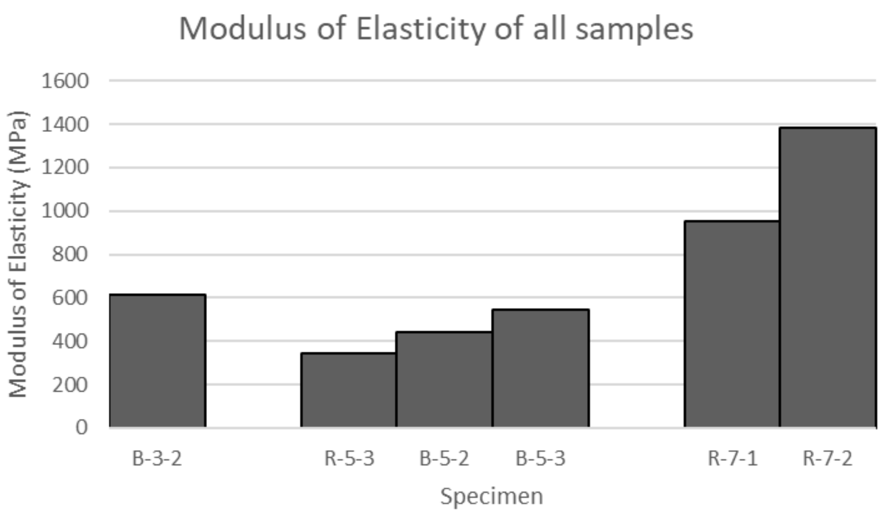

Fig. 6. Modulus of Elasticity of 3, 5 and 7 layer specimens

Conclusion

The main findings of the experimental investigation of the mechanical properties of cross-laminated panels made from date palm are the following:

- The mean maximum bending strength observed for a 3-layer configuration was 2.83 MPa. This value is relatively low, suggesting that palm leaves may not be the best material for achieving high bending performance in cross-laminated panels.
- The maximum rolling shear values for a 3-layer sample and a 7-layer sample were very similar (1.54 MPa and 1.57 MPa respectively), indicating that the number of layers has very little effect on the rolling shear strength of CL panels.
- The modulus of elasticity for the CL panels ranged from 346 MPa to 1386 MPa, where the 7-layer panel had significantly higher values for the modulus than 3-layer and 5-layer panels. An increase in MOE was observed with increasing thickness.
- Delamination was the most common type of failure in both the bending strength and rolling shear tests. This highlights the importance of quality assurance and the use of appropriate adhesives for CL panels. Furthermore, more tests are needed to draw final conclusions on the suitability of utilizing date palm leaves as a structural material.

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