

Advanced out-of-autoclave composite fabrication techniques and their advantages

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Abstract: Out-of-autoclave (OoA) composite manufacturing techniques have become an increasingly attractive alternative to conventional autoclave processing, due to their ability to reduce production costs, energy consumption and equipment complexity, while maintaining structural integrity and mechanical performance comparable to autoclave-based methods [1]. A comparative study was conducted on carbon fiber composites cured under different conditions using OoA techniques, with both mechanical and thermal tests carried out to evaluate performance. Tensile results revealed a balance between stiffness and maximum load capacity depending on the curing parameters, while thermal analyses demonstrated a significant improvement in heat deflection temperature (HDT) for samples cured at moderate temperatures. These findings confirm that OoA composites can achieve both reliable mechanical properties and enhanced thermal stability and demonstrate that OoA processes not only ensure reproducible and reliable composite properties, but also deliver clear advantages in terms of energy efficiency, scalability, and processing flexibility. The technology confirms that OoA composites can serve as a cost-effective and sustainable alternative to autoclave-cured systems, with high potential for widespread industrial adoption in aerospace and other engineering domains where high-performance lightweight structures are required.

Key Words: Out-of-autoclave processing, Carbon fiber composites, Sustainable manufacturing, Heat Deflection Temperature (HDT), Energy efficiency

1. INTRODUCTION

Carbon fiber–reinforced composite materials have become indispensable to the aerospace industry over the past decades, owing to their exceptional strength-to-weight ratio, dimensional stability, and superior fatigue performance. However, the widespread adoption of these materials in aircraft construction and other high-performance applications has raised a

significant end-of-life concern: recycling and reuse. Unlike metallic materials, which can be readily melted and reprocessed, carbon fiber–epoxy composites pose considerable challenges to recycling due to their thermoset nature and cross-linked polymeric network.

The present study is part of a broader line of research aimed at developing efficient and sustainable technologies for recycling composite materials originating from the aerospace sector. In this stage of the study, the process of manufacturing new laminated panels made of 200 g/m² carbon fiber twill fabric and L20/H161 epoxy resin was carried out and described in detail. These composites were subsequently subjected to mechanical and thermal characterization using two distinct curing approaches.

The first method involves curing at room temperature ($25\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$) for 24 hours, while the second consists of accelerated curing at $50\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ for 12 hours, utilizing an innovative mold configuration designed to enhance cross-linking uniformity and process efficiency.

The objective of this preliminary stage is to achieve a comprehensive understanding of the behavior of the studied materials, thereby enabling the development of efficient recycling and reuse strategies in subsequent project phases. The findings obtained at this stage provide a robust foundation for benchmarking the performance of recycled composites against their virgin counterparts.

Accordingly, the present work details both the fabrication process of the carbon fiber laminates and the mechanical and thermal tests conducted on the specimens.

The analysis focuses on identifying performance differences arising from the two distinct curing methods.

This study examines the fabrication of carbon fiber–reinforced polymers (CFRPs) through out-of-autoclave (OoA) processing techniques, which have emerged as a promising alternative to conventional autoclave manufacturing.

The growing adoption of OoA methods reflects ongoing efforts to reduce production costs and energy consumption while maintaining the high mechanical performance required for aerospace-grade composite structures.

Composite materials, particularly CFRPs, are essential in high-performance industries due to their excellent strength-to-weight ratio and fatigue resistance [2].

Autoclave processing ensures superior quality but is limited by high costs and lack of scalability [3].

OoA methods have emerged as efficient alternatives, especially for large structural components [4].

An autoclave is equipment used for manufacturing high-performance composite materials, providing high temperature and pressure conditions [5], [6]. However, it involves significant acquisition and operating costs, as well as size limitations of the produced parts [7]. For these reasons, alternative out-of-autoclave techniques have been developed, allowing the fabrication of composite parts at lower temperatures and pressures under more accessible conditions [8].

