Eco-sustainable sandwich panels: Influence of process parameters on adhesion and mechanical performance

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Abstract. In recent years, there has been a growing interest in recyclable and eco-friendly materials, driven by the need to develop components with complex geometries, variable thicknesses, and large dimensions, particularly in sectors such as building and automotive. Eco-Sustainable Sandwich Panels (ESSP), which combine lightweight cores with thermoplastic natural fiber-based composites, offer a promising solution to these demands by providing a balance between mechanical performance and sustainability. Despite their potential, ESSPs remain underexplored, with limited knowledge regarding the key factors necessary for their manufacturing. The low Technology Readiness Level (TRL) of these materials, along with challenges in ensuring reliable performance, particularly in terms of adhesion between skins and cores, hinders their broader industrial adoption. This study investigates the forming of Eco-sustainable Sandwich Panels (ESSP) consisting of an aluminum honeycomb core and skins made from flax fiber prepreg with a polypropylene matrix, manufactured by hot press molding. The aim is to evaluate the influence of process parameters on the adhesion between skins and core, which is critical for the mechanical performance of the panel. For this purpose, preliminary numerical analyses and destructive testing were made, and the results provide valuable insights for optimizing the production process of eco-sustainable sandwich panels and their potential industrial applications.

Introduction

The automotive industry in Europe is undergoing a profound transformation driven by increasingly stringent emission targets. By 2025-2029, passenger vehicles will be required to meet an average CO_2 emission target of 94 g/km, which will further decrease to 49 g/km for 2030-2034, culminating in a zero-emission target by 2035 [1]. Achieving these ambitious goals necessitates the adoption of a multifaceted strategy that includes the transition to electric vehicles, the use of biofuels, and advancements in energy storage technologies. Among these approaches, the increased use of lightweight materials, particularly composite materials, has emerged as a key enabler for reducing vehicle weight and enhancing efficiency. In fact, the use of composite materials in the automotive industry offers significant advantages, particularly in reducing vehicle emissions and fuel consumption due to their lightweight properties. By replacing traditional materials such as steel and aluminum, composites enable substantial weight reductions, which directly translate into lower energy requirements for vehicle propulsion. This weight-saving effect not only improves fuel efficiency in internal combustion engine vehicles but also extends the range of electric vehicles, addressing one of the key challenges of modern sustainable transportation [2].

In addition to their contribution to weight reduction, composite materials provide excellent mechanical properties, such as high stiffness and strength-to-weight ratios, which enhance vehicle performance and safety. Their corrosion resistance ensures longer service life, reducing the need for frequent repairs or replacements and contributing to overall lifecycle sustainability. Furthermore, the design flexibility of composites allows manufacturers to produce complex geometries and integrate multiple functionalities into a single component, enabling innovative vehicle designs that improve aerodynamics and reduce assembly complexity. Composites also support noise, vibration, and harshness (NVH) reduction, improving passenger comfort and vehicle acoustics. These materials can absorb and dampen vibrations more effectively than metals, making them ideal for applications in structural and semi-structural components. Combined, these attributes make composite materials a cornerstone of the automotive industry's transition towards more efficient, sustainable, and high-performing vehicles.

The automotive industry is at the forefront of efforts to achieve sustainability, driven by increasingly stringent environmental regulations and consumer demand for eco-friendly vehicles. Modern vehicles are now designed to be recyclable for over 85% of their total weight, and future trends suggest this percentage will continue to rise as industries adopt more sustainable materials and manufacturing practices. However, the widespread use of synthetic fibers and thermosetting resins in composite materials poses a significant challenge due to their environmental impact, non-recyclability, and the energy-intensive processes required for their production. In this context, natural fibers, such as hemp and flax, offer a compelling alternative [3]. These fibers are renewable, biodegradable, and exhibit excellent mechanical properties when used as reinforcement in composite materials [4]. Combined with recyclable thermoplastic matrices, such as polypropylene (PP), they provide a pathway to produce fully recyclable and sustainable components. This synergy between natural fibers and thermoplastic resins not only reduces the environmental footprint but also opens the door to innovative lightweight solutions essential for improving fuel efficiency and reducing emissions in vehicles [5,6].

