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# Selection of optimal test methods for developing process parameters in automated fiber placement technology

Aleksander Banaś[1,2*], Radosław Wojtuszewski[1,2], Michał Olejarczyk[1], Wojciech Krauze[3], Tomasz Gałaczyński[2], Tomasz Kurzynowski[1]

[1] Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] PZL Mielec, a Lockheed Martin Company, ul. Wojska Polskiego 3, 39-300 Mielec, Poland
[3] Institute of Aviation, Łukasiewicz Research Network, al. Krakowska 110/114, 02-256 Warsaw, Poland
* Corresponding author's e-mail: aleksander.banas@global.lmco.com

## ABSTRACT

This paper addresses the critical issue of selecting the optimal mechanical test method for the efficient development of process parameters in automated fiber placement (AFP) technology for manufacturing thermoplastic composite structures reinforced with unidirectional (UD) carbon fibers. Four commonly applied test methods were analyzed: Short beam strength (ASTM D2344), In-plane shear (ASTM D3518), Compression 0° and Compression 0–90° (ASTM D6641). Each method was evaluated based on four key criteria: sensitivity to AFP process parameter changes, repeatability of results, ease of specimen fabrication, and clarity of result interpretation. Test panels were manufactured from carbon fiber reinforced PEEK composite (CF/PEEK). Three distinctly varied AFP process parameter sets were employed for specimen preparation, intentionally designed to induce clear differences in laminate mechanical quality. Based on the conducted analyses, the Compression 0°–90° method was identified as optimal, demonstrating high sensitivity to AFP process parameter variations, low result variability, reliable fabrication of flat panels, and straightforward interpretation of test outcomes. Additionally, the conducted studies highlighted significant challenges associated with directly applying existing ASTM standards, originally developed for thermoset composites, to thermoplastic composites manufactured using AFP technology. Issues such as panel deformation, complex result interpretation, and atypical failure mechanisms arising from the significantly higher ductility of thermoplastic composites. These challenges emphasize the necessity for developing dedicated testing standards specifically tailored to thermoplastic composites produced by AFP technology. Selecting and indicating a specific test method enables faster and more efficient development of AFP process parameters for a wide range of thermoplastics reinforced with various fiber types. Consequently, this will significantly accelerate the process of introducing new composite materials into industrial production, supporting further advancement of automated manufacturing technologies for composite structures in aerospace and other sectors.

**Keywords:** automated fiber placement, additive manufacturing, mechanical testing, thermoplastic composites.

## INTRODUCTION

It is anticipated that the global composites market will grow at an annual rate of 10.8%, projected to reach a value of USD 181.7 billion by 2028, compared to USD 108.8 billion in 2023 [1]. Because of their beneficial characteristics, laminated composites play a key role in aircraft construction. Although initially more expensive, at the production stage than metallic structures, laminated composites allow for lighter structural design, translating into reduced fuel consumption during operation. Additionally, these materials do not corrode, significantly reducing aircraft maintenance costs. For example, the A350 XWB requires 50% fewer structural maintenance tasks, with a 12-year airframe inspection threshold compared to 8 years for the A380

[2]. Due to their unique properties, laminated composites are key group of materials used in aircraft construction.

The conservative approach in designing structures from new materials prolongs their implementation into serial production. Nevertheless, the usage of composites is systematically increasing, exemplified by Airbus and Boeing products. Airbus A300, manufactured in the 1970s, comprised 10% composite structures, whereas the Airbus A350-900, introduced in 2013, already consisted of over 53% composite structures [3, 4]. Comparatively, Boeing 747 aircraft in the 1970s had 1% composite structures, while the Boeing 787, introduced in 2009, included 50% composite structures [5]. Laminated composites are classified based on the matrix used into thermosetting and thermoplastic composites. Thermoplastic-matrix-based composites are increasingly utilized in the aviation industry, due to their excellent mechanical properties and significantly lower manufacturing costs. Recent advancements in technology and the development of automated composite tape placement systems such as automated fiber placement (AFP) and press forming (PF) technology have gradually increased the market share of thermoplastic composites, thereby reducing the usage of thermosetting composites [6].