OoA manufacturing techniques include Vacuum Bag Only (VBO), Resin Infusion, Pultrusion, Filament Winding, traditional Resin Transfer Molding (RTM), Vacuum-Assisted Resin Transfer Molding (VARTM), and Compression Molding. These processes reduce costs and enable large-scale production [9], [10].

For the purposes of the present study, the resin infusion manufacturing technique was used (see Fig. 1 below).

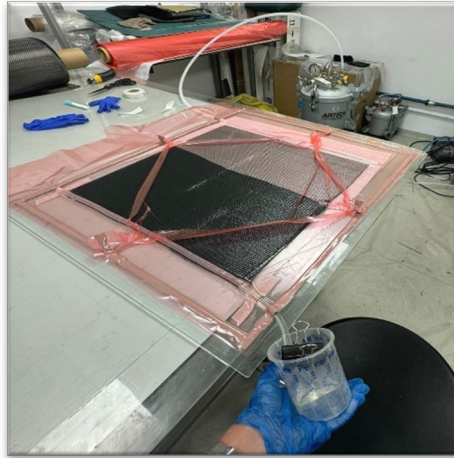


Fig. 1: Resin infusion manufacturing technique

In the resin infusion process, the dry reinforcement fibers are placed into the mold, covered with an airtight vacuum bag, and a vacuum is applied. The liquid resin is then introduced and impregnates the fibers due to the pressure differential [11].

Among the main advantages of this method are its low cost, simpler processing – use lightweight, flexible molds and local curing systems, suitability for manufacturing large components, and good material uniformity. However, the process also presents certain limitations, such as less precise control of porosity and lower mechanical strength compared to autoclave-cured parts [5].

Advantages of Out-of-Autoclave (OoA) Processing:

- Economic efficiency compared to autoclave-based techniques [2].
- Longer curing times under atmospheric pressure [3].
- Comparable mechanical properties to autoclave-cured composites when process parameters are properly optimized [4].
- Reduced energy consumption during processing [5].
- Scalability for the production of large structural components [10].
- Flexibility in the selection of materials and manufacturing routes [11].
- Simpler and easier-to-maintain equipment compared to autoclave systems [12].

Challenges and Limitations of Out-of-Autoclave Processing:

- Higher porosity levels compared to autoclave processing [13].
- Inferior surface finish quality in certain cases [14].
- Requirement for specialized, low-viscosity resin systems [15].

Out-of-autoclave (OoA) processing represents an efficient, scalable, and sustainable alternative to traditional autoclave manufacturing.

With ongoing innovations in resin chemistry and processing technologies, OoA methods are poised to transform large-scale composite production within the aerospace and related high-performance industries [2], [3], [10].

2. MATERIALS, MANUFACTURING AND TESTING

The fabrication and characterization of composite materials involve several experimental stages, ranging from specimen manufacturing and preparation into appropriate geometries to

the testing of their structural, mechanical, and thermal properties. Each stage requires the use of specialized equipment selected to ensure precision, reproducibility, and compliance with international standards.

Accordingly, for resin infusion manufacturing, a specialized kit from Airtech equipped with a vacuum pump was employed to ensure uniform fiber impregnation. The resulting specimens were subsequently processed by waterjet cutting using the WAZER Pro system, which guarantees clean edges and eliminates thermally affected zones.

The mechanical properties were determined using an Instron 5982 universal testing machine equipped with a 100kN load cell. In addition, the thermal resistance of the materials was analyzed using an HDT/Vicat testing system, designed to determine the heat deflection temperature under load.

2.1 Materials Used

The reinforcement material employed was a carbon fiber twill fabric with an areal density of 200 g/m², supplied by Easy Composites (see Fig. 2a). This fabric offers the advantage of combining high processing flexibility with excellent mechanical strength, making it a preferred choice for applications that require good conformability on complex mold geometries.