The use of flax fiber-reinforced thermoplastic composites in the automotive sector offers several advantages. These materials are lightweight, cost-effective, and compatible with high-volume manufacturing processes. Additionally, they allow for end-of-life recycling, aligning with circular economy principles [7]. The combination of natural fibers and thermoplastics enables the production of parts with a balanced performance-to-cost ratio, making them increasingly attractive for structural and semi-structural applications [8].

Despite these advantages, the adoption of these innovative materials presents several challenges that span both manufacturing and post-processing stages. One critical issue lies in the limited knowledge of process parameters for both machining and forming operations involving these composites [9]. Machining processes, such as drilling, are essential for integrating composite components into vehicle assemblies. However, the anisotropic nature of natural fibers and the thermal sensitivity of thermoplastic matrices pose significant challenges in achieving precision, quality, and repeatability during machining [10]. Issues such as delamination, fiber pull-out, and heat-induced matrix degradation often arise, emphasizing the need for optimized tool designs and machining parameters [11].

When it comes to sandwich structures, additional complexities emerge. These materials, composed of lightweight cores and high-performance skins, require precise control of the bonding and consolidation process to ensure optimal mechanical performance. In particular, hot-press moulding, widely used for its efficiency and rapid cycle times, introduces specific challenges. The pressure and temperature applied during the process must be carefully balanced to achieve sufficient adhesion between the skins and the core without damaging the core structure or causing resin migration. Inadequate consolidation can lead to void formation, poor interfacial adhesion, or uneven resin distribution, which compromise the structural integrity and durability of the final component.

Moreover, the thermal and rheological behavior of the thermoplastic matrix during forming plays a crucial role in determining the quality of the consolidated part. Understanding key thermal transitions, such as melting and crystallization, is essential for identifying the processing conditions that allow the resin to flow adequately and wet the natural fibers effectively. Additionally, the chemical stability of the matrix must be ensured to prevent any undesirable changes that could compromise its performance during consolidation.

These factors are closely linked to the ability of the matrix to achieve proper bonding with the core surface and uniform distribution across the sandwich structure. By carefully evaluating these characteristics, it becomes possible to refine the forming process, ensuring consistent mechanical properties and optimal adhesion throughout the panel.

Overall, these challenges highlight the need for a deeper understanding of both forming and machining processes for these new material systems. Developing robust process models and conducting extensive experimental studies are critical to optimizing the manufacturing parameters. This will enable the production of high-quality sandwich panels that meet the stringent performance and durability requirements of the automotive sector while maintaining the sustainability benefits inherent to these materials.

This study investigates the feasibility of hot-press moulding for manufacturing sandwich structures composed of aluminum honeycomb cores and flax/PP prepreg skins. The research focuses on identifying the optimal process parameters, specifically temperature and forming force of the heated platens, to achieve high mechanical performance. A preliminary numerical model was employed to guide the selection of the forming temperatures of interest, providing a foundation for future process design optimization. The evaluation of the mechanical performance of the manufactured panels was conducted exclusively through three-point flexural testing, with a focus on determining flexural strength as a key performance metric. By addressing these aspects, this work contributes to advancing the processability of sustainable sandwich structures and supports their potential adoption in high-performance applications, particularly within the automotive industry.

Materials and Methods

This study utilized a prepreg made of woven flax fiber and polypropylene matrix, identified as Amplitex 5040 and manufactured by Bcomp. The fabric features a 2/2 twill weave pattern with an areal weight of 300 g/m², selected for its combination of mechanical properties and sustainability. Its mechanical properties are reported in Table 1.

Table 1 – Mechanical properties of Amplitex 5040 prepreg

Property	Value
Weave	Twill 2x2
Areal weight [g/m^2]	300
Tensile modulus [GPa]	17.5
Tensile strength [MPa]	145
Strain to failure [%]	1.3
Fibres density [kg/m^3]	1470

The core of the sandwich panel consists of an aluminum 5052 alloy honeycomb structure, chosen for its high specific mechanical properties. The mechanical properties of the honeycomb are reported in Table 2.

Table 2 – Mechanical properties of the used honeycomb.

