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THE BENDING PERFORMANCE OF BIONICS-INSPIRED LIGHTWEIGHT WOOD-BASED SANDWICH PANELS

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ABSTRACT: The use of lightweight wood-based sandwich panels (LWSPs) is gaining traction in the construction industry due to their environmental friendliness. These panels consume fewer resources, apply smaller loads on foundations, and reduce transportation costs and CO_2 emissions. This study was focused on the development of LWSPs with core structures inspired by natural structures. LWSPs were fabricated using aspen (*Populus tremuloides*) wood cores and aspen plywood surface layers, and their bond quality and bending properties were assessed. LWSP specimens of four configurations were tested under bending in both major and minor orientations. The largest apparent modulus of elasticity (MOE_{app}) and modulus of rupture (MOR_{app}) were observed in softwood-core panels in the major direction, reaching 3,922 MPa and 38.42 MPa, respectively, with a panel density of 316 kg/m^3. Honeycomb-core panels demonstrated more balanced performance across orientations. Theoretical MOE predictions were relatively accurate in the panels of stiff configurations but substantially underestimated values in transverse orientations.

KEYWORDS: lightweight wood-based sandwich panel, aspen wood core, aspen plywood, bending stiffness, bending moment.

1 INTRODUCTION

The increasing demand for lightweight, sustainable building materials is driven by environmental considerations, energy efficiency, and cost-effectiveness in modern construction. Lightweight wood-based sandwich panels (LWSPs) have emerged as viable alternatives to traditional materials, such as concrete, steel, solid wood products, and traditional engineered wood products, providing superior strength-to-weight ratios, reduced material consumption, and lower transportation costs.

Sandwich panel technology, originally developed in the mid-20th century for aerospace applications, initially utilized metal and foam cores [1,2]. Transitioning to natural and renewable materials has led to the adoption of wood-based cores due to their sustainable nature and less carbon footprint[3].

Early wood-based sandwich panels were constructed using solid wood or plywood cores, providing high bending strength but increasing overall weight [4]. While these materials offered robust structural performance, they were not optimized for lightweight applications. Sample modern wood-included sandwich panels are given to the structural insulation panels (SIPs), which are made of plywood/OSB faces and polyurethane (PUR) form cores, providing thermal insulation and structural strength for wall and roof applications [5]. In these two types of sandwich panels, the core is solid. In response, engineers and researchers explored cellular wood-core designs, such as honeycomb and rib-stiffened configurations, which provided high stiffness while minimizing material usage [6,7]. These innovations were inspired by the nature. Such biomimetic approaches further advanced this technology by mimicking efficient natural load-bearing structures found in plants and animal skeletons, significantly enhancing panel performance with minimal resource utilization [8–11].

Wood-based hollow cores provide notable advantages including high strength-to-weight ratios, excellent energy absorption, and enhanced thermal and acoustic insulation

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properties, suitable for flooring and modular construction [12–16]. However, engineering challenges persist, notably susceptibility to shear buckling in honeycomb-core structures due to thin-walled cellular elements [17] , and the comparatively weaker adhesion between wood cores and face layers due to reduced adhesive bonding area [18]. These bonding challenges require meticulous moisture management and adhesive application, complemented by advanced adhesive formulations and protective coatings to ensure durability and prevent delamination. Additionally, the hygroscopic nature of wood presents dimensional stability concerns under varying environmental moisture conditions, necessitating careful material selection and protective treatments [19].

Inspired by natural cellular structures, this research program was ultimately aimed at developing LWSPs by using the wood cores of honeycomb and softwood cellular structures and plywood faces. Both the cores and faces were fabricated using aspen wood, which is abundant in Canada, but is treated as underutilized species. The specific objective of this preliminary study was to develop LWSPs of bionics-inspired hollow aspen wood cores and aspen plywood faces and assess their mechanical performance in terms of modulus of elasticity (MOE) and modulus of rupture (MOR). This could provide a solution to utilization of low-quality aspen wood for applications in construction.