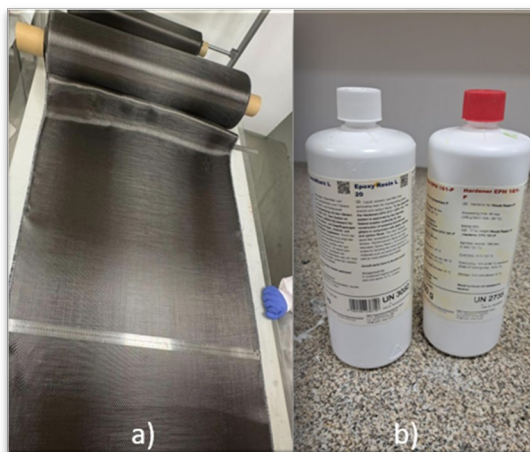


Fig. 2: a) Carbon fiber twill fabric; b) L20 resin and H161 hardener

The binder used in this study was an epoxy system consisting of L20 resin and H161 hardener, both supplied by R&G Faserverbundwerkstoffe GmbH, mixed in a 4:1 ratio according to the manufacturer's specifications. This system is well known for its stable mechanical properties and high compatibility with carbon fiber reinforcements.

For the implementation of the out-of-autoclave resin infusion process, the following consumable materials were employed (see Fig. 3):

- Mold release wax – a surface treatment applied to the mold surface to prevent sticking and allow easy removal of the cured part.
- Peel ply – a white (nylon or polyester) release fabric with red stripes, which leaves the surface properly prepared for bonding or the application of additional layers.
- Flow mesh / flow media – a green mesh material that ensures uniform distribution of the resin throughout the laminate.
- Vacuum bag film – a specialized sealing film used to encapsulate the entire system under vacuum conditions.

- Sealant tape (mastic) – an adhesive sealing tape used to ensure vacuum integrity by securing the bag film to the mold.
- Resin feed lines – spiral tubes through which the resin is introduced, facilitating uniform impregnation of the fibers.
- Spiral tubing-spiral tubes through which the resin is distributed, facilitating uniform impregnation of the fibers.
- Vacuum lines – tubing used to extract air and maintain the vacuum level during the infusion process.

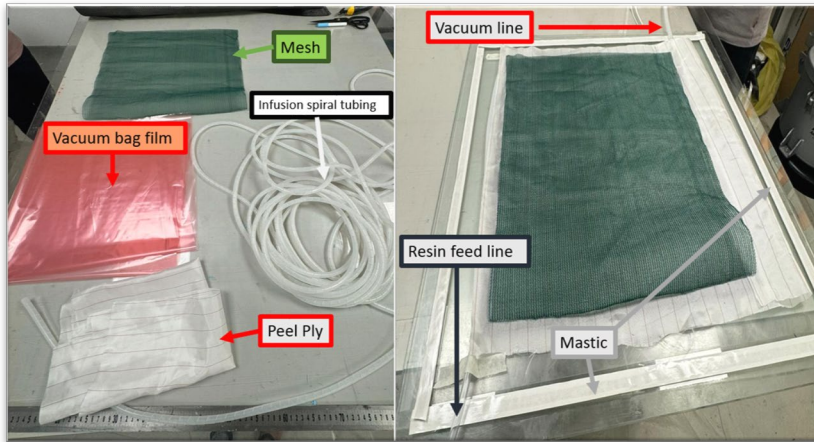


Fig. 3: Consumables for the out-of-autoclave resin infusion technique

2.2 Manufacturing Technology

The two laminated composites were fabricated using the resin infusion method, a technique commonly preferred for producing high-quality composite panels as it ensures effective resin penetration into the fiber layers while minimizing porosity and other internal defects. The infusion resin process is illustrated in Fig. 4.