Property	**Value**
Cell size [mm]	4.8
Height [mm]	12.7
Density [kg/m^3]	91
Compressive strength [MPa]	2.83
Shear strength [MPa]	3.17

The forming process was carried out using a Fontijne LabTop laboratory press with a maximum capacity of 150 kN. The heated platens, cooled with water, had an effective surface area of 200 × 200 mm. To ensure process quality and prevent the prepreg from adhering to the platens, a release film was applied. The optimal processing temperature range for the prepreg was determined in a previous study by the same authors [12] where DSC tests conducted on the flax/PP prepreg material revealed that complete melting of the polypropylene matrix occurs at temperatures above 171°C. Based on this result, the experimental plan was designed to start at a minimum temperature of 180°C, ensuring that the matrix fusion is fully achieved during the forming process.

A 2D finite element model was developed to evaluate the thermal behavior of the system and verify the feasibility of the forming process. The analysis focused on the temperature distribution at the skin-core interface, a critical factor for ensuring proper adhesion and processability. The model employed 4-node linear quadrilateral elements (known as type 39), selected for their simplicity and efficiency in capturing the temperature field within the system. The implemented model is based on heat conduction (Eq. 1), which governs the thermal evolution within the laminate. This model assumes heat transfer occurs predominantly through conduction, neglecting convective and radiative effects. The governing equation is expressed as Eq.1:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k \, \nabla T), \tag{1}$$

where T represents the temperature, ρ is the material density, c_p is the specific heat capacity, and k is the thermal conductivity.

The model was validated through a numerical-experimental comparison using eight type K exposed-junction thermocouples. These were placed both at the central section and the periphery of the laminate, with one thermocouple per interface. Specifically, four key interfaces were monitored: upper plate/prepreg, prepreg/core (upper side), prepreg/core (lower side), and prepreg/lower plate. The model exhibited an error of 4.3% relative to the measured mean value, which remains within the measured experimental dispersion of approximately 6.7%. The material parameters and the heating and cooling rates used to interpolate the actual thermal cycles are summarized in Table 3. The mesh used for the numerical analysis is reported in Figure 1. The boundary conditions of the model included imposed temperatures, obtained from experimental measurements using thermocouples positioned on the heated platens of the press. A transient analysis was performed to simulate the heating phase, providing a detailed representation of the temperature evolution during the forming process.

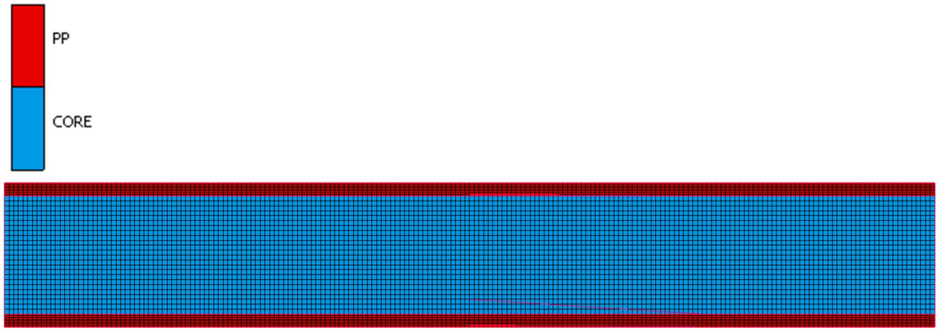

Figure 1 – Mesh used for the numerical analysis

The sandwich panel configuration consisted of two plies for each outer skin and a core with a nominal thickness of 12.7 mm. The forming process was divided into several steps: the materials were stacked on the lower platen, the platens were closed to apply the target forming pressure, and a controlled thermal cycle was executed. During this cycle, the system was heated to the target temperature, held for sufficient time to ensure matrix melting and adhesion to the core, and then cooled.

Table 3 – Parameter used for preliminary numerical analyses

Parameter	Value
Prepreg thermal conductivity [W/m K]	0.4
Prepreg specific heat capacity [J/kg K]	1800
Core thermal conductivity [W/m K]	5
Core specific heat capacity [J/kg K]	100
Heating rate [°C/min]	10
Cooling rate[°C/min]	60

This approach allowed for the direct consolidation of the structure during the forming process. After cooling, the plates were opened, and the sandwich panel was carefully removed avoiding damage.