2 METHODS

2.1 MATERIALS

Trembling aspen (*Populus tremuloides*) lumber was selected as the core materials for making sandwich panels, due to its abundant availability in North America and low density. Aspen lumber boards were cut from the lumber and measured, weighed, and sorted according to density. The density at time of preparing the specimens ranged between 429 and 488 kg/m³ at an average moisture content (MC) of about 13%. This sorting step was crucial to maintaining consistency in material properties across all specimens. After sorting, the boards were planed and sanded to achieve a uniform size of 1,000 mm in length, 90 mm in width, and 20 mm in thickness, ensuring smooth and even surfaces for subsequent processing and assembly.

Three-ply aspen plywood was utilized for the face layers to provide structural integrity, which was purchased from a local building materials store, with the dimensions of 2,440 mm in length, 1,220 mm in width, and 6 mm in thickness. The average density and MC of plywood at fabrication of specimens were 483 kg/m^3 and 8%, respectively.

Gorilla polyvinyl acetate (PVA) adhesive was purchased from a local building materials store as well, which was used for edge-bonding aspen lumber boards to form panel blanks to make the cores using a CNC router. Bostik ISOSET HX1060 polyurethane (PUR) adhesive plus ISOSET EXP HX300 water-based primer was used to bond the core and two faces of each sandwich panel.

2.2 DESIGN AND FABRICATION OF LWSP

To enhance the structural performance of sandwich panels, core structures are critical. This study was inspired by bionics and designed the core structures with reference to the cellular anatomy of softwood and honeycomb. The softwood structure, with its wood rays in the radial direction, functions as a natural rib system offering the one-way reinforcement, while the honeycomb mimics efficient natural patterns providing two-way action capability. These two structures have optimized strength and weight features, Figure 1. The core designs were created using AutoCAD 3D to model structures based on natural patterns. By integrating bionic principles, such designs would improve efficient load and stiffness capacities, making wood-based sandwich panels more structure-effective and material-sustainable.

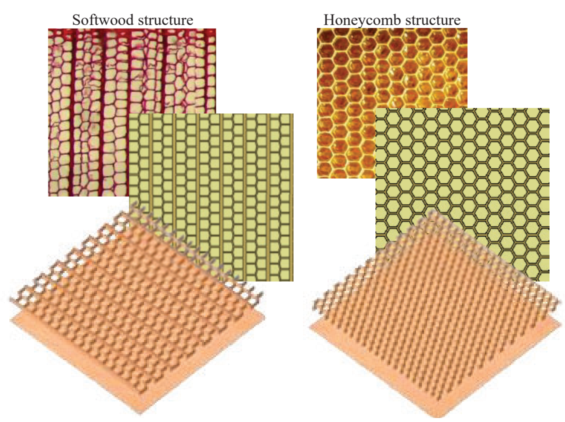

Figure 1.Natural softwood and honeycomb cellular structures

A step-by-step process was used to manufacture the LWSPs in this study. Initially, the aspen boards were edge-glued using the PVA adhesive and clamped for 12 hours for creating the core panels, measuring 919 mm in length, 730 mm in width and 20 mm in thickness. CNC machining was then used to precisely mill cellular patterns into the core structure designed with AutoCAD, followed by sanding to ensure smooth and flat surfaces. Figure 2 provides the geometry and dimensions of each type of core structure. The core was finally trimmed to

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470 mm in length, 90 mm in width, and 20 mm in thickness. The plywood sheets for the faces were full-sized (2,440 mm in length, 1,220 mm in width, and 6 mm in thickness) as previously mentioned.

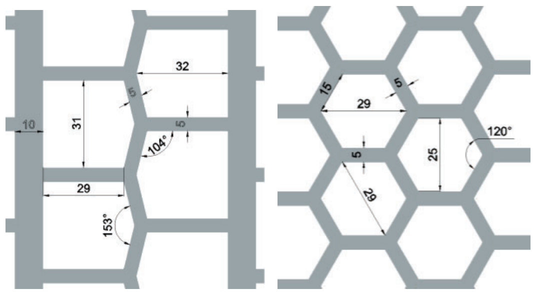

Figure 2. Geometry and dimensions of softwood (left) and honeycomb (right) cellular structure

For final sandwich assembly, two or three core panels (depending on the LWSP configuration) were placed side-by-side on a plywood sheet. PUR adhesive was applied at a rate of 210 g/m^2 to both the core surfaces and the plywood face sheets. A second plywood sheet was then placed on top, making an assembly, which were pressed in a cold press under 180 psi pressure for 200 minutes, which is available at the Wood Science and Technology Centre, the University of New Brunswick, Fredericton, Canada. The presence of fine adhesive beads squeezing out from the glue line served as confirmation of adequate pressure and spread rate of the adhesive. After pressing, the panels were cut into LWSP bending test specimens and conditioned for mechanical testing.