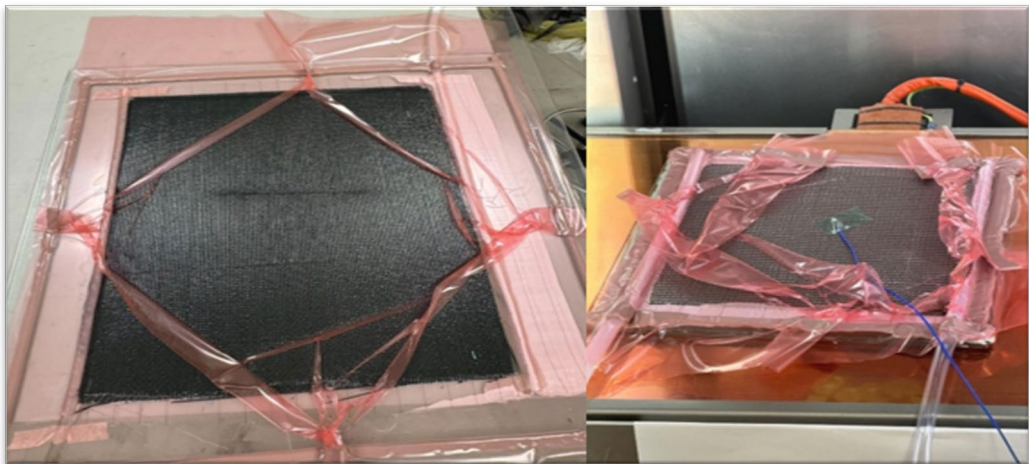


Fig. 4: Resin infusion process

The stacking sequence of the six layers, as shown in Fig. 5, was $[0^\circ, 90^\circ, -45^\circ, +45^\circ, 0^\circ, 90^\circ]$, resulting in a quasi-isotropic configuration that is structurally balanced and well-suited to withstand multiaxial loading conditions.

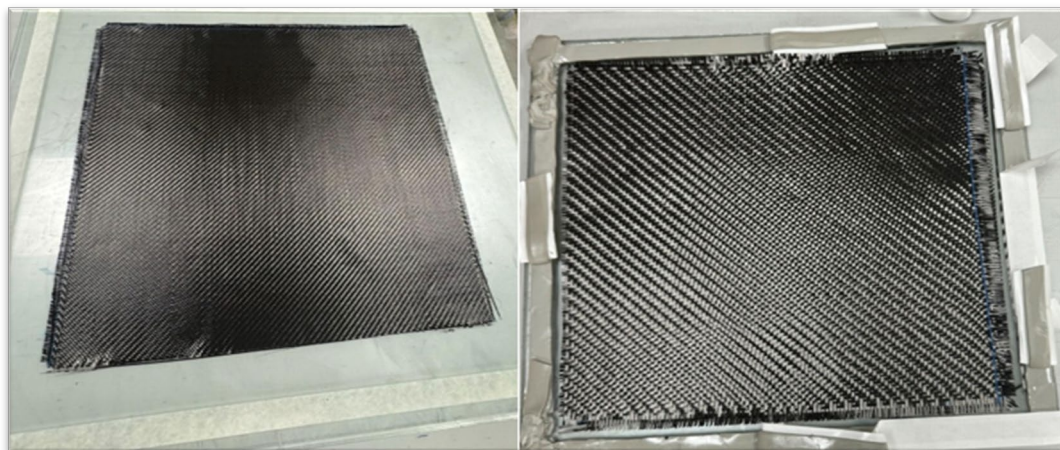


Fig. 5: Carbon fiber plies for quasi-isotropic sample configuration

The fabricated composite laminates exhibited a final thickness of $1.24 \text{ mm} \pm 0.03 \text{ mm}$, indicating excellent control over the manufacturing process and a high degree of uniformity across the material structure.

The first laminate plate was left to cure for 24 hours at room temperature ($25^\circ\text{C} \pm 2^\circ\text{C}$). The second plate was subjected to an accelerated curing process at $50^\circ\text{C} \pm 2^\circ\text{C}$ for 12 hours, using a conductive-layer mold.

After curing, the composite plates were cut by waterjet machining using the WAZER Pro system, which ensured high dimensional precision and eliminated the risk of thermal or mechanical damage to the specimen edges.

Standardized specimens were then prepared for mechanical testing: $100 \times 15 \text{ mm}$ samples for three-point bending tests, and $100 \times 32 \text{ mm}$ samples for heat deflection temperature (HDT) determinations. The prepared test specimens are shown below in Fig. 6.