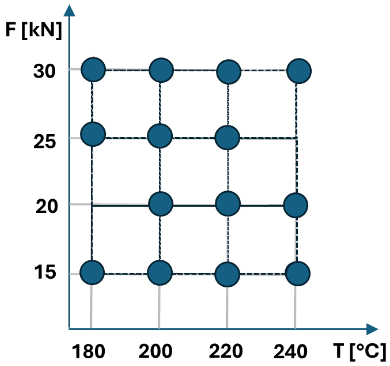

Figure 2 – Fractional factorial experimental design adopted in this study.

The experimental plan followed a fractional factorial design, as shown in Figure 2, with three replicates for each condition.The fabricated panels were subsequently cut into specimens according to the ASTM C393 standard. From each panel, three specimens were obtained, measuring 200 × 30 mm with a thickness of about 14 mm, suitable for three-point bending tests. An example of manufactured specimens is reported in Figure 3. The flexural tests were conducted using a universal testing machine equipped with a 5 kN load cell and compliant with ASTM C393 standards.

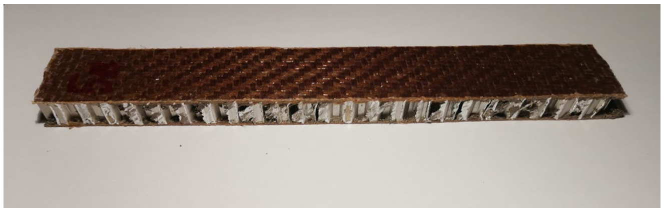

Figure 3 – Example of manufactured specimen

The crosshead speed was set to 3 mm/min, and the span between the lower supports was 140 mm (Figure 4). For each batch, three specimens were tested to evaluate the panel's performance in terms of flexural strength.The mechanical properties obtained from the tests were statistically analyzed using analysis of variance (ANOVA). This analysis allowed for the evaluation of the effects of process parameters, such as temperature, forming force, and thermal cycle, on the mechanical performance of the panels.

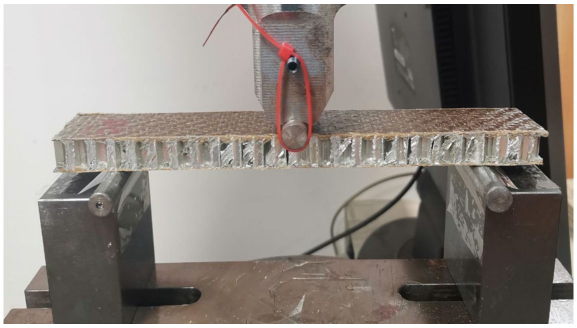

Figure 4 – Flexural specimen during testing

Results and Discussions

The numerical results are presented in Figure 5 and Figure 6, illustrating the thermal behavior of the sandwich structure during the heating and cooling phases. During the heating phase, the temperature gradient between the outer surface of the skin and the skin-core interface is approximately 2°C, indicating a highly uniform temperature distribution across the skin layers. This low gradient ensures effective heat transfer to the interface, promoting matrix fusion and adhesion. The core, due to its higher thermal conductivity compared to the skins, maintains a uniform temperature throughout the process, further contributing to the overall thermal equilibrium. In contrast, during the cooling phase, the thermal behavior becomes significantly less uniform. The temperature gradient between the outer skin surface and the skin-core interface increases, reaching a maximum of 20°C. This behavior highlights the disparity in cooling rates between the core and the skins, which can lead to localized thermal stresses. These results underline the importance of carefully controlling the cooling phase to mitigate potential thermal-induced defects in the sandwich structure.