It was interesting to find during the fabrication of LWSP in this study that the PUR adhesive could play a dual role in the sandwich panel structure. In addition to bonding the face layers to the core, the adhesive partially penetrated and filled the cellular cells, forming hardened fillets along the inner walls. This secondary effect reinforced the thin cell walls, increased local stiffness, and reduced the risk of shear buckling. As a result, the adhesive not only ensured interfacial bonding but also could contribute to the mechanical performance of the core itself by acting as an internal stiffening agent. This should be verified in future studies.

The experimental design considered three factors influencing bending behaviour: (1) core type – softwood (S) or honeycomb (H), (2) plywood grain/core alignment – longitudinal (L) or transverse (T), and (3) loading orientation – major (parallel) or minor (perpendicular) to the core boards and plywood face layers. Major orientation corresponds to bending along the direction of the edge-glued aspen core boards and the primary grain of the plywood, while minor orientation refers to loading across these directions. This classification resulted in four panel configurations: S-L: softwood core with longitudinal plywood grain, S-T: softwood core with transverse grain, H-L: honeycomb core with longitudinal grain, and H-T: honeycomb core with transverse grain. Each configuration was tested in both major and minor directions, as summarized in Table 1.

Table 1. LWSP Configurations and bending specimen orientations

LWSP type	Core Type	Plywood/Core Orientation	Bending Orientation
S-L-Major	S	Longitudinal	Major (Parallel)
S-L-Minor			Minor (Perpendicular)
S-T-Major	S	Transverse	Major (Parallel)
S-T-Minor			Minor (Perpendicular)
H-L-Major	H	Longitudinal	Major (Parallel)
H-L-Minor			Minor (Perpendicular)
H-T-Major	H	Transverse	Major (Parallel)
H-T-Minor			Minor (Perpendicular)

2.3 SPECIMEN FABRICATION

All specimens were conditioned in a controlled climate chamber prior to testing, in accordance with standard procedures for wood-based materials.

2.3.1 Plywood and core bending specimens

To predict the MOE of a sandwich panel, the MOE of the plywood faces and cellular core panels should be directly measured. A total of 10 plywood face specimens were cut from full-size sheets (2,438 mm in length, 1,219 mm in width, and 6 mm in thickness) to dimensions of 176 mm in length, 50 mm in width, and 6 mm in thickness, considering major and minor orientation. Six (6) aspen core specimens were prepared by cutting cellular cores to dimensions of 470 mm in length, 90 mm in width, and 20 mm, considering major direction.

2.3.2 LWSP bending specimens

LWSP bending specimens were prepared from full-size sandwich panels (LWSPs) according to standardized dimensions to ensure accuracy and repeatability. A total of 48 specimens were cut from the LWSP for the bending tests, with 12 LWSP bending specimens from each panel type. The final dimensions of the LWSP bending specimens were 600 mm in length, 90 mm in width, and 32 mm in thickness. Cutting layouts for bending specimens from S-L, presented in Figure 3.

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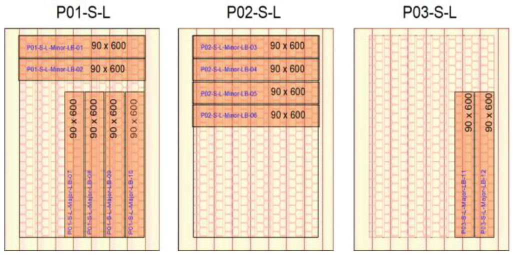

Figure 3. Cutting layouts for LWSP bending specimens from S-L panels

2.4 TESTING

The average MC of the LWSP bending specimens during testing was 15%, and the average density of LWSP bending specimens with a softwood core was 316 kg/m³, with the honeycomb - 319 kg/m³ determined in accordance with ASTM C271 [20].