Currently, thermoplastic composites are successfully used to manufacture even critical structures. Notable examples include Airbus A340 and A380 models, which incorporate thermoplastic composite wing leading edges, as well as the Gulfstream Aerospace G650, where thermoplastic composites are used in the vertical and horizontal stabilizers [7].

Two primary manufacturing methods for thermoplastic composites are distinguished. The first method is thermoforming in presses at elevated temperatures and pressures, known as press forming technology [8]. The second method, and the focus of this article, involves layer-by-layer deposition of unidirectional tapes using robotic systems, known as automated fiber placement [9, 10].

AFP technology is often described in the scientific literature as an additive manufacturing technology [11–14]. In AFP, pre impregnated (prepreg) fiber tapes are applied layer by layer onto a mold, aligning with the fundamental definition of additive manufacturing, which involves creating products through successive material addition. AFP technology involves robotic placement of thermoplastic unidirectional composite tapes, with appropriately selected process parameters allowing for fully consolidated parts ready for aircraft application without costly consolidation at autoclave process [15, 16]. The robotic nature of the process makes it rapid, repeatable, easy to supervise, and generates less scrap compared to conventional methods [17]. The advantages of AFP technology compared to traditional manufacturing methods are presented in Table 1 [18].

Currently, the aviation industry predominantly employs thermoplastic composites, composed of a semi-crystalline thermoplastic matrix, characterized by high processing temperatures and reinforcement fibers made of glass, aramid, or carbon [19]. Selection of fibers and matrix material is performed individually for each designed component or product group, considering load conditions, operational environment and costs.

Although thermoplastic composites constitute a distinct category of structural materials, the industry has not yet developed separate standards for them. Due to this lack of dedicated standards, thermoplastic composite quality is evaluated based on norms created for thermosetting composites. Standardized testing methods such as Short Beam Strength per ASTM D2344/D2344M [20], In-Plane Shear per ASTM D3518/D3518M [21], Compression 0° and Compression 0–90° per ASTM D6641/D6641M [22], while well-established for thermosetting composites, may not always be suitable for thermoplastic composites, especially when using AFP technology.

Modern manufacturing technologies like AFP have precisely controllable process parameters, where even slight deviations beyond the processing window, significantly affect the quality and strength of produced parts [23]. The process of parameter selection and optimization for new materials is time-consuming, and the evaluation of outcomes is often ambiguous. Therefore, identifying an optimal method that is highly responsive to changes in process parameters is crucial for streamlining parameter selection.

Composite materials produced via AFP exhibit strong anisotropy and unique properties compared to other composites. There is a pronounced need to select an optimal testing method that limits the number of required tests, featuring high sensitivity to changes in manufacturing parameters while maintaining low costs for sample manufacturing and testing. Such a method would be applicable during the search

**Table 1.** Comparison of AFP with traditional composite manufacturing methods

| Specification | ATL method | AFP method | Conventional methods |
|---|---|---|---|
| Material scrap | Low | Low | High |
| Labor costs | Low | Low | High |
| Repeatability | High | High | Low |
| Accuracy | High | High | Low |
| Productivity | High | High | Low |
| Cost effective | Yes | Yes | No |
| Material types | Wide tapes | Narrow tows | Wide tapes |
| Lay-up speed | Very high | Relatively high | Very high |
| Component geometry | Large components | Curved and contoured surface | Large components |

for optimal process parameters, for new AFP-produced materials comprising various reinforcements and thermoplastic matrices, as well as for assessing product quality and ensuring the established process correctness.