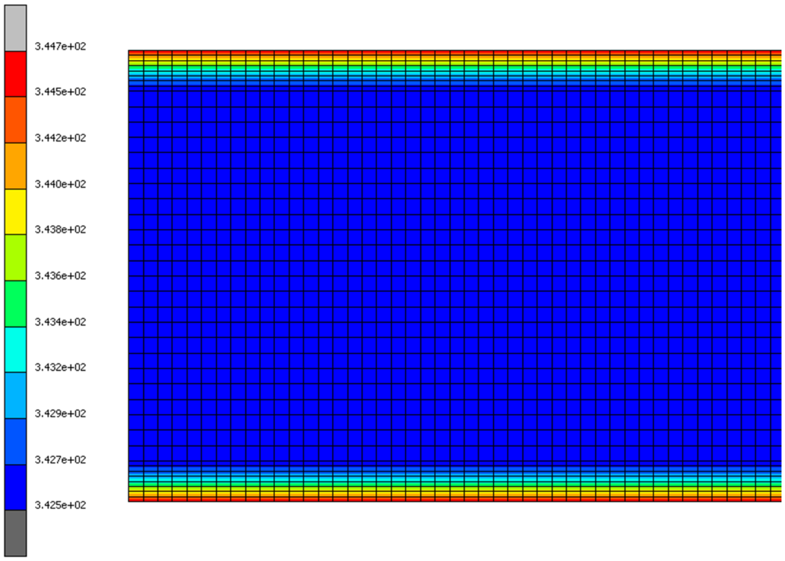

Figure 5 – Particular of temperature field during heating phase (temperature in K)

During the panel forming process, it was observed that critical process parameters, such as high temperatures and forming forces, led to core crushing by compression. This phenomenon occurred despite the applied loads being significantly lower than those recorded in preliminary tests conducted at room temperature. The combined effect of temperature and pressure on the core's crushing resistance resulted in a reduction in mechanical performance of over 70%. Although these panels are widely used in the aerospace sector, they demonstrated a high sensitivity to process temperature, with crushing observed at temperatures above 200 °C, even under loads well below the nominal values. To obtain complete response curves, a penalization approach was adopted in subsequent statistical analyses, assigning null values for flexural strength to panels affected by crushing.

It was observed that the failure mode of the specimens varied significantly with the process parameters. At lower temperatures and pressures, flexural failure predominantly occurred at the core-to-skin interface, leading to reduced performance (Figure 7a). In contrast, specimens formed at higher temperatures and pressures exhibited tensile failure of the skin on the side opposite to the punch (Figure 7c). Specimens subjected to intermediate levels of forming force and temperature demonstrated mixed-mode failures, combining characteristics of both failure mechanisms (Figure 3b). Flexural strength results obtained from testing are reported in Figure 8.

The results highlight a complex relationship between temperature, forming force, and the mechanical performance of the panel. At lower temperatures (up to 200 °C) and moderate forming forces (15-20 kN), a greater data dispersion is observed, indicating variability in the structural quality of the panel. This behavior can be attributed to uneven adhesion between the skin and core or suboptimal matrix distribution. As the temperature increases to around 220 °C, the average performance of the panel improves significantly, suggesting that the matrix fusion and core adhesion are more effective under these conditions. Another notable aspect is the reduction in data dispersion with increasing forming force. At lower forces, the higher variability in performance could be due to uneven adhesion or a less consolidated structure of the skins. In contrast, higher forces (25-30 kN) tend to homogenize the mechanical response of the panels, with significantly reduced dispersion. This behavior can be explained by the compacting effect of high pressures, which promotes better matrix distribution and greater structural uniformity of the skins.

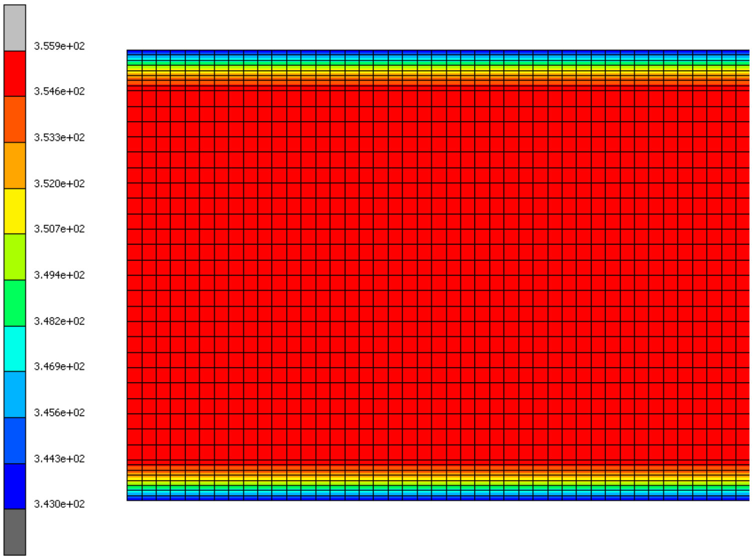

Figure 6 – Particular of temperature field during cooling phase (temperature in K)