The mechanical performance of the LWSP bending specimens was evaluated through a series of four-point bending tests conducted using a universal testing machine (Model: Instron 5984) at a load rate of 2 mm/min. A deflectometer was placed at the midpoint of the bottom of a specimen to measure displacement. Testing was carried out at two stages.

Initially, the building elements - plywood face specimens and aspen core specimens - were tested separately to determine their the elastic modulus and bending strength, Figure 4. The plywood face specimens were tested at a rate of 2 mm/min according to ASTM D3043 [21] using a span of 126 mm and a span-to-depth ratio of 21. The aspen core specimens were tested at a rate of 2 mm/min following ASTM D198 [22] with a span of 420 mm and a span-to-depth ratio of 21 as well.

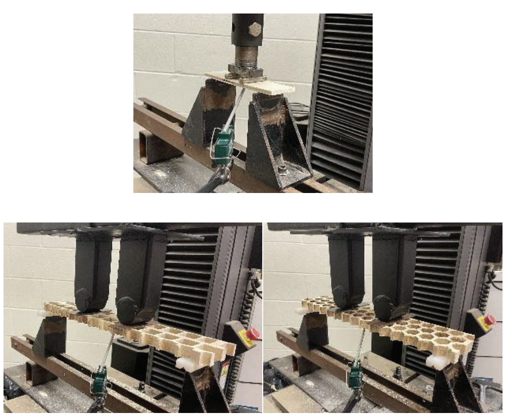

Figure 4. Plywood face specimen (top), the softwood aspen core specimen (bottom left) and honeycomb (bottom right) aspen core specimen under the four-point bending test

In the second stage, LWSP bending specimens were tested to assess their overall bending behaviour. The test was performed at a rate of 2 mm/min using a 544-mm span, giving a span-to-depth ratio of 17, in accordance with ASTM C393 [23], as shown in Figure 5.

Figure 5. LWSPs bending specimens under the four-point bending test

2.5 CALCULATIONS

The bending performance of the LWSP specimens was evaluated experimentally and theoretically using parameters that describe stiffness and strength under bending loading. The modulus of elasticity and modulus of rupture were first determined for the plywood face layers and aspen core structures and then for the LWSP specimens, using Equations (1) and (2):

$$Modulus\ of\ elascity = \frac{23 \cdot P \cdot L^3}{108 \cdot b \cdot t^3 \cdot \Delta} \qquad (1)$$

$$Modulsus\ ofreupture = \frac{3 \cdot P_{max} \cdot L}{2 \cdot b \cdot t^2} \qquad (2)$$

Where, P – an applied load (N) within the linear elastic region, P_{max} - maximum load at failure (N), L – span between supports (mm), b – specimen width (mm), t – specimen thickness (mm), and Δ – deflection at the mid-span (mm).

For the cellular core in the minor direction, modulus of elasticity was not experimentally measured but were estimated based on the assumption for wood-based materials, such as cross-laminated timber (CLT), which suggests using a ratio [24] from Equation (3):

$$\frac{Modulus\ of\ elascity_{Major}}{Modulus\ of\ elascity_{Minor}} = 30 \qquad (3)$$

A simplified analytical model based on the classical mechanics of composites was employed to predict the modulus of elasticity $E_{predict}$ (MPa) [25], of a composite panel, assuming perfect bonding and linear-elastic behaviour of all layers. $E_{predict}$ can be calculated using Equation (4):

$$E_{predict} = \frac{1}{t}(2E^f t^f + E^c t^c) \quad (4)$$

Where, E^f and E^c are the moduli of elasticity of the face layers and core (MPa), respectively, and t^f and t^c are their thicknesses (mm), and t – the thickness of the whole panel (mm).

3 RESULTS AND DISCUSSION

3.1 BENDING PROPERTIES OF FACE AND CORE MATERIALS

Plywood specimens achieved an average $MOE_{plywood}$ of 7,794 MPa and an average $MOR_{plywood}$ of 91.85 MPa in the major direction, which were 414% and 128% larger than those in the minor direction, respectively. This difference reflects the grain direction of the veneer making the plywood examined, as bending parallel to the grain provides greater resistance due to anisotropic nature of wood [25]. The MOE ratio between the major and minor directions was approximately 5:1, confirming the strong anisotropic nature of aspen plywood used in this study.