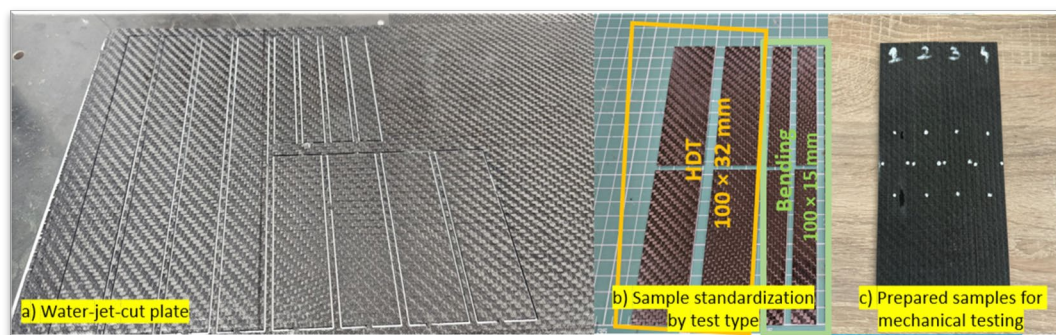


Fig. 6: Specimens prepared for mechanical and thermal testing

2.3 Testing Methodology

For this study, three-point bending mechanical test and heat deflection temperature (HDT) thermal test were conducted.

The three-point bending tests were performed in accordance with ISO 178, using a support span of 32 mm.

The specimens were preloaded at a rate of 0.5 mm/min , after which the test load was applied at a crosshead speed of 2 mm/min .

Rectangular specimens with dimensions of 100×15 mm were used for the flexural tests (see Fig. 7).



Fig. 7: Specimens subjected to bending

The Heat Deflection Temperature (HDT) test was performed using a Vicat equipment to evaluate the thermal behavior of the polymer samples under a constant mechanical load as the temperature increased progressively.

This method provides insight into the thermal resistance and dimensional stability of materials when subjected to both heat and stress.

During the experiments, the temperature at which the specimens exhibited a defined level of deformation under load was recorded. The obtained HDT values were then compared for the two distinct crosslinking methods, with the results summarized in Table 1 and graphically represented in Fig. 13.

For the HDT measurements, rectangular specimens with dimensions of 100×32 mm were used (see Fig. 6), and a visual representation of the HDT testing process for a single specimen is provided in Fig. 8.

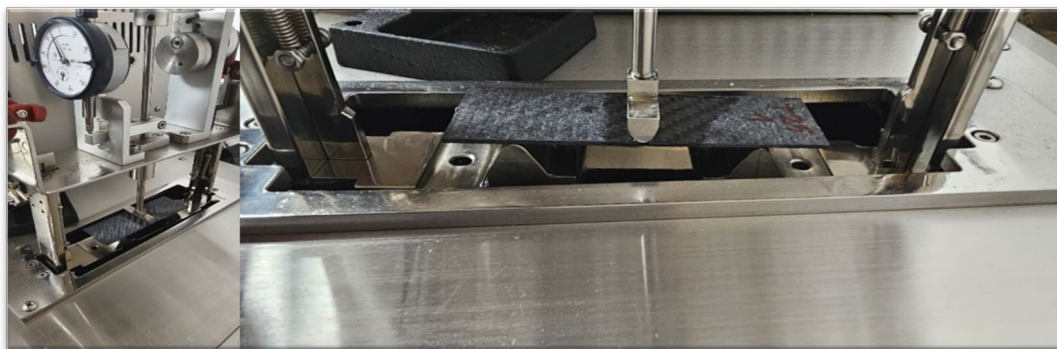


Fig. 8: Heat Deflection Temperature test of a specimen

Each test was performed 3 times to ensure the accuracy and reproducibility of the results.

3. RESULTS AND DISCUSSIONS

3.1 Bending test results

Fig. 9 and Fig. 10, along with Table 1 and Table 2, present the bending test results for the three specimens prepared from the crosslinked composites cured at ambient temperature (25°C) for 24 hours.