However, the combination of temperatures above 220 °C and forming forces exceeding 25 kN, while improving the quality of the skins, introduces a significant risk of core crushing, compromising the panel forming process. Under these conditions, the core proves to be the critical component, unable to withstand the compressive loads generated, despite the overall improvement in panel performance. It is therefore essential to balance the process parameters, taking into account the differing requirements of the core and skins, in order to maximize the panel's overall performance without compromising its structural integrity.

Figure 5 supports this analysis by providing a clear visualization of how temperature and forming force individually influence the flexural strength of the panels. For the forming force, the plot reveals a steady increase in performance as the force rises from 15 kN to 25 kN, with values ranging from approximately 70 MPa to 95 MPa. This trend aligns with the hypothesis that higher forming forces enhance compaction and improve adhesion between the skin and core, resulting in more consistent structural integrity.

In the case of temperature, the plot highlights a more pronounced nonlinear effect. Flexural strength improves significantly as the temperature increases from 180 °C to 220 °C, reaching a peak of approximately 105 MPa. However, at 240 °C, there is a clear decline in flexural strength, indicating that excessively high temperatures negatively impact the core. This behavior is consistent with the risk of core crushing at elevated temperatures, where the compressive loads during forming exceed the core's structural capacity. While such conditions may promote even better skin adhesion, the mechanical stability of the panel is ultimately compromised.

The experimental results were analyzed using ANOVA to evaluate the correlations between mechanical performance and process parameters. The core crushing observed under specific process conditions represents an undesirable phenomenon that does not align with the design objectives of the panels. Since this type of failure is attributable to extreme process parameters and does not reflect the intended mechanical performance, the null values for strength associated with such events were excluded from the statistical analysis using ANOVA. This decision allows for a more accurate evaluation of the correlations between process parameters and panel performance, avoiding distortions in the results.

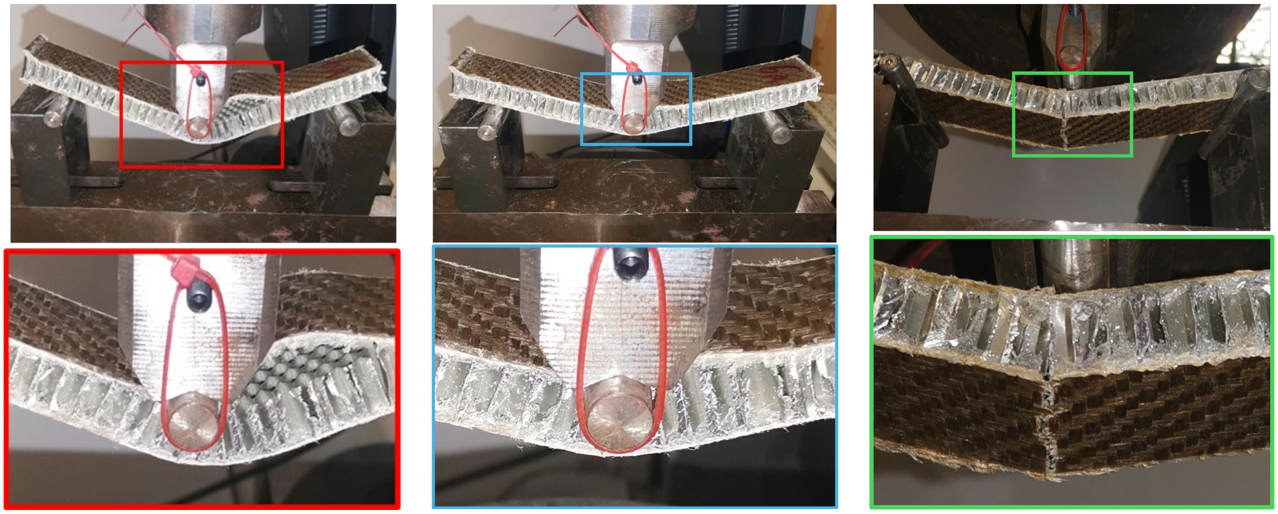
a)	b)	c)