In comparison, Smardzewski et al. [16] tested two types of plywood: poplar plywood (18.4 mm thick, density 515 kg/m³) and exotic plywood (7.9 mm thick, density 354 kg/m³). For poplar plywood, the MOE was 4,879 MPa and MOR was 40.5 MPa (Major direction, along the fibers). For exotic plywood, the MOE was 3,393 MPa and MOR was 32.9 MPa. The 6-mm-thick plywood tested in this study showed about 60–130% higher stiffness and more than twice the bending strength in the major direction, compared to both poplar and exotic plywood reported in [16]. In the minor direction, however, the $MOE_{plywood}$ of the aspen plywood tested in this study was 1,515 MPa, which was lower than the MOE of 4,725 MPa reported for poplar plywood [16]. With more veneer layers, plywood becomes less anisotropic, so the MOE difference between directions decreases. While a direct comparison is limited by differences in plywood thickness and structure, these results provide a general indication of how veneer orientation, material density, and number of veneer layers influence the bending performance of plywood panels.

In the major direction, softwood core specimens reached an average MOE_{app_c} of 2,215 MPa and MOR_{app_c} of 20.06 MPa. In contrast, honeycomb core specimens in the same direction showed significantly lower values, averaging 486 MPa for MOE_{app_c} and 3.95 MPa for MOR_{app_c}. This is because the softwood cellular core had 10-mm-thick vertical ribs, mimicking wood rays, which provide one-way support in the major direction, making the structure stiffer and stronger. The honeycomb core had a uniform structure with the walls of the same thickness, offering a two-way stiffness and strength capacity. Since these tests were done on the cores only (without face layers), the mechanical response directly reflects the contributions of the internal geometry and material properties.

Based on Equation (3), the softwood core in the minor direction was estimated as 74 MPa for MOE_{app_c}, and for honeycomb core as 16 MPa., Figure 6. These values reflect the expected decrease in bending properties when loaded transversely.

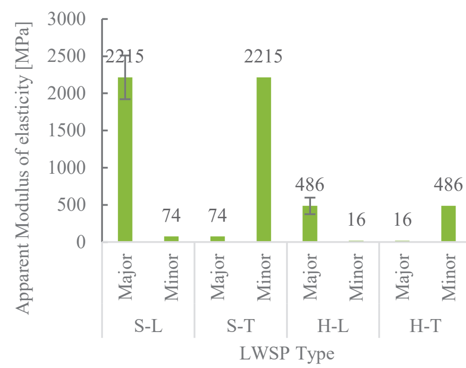

Figure 6. Modulus of elasticity (MPa) of cellular cores

These findings are in line with the mechanical properties of aspen. According to the Wood Handbook aspen at 12% moisture content has a MOE of 8,100 MPa and a MOR of 58 MPa [26]. This natural anisotropy and relatively low density help explain the observed performance of the softwood and honeycomb core specimens, whose mechanical response is governed by both geometry and wood behavior.

These results confirm that both the face material orientation and core structure significantly influence bending stiffness and strength, with plywood and softwood core showing the best performance in the major direction.

3.2 BENDING PROPERTIES OF LWSPs

Table 2 summarizes the experimental results, revealing that both the cellular core structure and specimen orientation had a significant effect on the MOE_{app} and MOR_{app} of the LWSP bending specimens . This is not

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surprising from the mechanics of composites point of view, i.e., the bending stiffness and strength of a composite depend on the properties of those building elements making it. The findings in 3.1 already provide hints on this.