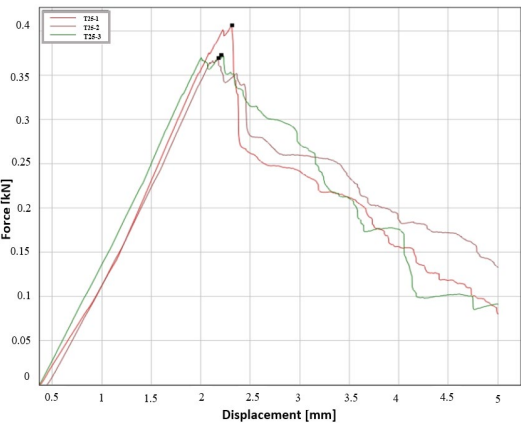


Fig. 9: Force–Displacement diagram of the sample cured at 25 °C

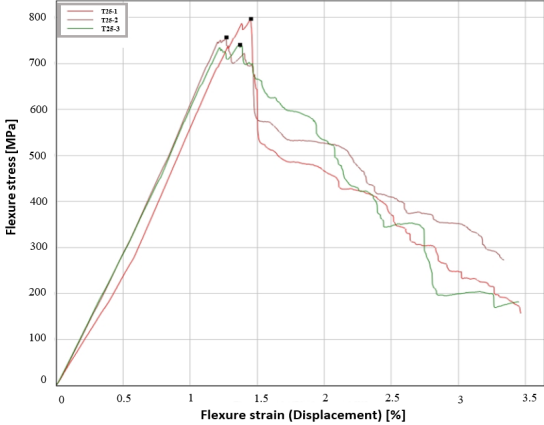


Fig. 10: Flexural Stress–Strain diagram of the sample cured at 25 °C.

Table 1: Bending Test Results for the sample cured at T = 25 °C

No.	Specimen Label	Thickness [mm]	Width [mm]	Loading Rate [mm/min]	Young’s Modulus [GPa]	Secant Modulus 0.5%–1% [GPa]
1	T25-2	1.28	14.95	2.00	67.82	64.44
2	T25-3	1.25	15.00	2.00	69.59	64.72
3	T25-4	1.27	14.98	2.00	67.06	63.22
Mean		1.27	14.98	2.00	68.15	64.13
Standard Deviation		0.02	0.03	0.00	1.30	0.80

Table 2: Flexural Test Results for the sample cured at 25 °C (cont.)

No.	Specimen Label	Flexural Stress at First Peak (10% of Force) [MPa]	First Peak (10% of Force) [N]	Energy at First Peak (10% of Force) [J]	Flexural Strain (Displacement) at First Peak (10% of Force) [%]
1	T25-2	797.03	406.72	0.39	1.45
2	T25-3	756.31	369.29	0.32	1.27
3	T25-4	740.82	372.90	0.37	1.37
Mean		764.72	382.97	0.36	1.36
Standard Deviation		29.03	20.65	0.04	0.09
Range		56.21	37.43	0.07	0.18

Fig. 11 and Fig. 12 along with Table 3 and Table 4, present the bending test results for the three specimens prepared from the hot-cured crosslinked sample at 50 °C for 12 hours.