Figure 7 – Examples of failure in specimens: a) interface skin/core failure; b) mixed mode failure; c) outer skin failure

The ANOVA results are reported in Table 4. The analysis shows that both temperature and forming force significantly influence the flexural strength of the panels, as demonstrated by the P-Values of 0.000 for both factors. This confirms that the effects of temperature and forming force are statistically significant at a 95% confidence level. Temperature contributes 38.94% to the overall variability, while forming force has a slightly higher contribution of 39.10%. These results indicate that both parameters have an almost equivalent impact on the mechanical performance of the panels. The error, representing the variability unexplained by the model, accounts for 21.96%.

Table 4 – ANOVA results for flexural tests

Source	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature [°C]	4829.6	38.94%	8131.6	2710.5	18.90	0.000
Forming force [kN]	4849.9	39.10%	4849.9	2424.9	16.91	0.000
Error	2724.5	21.96%	2724.5	143.4		
Total	12404.0	100.00%				

This portion of unexplained variability may arise from other unmodeled influences, such as minor variations in material properties or fluctuations in the forming force inherently tied to the production process. The F-Values for both factors (18.90 for temperature and 16.91 for forming force) further highlight their significant contribution to the overall variability. In particular, the slightly higher F-Value for temperature suggests that this parameter may have a slightly more pronounced impact on performance compared to forming force.Figure 10 and Figure 11 show respectively 3D response surfaces and contour plot illustrating the dependence of flexural strength on temperature and forming force.

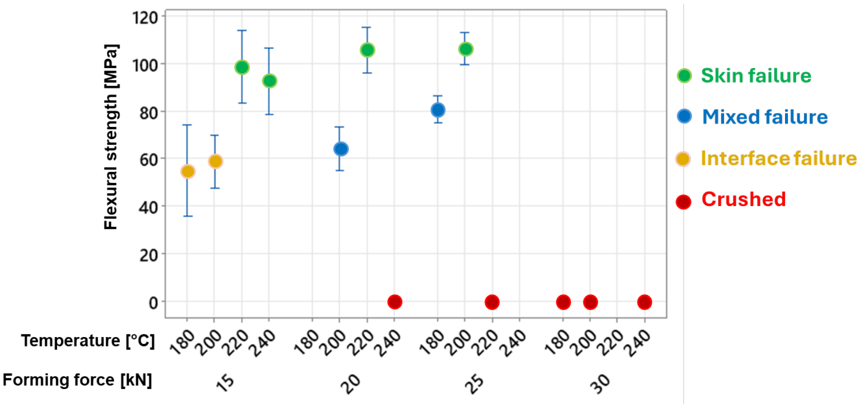

Figure 8 – Flexural strength results: null values identify crushing of cores during forming process

These representations highlight that maximum performance is achieved near critical process conditions, where the interaction between the two parameters becomes more significant. The 3D surface (Figure 10) demonstrates that the highest flexural strength values (>100 MPa) are reached at temperatures around 220 °C and forming forces between 20 and 25 kN, conditions that approach the structural stability limit of the core. This suggests that, while the panel exhibits peak performance under these conditions, the risk of core crushing increases rapidly with further increases in temperature or force. 2D contour map (Figure 11) supports this observation, clearly delineating regions of maximum performance and identifying boundaries between optimal operating conditions and those leading to crushing during forming process. It is possible to observe how the process optimization requires a delicate balance between enhancing skin performance and preserving core integrity.