Table 2. Mechanical properties of the LWSP specimens

Plywood and Core Orientation	Core Structure Direction*	MOE_{app} (MPa)	Standard Deviation (MOE) (MPa)	MOR_{app} (MPa)	Standard Deviation (MOR) (MPa)
S-L	Major	3,474	325	38.42	2.49
	Minor	2,881	175	29.46	2.39
S-T	Major	3,922	344	32.74	1.99
	Minor	2,755	267	27.61	7.64
H-L	Major	3,438	205	32.49	3.84
	Minor	3,143	60	30.80	3.00
H-T	Major	3,906	598	36.88	4.11
	Minor	2,602	231	26.75	2.29

Some LWSP bending specimens with softwood core demonstrated higher MOE_{app} and MOR_{app} values than those with honeycomb cores, though overall differences between the two core types were small and configuration-dependent. Among the longitudinally oriented LWSP bending specimens, the softwood core in the major direction (S-L major) achieved the highest MOE_{app} of 3,474 MPa and MOR_{app} of 38.42 MPa. Compared to the corresponding honeycomb core LWSP bending specimens (H-L major), this represented a no difference in MOE_{app} and an 18% increase in MOR_{app}. In contrast, the softwood core LWSP bending specimens in the transverse-minor direction (S-T minor) showed the lowest performance (MOE_{app} = 2,755 MPa, MOR_{app} = 27.61 MPa), indicating a strong orientation dependency.

For honeycomb core LWSP specimens, values were more uniform, but the major direction still resulted in higher stiffness and strength. The H-T major configuration had an average MOE_{app} of 3,906 MPa and MOR_{app} of 36.88 MPa - approximately 50% and 38% higher, respectively, than those of the H-T specimens. Overall, transverse configurations (S-T, H-T) demonstrated higher MOE_{app} values, while longitudinal configurations (S-L) showed slightly better MOR_{app} for softwood core specimens. This indicates that the effect of plywood orientation on bending performance depends on the specific core structure and property considered. Within each orientation, the bending properties in the major direction consistently outperformed those in the minor direction. For instance, in the S-L group, the major orientation resulted in a 21% increase in MOE_{app} and 30% increase in MOR_{app} compared to the minor orientation. These trends were also reflected in the standard deviations. Softwood core LWSP bending specimens generally showed greater variation, likely due to the natural heterogeneity of the solid wood. However, the honeycomb core LWSP bending specimens also showed noticeable variability in some configurations. For example, the H-T major group had the highest standard deviation in MOE (598 MPa), suggesting that even uniform core geometry can be affected by factors such as wood grain direction and quality variation, and likely CNC cutting precision. Therefore, the variation observed in the honeycomb LWSP bending specimens could not be considered small in all cases and might reflect sensitivity to wood materials and manufacturing conditions.

In this study, the transverse configurations - especially S-T and H-T in the major direction - showed bending performance that was similar to or even better than the longitudinal ones. One possible reason for the strong performance of the transverse configurations is the cross-orientation between the plywood direction and wood grain direction of the core boards. This design may behave somewhat like a CLT panel [24], where the alternating directions help distribute stresses more evenly and improve stiffness in two directions. Although this was not the main goal of the design in this study, the combination of transverse plywood and longitudinal core alignment could have contributed to the better-than-expected bending results in some configurations.

The mechanical performance of the developed LWSP was compared to lightweight honeycomb panels studied by Smardzewski et al [16]. Their panels were made of paper honeycomb cores (5 mm thick) combined with various face materials such as high-density fiberboard (2.0–2.5 mm thick), oak veneer (2.3–2.75 mm thick), or synthetic leather (0.6 mm thick). The total panel thickness was around 10 mm, with a density ranging from 382 to 517 kg/m³. In the L direction (along the fibers), Smardzewski et al. reported MOE values from 2,195 to 2,986 MPa and MOR values from 6.6 to 19.7 MPa. In comparison, the H-T panel (major direction) examined in this study reached MOE of 3,906 MPa and MOR of 36.88 MPa, while the S-T panel showed MOE of 3,922 MPa and MOR of 32.74 MPa. While a direct comparison is limited due to differences in panel thickness, the data suggest that aspen cores with engineered geometry can be competitive with traditional paper-core honeycomb panels in terms of stiffness and strength.

3.3 FAILURE MODES

Figure 7 illustrates the load-deflection curves of eight (8) representative specimens, one from each group. It can be found that there are largely two types: (1) more brittle failure (specimens S-L-Minor-04, S-L-Major-07, S-T-Minor-17, H-L-Minor-27) and more ductile failure (specimens S-L-Major-07, S-T-Major-22, H-L-Major-35, H-T-Minor-40, H-T-Major-47). This suggests the difference in failure mechanism between these LWSP bending specimens.