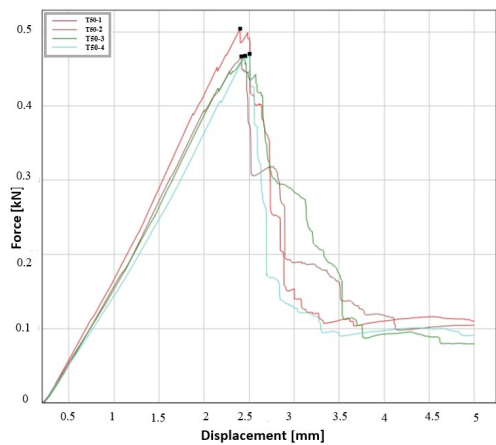


Fig. 11: Force–Displacement diagram of the sample cured at 50 °C

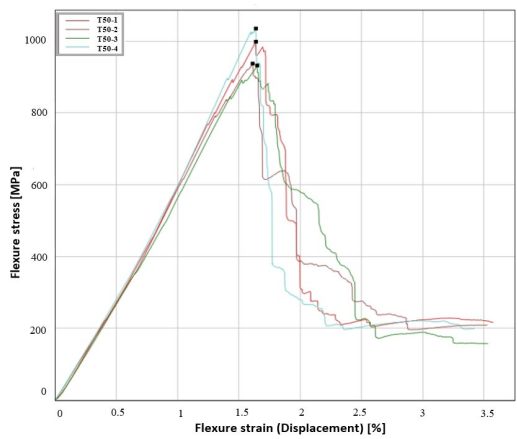


Fig. 12: Flexural Stress–Strain diagram of the sample cured at 50 °C

Table 3: Bending Test Results for the sample cured at T = 50 °C

No.	Specimen Label	Thickness [mm]	Width [mm]	Loading Rate [mm/min]	Young’s Modulus [GPa]	Secant Modulus 0.5%–1% [GPa]
1	T50-1	1.27	15.05	2.00	70.85	64.55
2	T50-2	1.26	15.05	2.00	68.41	64.07
3	T50-3	1.26	15.17	2.00	66.48	59.06
4	T50-4	1.22	14.66	2.00	75.28	63.11
Mean		1.25	14.98	2.00	70.25	62.70
Standard Deviation		0.02	0.22	0.00	3.80	2.50
Range		0.05	0.51	0.00	8.80	5.49

Table 4: Flexural Test Results for the sample cured at 50 °C (cont.)

No.	Specimen Label	Flexural Stress at First Peak (10% of Force) [MPa]	First Peak (10% of Force) [N]	Energy at First Peak (10% of Force) [J]	Flexural Strain (Deflection) at First Peak (10% of Force) [%]
1	T50-1	997.75	504.57	0.54	1.64
2	T50-2	937.36	466.60	0.51	1.61
3	T50-3	931.57	467.41	0.52	1.65
4	T50-4	1035.38	470.67	0.52	1.64
Mean		975.52	477.31	0.52	1.64
Standard Deviation		49.89	18.26	0.01	0.02
Range		103.82	37.97	0.03	0.04

Bending tests revealed pronounced differences between the two cured conditions. The room-temperature crosslinked specimens exhibited a Young’s modulus of approximately 68 GPa, a flexural stress of approximately 765 MPa, and a maximum load of approximately 383 N. In contrast, specimens crosslinked at 50 °C showed superior properties, with a Young’s modulus of approximately 70 GPa, a flexural stress of approximately 975 MPa, and a maximum load of approximately 477 N.

The slightly higher modulus (+2 GPa) indicates increased stiffness and reduced deformability under load. The substantial rise in flexural stress (+210 MPa) and maximum load (+94 N) confirms enhanced load-bearing capacity. These improvements suggest that thermal cured at 50 °C promotes a higher degree of crosslinking or improved fiber alignment, resulting in greater structural stability and overall mechanical performance.

3.2 Heat Deflection Temperature (HDT) test results

Table 5 and Fig. 13 present the results of the Heat Deflection Temperature (HDT) tests for the specimens prepared from the two crosslinked composites, cured at $T = 25\text{ }^{\circ}\text{C}$ and $T = 50\text{ }^{\circ}\text{C}$. The tests were performed in accordance with the ASTM D648 standard. For each specimen, the temperature ($^{\circ}\text{C}$) was recorded at different deflection levels (mm).