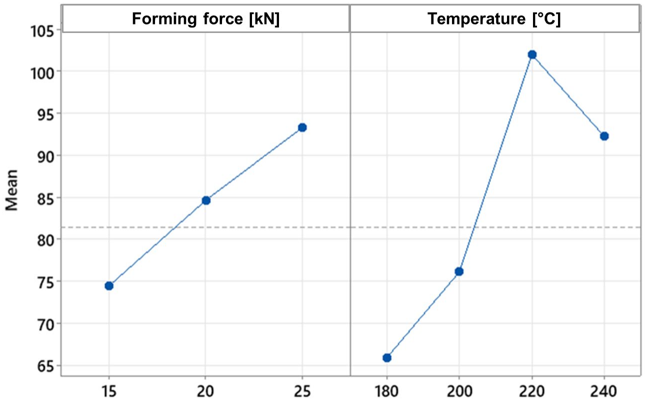

Figure 9 – Main effect plot for flexural strength (values in MPa)

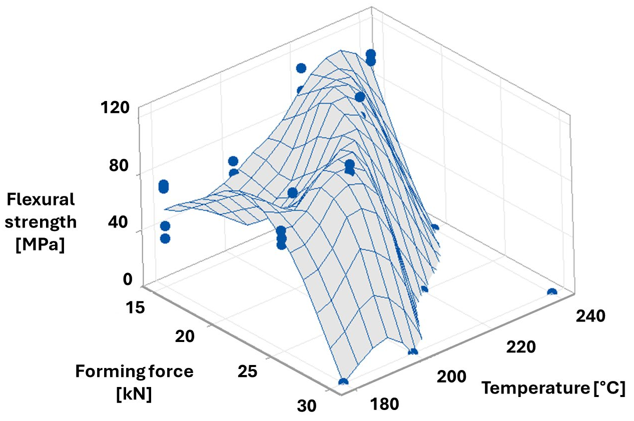

Figure 10 – 3D response surface showing the combined effect of temperature and forming force on flexural strength

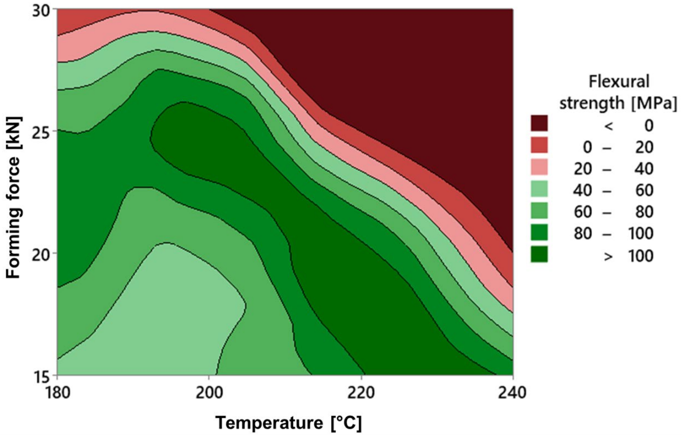

Figure 11 – Contour plot showing the flexural strength as a function of temperature and forming force

Conclusions

This study investigated the influence of temperature and forming force on the flexural strength of sandwich panels manufactured via hot press forming, using flax fiber-reinforced polypropylene skins and an aluminum honeycomb core. The results provide key insights into the processability of these sustainable composite materials, an area that remains the focus of ongoing research.

The findings demonstrate that the hot press forming process enables the production of sandwich panels with excellent mechanical performance when operating within a carefully defined process window. Maximum flexural strength, exceeding 100 MPa, was achieved at a temperature of 220 °C and a forming force of 20-25 kN, conditions that ensure optimal matrix fusion and adhesion between the skins and core. However, the study also highlights the critical challenges associated with this process: when temperatures exceed 220 °C or forming forces surpass 25 kN, the core becomes highly susceptible to crushing, leading to a significant reduction in panel performance.

This work makes a significant contribution to the state of the art by demonstrating the feasibility of processing sandwich panels made with flax fiber-reinforced polypropylene and aluminum honeycomb cores using a hot press forming method. The results highlight the potential of these materials as lightweight, sustainable alternatives for applications in high-performance sectors such as aerospace. Moreover, the study provides a comprehensive understanding of the process-property relationships for this class of materials, addressing a key gap in the current literature.

In conclusion, this research advances the understanding of the processability of bio-based composite materials, emphasizing the importance of precise process parameter control to balance enhanced skin properties and core stability. Future studies could build on this work by exploring additional variables, such as heating and cooling rates or alternative core configurations, to further optimize the performance and expand the application potential of these innovative sandwich panels.

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