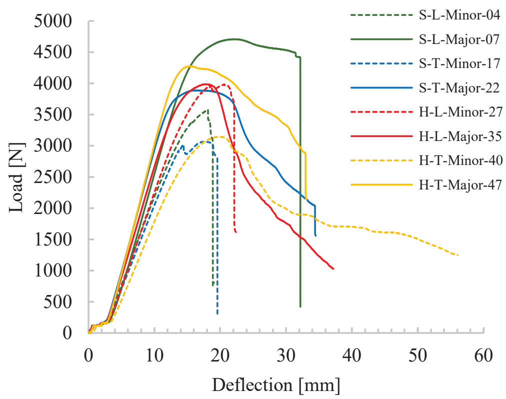

Figure 7. The load-deflection curves of LWSPs

Failure modes varied depending on the LWSP configuration, and many specimens exhibited combined failure modes [2,27]. Among specimens with softwood cores, the most frequent types were core failure and face failure, which often occurred together, particularly in the minor direction. In contrast, honeycomb-core LWSP bending specimens were most frequently affected by face wrinkling, especially in the major direction. This mode was occasionally combined with face failure or bond failure. Delamination and bond failure were rare but occurred sometimes across both core types and test directions.

A directional trend was observed: specimens tested in the minor direction showed more frequent core failure, while those tested in the major direction more often experienced face wrinkling. For instance, specimen S-T-Minor-17 and H-L-Minor-27 exhibited core failure with face failure and delamination, while specimens S-T-Major-22 and H-L-Major-35 showed face wrinkling with localized delamination, Figure 8.

All 48 LWSP bending specimens were visually examined, and the failure types were classified. Since many specimens exhibited more than one failure mode, the total count of failure modes exceeds the number of specimens. A summary of failure mode frequency is presented in Table 3.

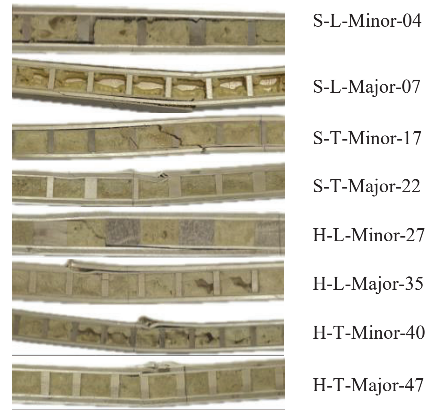

Figure 8. Failure modes of LWSP

Table 3. A summary of failure mode frequency

Failure Mode	Frequency	Occurrence in specimens			
		S-L	S-T	H-L	H-T
Core failure	25	9	6	7	3
Face wrinkling	25	3	7	11	4
Face failure	23	5	10	2	6
Delamination	14	3	6	2	3
Bond failure	4	1	1	2	0

Additionally, the number of failure modes observed per specimen varied. Fourteen specimens exhibited only one type of failure, twenty-three specimens showed two failure modes, ten specimens showed three, and one specimen exhibited four distinct failure modes. Face wrinkling failure mode dominated in group H-L, whereas face failure mode was more common in group S-T. This suggests that plywood orientation significantly influences surface stability. In contrast, the low incidence of bond failure confirms the effectiveness of PUR bonding, regardless of configuration. This further confirms that combined failure behaviour was common among the tested LWSP bending specimens.

Bonding performance was assessed through analysis of failure modes and post-test inspection of fracture surfaces. Across all specimens, the PUR adhesive demonstrated reliable adhesion between the core and face layers. No complete delamination at the interface was observed, and most specimens failed in core due to shear or in face due of rupture in the top layer, indicating that the bond line remained structurally intact under loading. Localized delamination between plywood veneers occurred in 14 cases, particularly near high-stress regions, but this did not compromise the global performance of the LWSP bending specimens. The adhesive filling of cellular voids likely contributed to local reinforcement and enhanced bond continuity, Figure 9.

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Figure 9. Adhesive filling of cellular voids

These observations confirm that the bonding system used in this study provided sufficient structural integrity and contributed to the effective transfer of loads between components.