The average temperatures at which the material exhibited thermal deformation were as follows:

- T23: approximately 57.03 $^{\circ}\text{C}$
- T50: approximately 74.10 $^{\circ}\text{C}$

Table 5: HDT test results

Displacement (mm)	T25 ($^{\circ}\text{C}$)			T50 ($^{\circ}\text{C}$)		
	T25-1	T25-2	T25-3	T50-1	T50-2	T50-3
0.01	51.5	51.4	51.8	68.0	61.0	69.6
0.02	52.3	52.3	52.5	68.8	63.8	70.6
0.04	53.5	53.6	54.0	71.1	66.9	72.2
0.06	54.8	54.7	55.0	71.9	68.6	73.2
0.08	56.0	55.7	55.9	73.6	70.1	74.2
0.10	57.1	57.0	57.0	75.0	71.4	75.9
Mean	57.03			74.10		

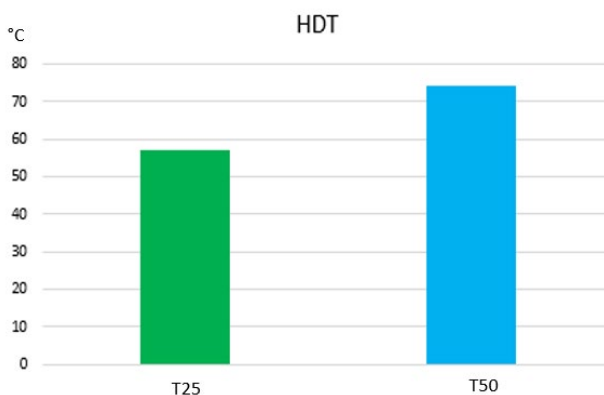


Fig. 13: Comparative HDT results at 25 $^{\circ}\text{C}$ and 50 $^{\circ}\text{C}$

The comparative bar chart in Fig. 13 clearly highlights the difference between the two specimens:

- T50 withstands temperatures approximately 17 $^{\circ}\text{C}$ higher than T25, indicating a significant improvement in thermal stability.

The T50 specimen exhibits considerably higher thermal resistance compared to T25. The increase in HDT from approximately 57 $^{\circ}\text{C}$ to approximately 74 $^{\circ}\text{C}$ demonstrates that the material crosslinked at 50 $^{\circ}\text{C}$ can be used in applications involving higher operating temperatures. The results are consistent and reproducible, confirming the reliability of the test.

The difference of approximately 17 °C between T25 and T50 is substantial and can be attributed to the distinct technological process involving thermal crosslinking.

4. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

4.1 Conclusions

The experimental results demonstrate clear differences between the two crosslinking conditions in terms of mechanical and thermal performance.

Bending tests showed that specimens crosslinked at room temperature exhibited a Young's modulus of approximately 68 GPa, a flexural stress of approximately 765 MPa, and a maximum load of approximately 383 N. In contrast, specimens crosslinked at 50 °C achieved superior values — a Young's modulus of approximately 70 GPa, a flexural stress of approximately 975 MPa, and a maximum load of approximately 477 N. The increased modulus and flexural stress indicate greater stiffness and higher load-bearing capacity, suggesting that elevated-temperature crosslinking promotes a more efficient network structure and improved fiber–matrix interaction.

HDT tests further confirmed the superior thermal performance of the hot-cured specimens. The heat deflection temperature increased from approximately 57 °C for the room-temperature crosslinked samples to approximately 74 °C for those crosslinked at 50 °C — an improvement of about 17 °C. This significant increase reflects enhanced thermal stability and a higher degree of crosslinking, allowing the material to maintain its structural integrity at elevated operating temperatures.

Overall, the results indicate that crosslinking at 50 °C provides a balanced improvement in both mechanical strength and thermal resistance, making it a more suitable process for applications requiring high stiffness and thermal stability.

4.2 Future Research Directions

Future work will focus on developing and validating recycling methods based on mechanical shredding and grinding of the composite materials. This approach aims to separate carbon fibers and epoxy matrix fragments for reuse in new composite products.

Both mechanical and complementary separation and cleaning techniques will be explored, with particular attention to optimizing fragment size and assessing its influence on the mechanical behavior of recycled composites. Additionally, recovered fibers will be integrated with new epoxy resins to produce hybrid materials with properties comparable or superior to those of the original composites.

Further research will include environmental and economic assessments of the recycling process, comparing resource consumption and carbon footprint with conventional waste disposal methods. These studies are expected to support the development of sustainable waste management solutions for aerospace composites and to advance circular economy principles in advanced materials engineering.

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