3.4 COMPARISON WITH THEORETICAL PREDICTIONS

The experimentally obtained MOE_{app} values of the LWSP bending specimens were compared with theoretical predictions ($MOE_{predict}$) calculated using Equation 4.

Figure 10 presents a summary of these results. For the S-L specimens in the major direction, the $MOE_{predict}$ was 4,307 MPa, while the average MOE_{app} was 3,474 MPa, indicating an overestimation by 24%. For the H-L specimens in the major direction, the $MOE_{predict}$ and average MOE_{app} were 3,226 MPa and 3,438 MPa, respectively, resulting in a difference of approximately 7%. This could be attributed to the uniform structure and properties of the honeycomb core in the major and minor directions.

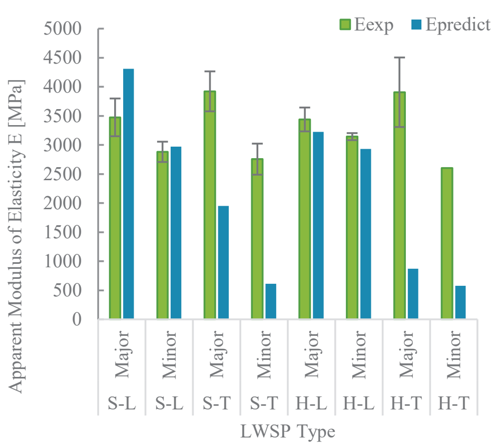

Figure 10. Comparison between theoretically predicted and experimentally tested apparent modulus of elasticity

In contrast, large differences were observed in the transverse direction. For the S-T specimens in the major direction, the predicted $MOE_{predict}$ was 1,952 MPa, significantly lower than the experimental value of 3,922 MPa, resulting in a 50% underestimation. Similarly, the H-T specimens in the major direction showed a predicted $MOE_{predict}$ of 872 MPa compared to the measured value of 3,906 MPa, representing a 78% underestimation.

For the minor direction, similar trends were observed. In the S-L minor group, the predicted $MOE_{predict}$ was 2,969 MPa, while the experimental MOE_{app} was 2,881 MPa, leading to a 3% overestimation. For the H-L minor group, the model slightly underestimated the MOE by 7% (2,933 MPa predicted vs. 3,143 MPa measured). However, significant differences occurred in the S-T minor group, where the predicted value of 614 MPa was significantly lower than the measured 2,755 MPa, resulting in an 78% underestimation. Similarly, the H-T minor group showed a predicted MOE of 578 MPa, whereas the experimental value was 2,602 MPa, yielding a 78% underestimation.

These findings suggest that Equation 4 could be used to predict the MOE of LWSPs developed in this study in the longitudinal direction only. This may be due to the method used to estimate the MOE of the core layers, which applied a fixed ratio Equation (3) rather than experimentally measured values. Such simplification does not account for the anisotropic nature of wood, especially when combined with the specific geometry and orientation of the cellular core. In the bionics-inspired structures like ribbed softwood cores and honeycomb, the internal layout can significantly influence load transfer. Therefore, more accurate predictions would require experimental determination of core properties in both directions. This will be addressed in future studies.

4 – CONCLUSIONS

Based on the above results and discussion, the following key conclusions could be drawn:

- Softwood cellular cores provided higher stiffness in the major direction, while honeycomb cores showed more balanced mechanical behaviour across orientations.
- The highest MOE_{app} was 3,922 MPa in the S-T panel (major orientation), with density 316 kg/m^3.
- Theoretically predicted $MOE_{predict}$ were relatively close to the experimentally tested MOE_{exp} for two LWSP groups of stiff configuration, i.e., S-L and H-L, with deviations of 24% overestimation and 7% underestimation. But this estimation approach did not work for the other two groups of transverse configuration.

- The major failure modes occurred in the bending specimens, including face wrinkling and core failure, suggesting a good bond quality between the faces and core of the LWSPs made in this study.

Future work would be recommended as follows:

- To revisit, modify, and develop the prediction models.
- To explore advanced numerical simulations and conduct full-scale testing under variable humidity and long-term loading conditions.
- To assess LWSPs for practical structural uses such as raised access floors, modular roofs, and partition walls.

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