Several recent studies have investigated the mechanical behavior of thermoplastic composites manufactured using AFP technology. The influence of process parameters on laminate microstructure and strength was demonstrated in [24]. The interlaminar shear strength (ILSS) of carbon fiber reinforced PEEK composite (CF/PEEK) composites has been shown to be sensitive to even small deviations in AFP process settings [25]. Additionally, Mode I fracture studies revealed that ductile matrix behavior, combined with AFP consolidation pressure, may lead to non-standard failure mechanisms [26]. These findings underscore the need to update current testing standards to better reflect the mechanical response of AFP-manufactured thermoplastic composites.

Despite the widespread use of the described mechanical test methods, a review of the relevant literature has not identified any comprehensive attempts to evaluate their effectiveness specifically in the context of thermoplastic composites manufactured using AFP technology. This further emphasizes the novel character of the present study.

This article addresses manufacturing thermoplastic composites from unidirectional tapes, using a robotic AFP system. The studies presented herein aim to select optimal test methods for developing process parameters in AFP technology. All conducted tests were performed in accordance with ASTM standards to ensure result standardization.

Four testing methods were chosen to evaluate the quality of thermoplastic composites produced by AFP: Short beam strength, In-plane shear, Compression 0°, and Compression 0–90°. These standardized, cost-effective methods evaluate a broad spectrum of mechanical properties critical to aircraft structures, enabling result comparisons with other materials and technologies. Each method was assessed according to criteria proposed in this article.

## MATERIALS AND SAMPLE MANUFACTURING

### Material

All panels used for specimen fabrication were manufactured using Suprem™ T thermoplastic composite, composed of a PEEK-150 matrix reinforced with unidirectional, high-tensile-strength AS4 carbon fibers, processed through AFP technology. The material was supplied in a cut to size form, as slit tape with a nominal width of 6.35 mm (tolerance +0.00/−0.15 mm) and thickness of 0.13 mm. The nominal fiber volume content is 59%, corresponding to a resin content of 35% by weight, and the fiber areal weight is 134 g/m$^2$.

### Automated fiber placement process and system configuration

The AFP process involves the robotic deposition of unidirectional prepreg tapes along predefined paths and geometry [27, 28]. The process is additive, with material deposited layer by layer until the desired final geometry and specified laminate thickness with desired lay-up are achieved. Each individual layer can be oriented differently, enabling the design of optimized structural components capable of effectively bearing complex load conditions [29, 30]. A schematic illustration of the AFP process is shown in Figure 1. The actual AFP equipment used to manufacture the test specimens is depicted in Figure 2.

All composite panels used in this study were fabricated using the Coriolis composites C1 AFP system (Quéven, France). The main components of the Coriolis C1 system include a robotic arm, mounted on linear rails, equipped with a deposition head, capable of laying up to eight tapes. Each of the tape has width of 6.35 mm (Figure 3). The compaction force is applied via a pressure roller, adjustable in the range of 1–1200 N. The compaction roller, specifically designed for thermoplastic processing, consists of an internally cooled foam core, with a Shore A hardness of 50, covered by a plastic outer shell. Material is delivered to the deposition head from a climate-controlled creel system that accommodates eight individual spools (Figure 4).

The energy in process is supplied by a 3 kW diode laser equipped with an optical unit that generates a rectangular beam measuring 8 × 52 mm. The laminate surface temperature during the tape placement process is monitored in real time using an Optris PI400 infrared (IR) camera. Robot motion and process control are managed via a dedicated Human-Machine Interface (HMI) located in the operator's control room. The layup programming is performed using CADFIBER software, which also controls key processing parameters such as laser power, layup speed, and compaction force.

The AFP process is carried out on heated tooling, where tool surface temperature is recognized as one of the critical process parameter [31, 32]. Throughout this paper, the term "process parameters" refers to specific AFP machine settings, such as layup speed, compaction force, laser power, and tool temperature. The term "parameter sets" denotes predefined combinations of these settings (Set 1, Set 2, Set 3) used for experimental comparison. For clarity and consistency, the term "process parameters" is used throughout to describe these input variables.

## Panels manufacturing and specimens preparation

Due to the nature of AFP technology, direct fabrication of test specimens is not feasible. Therefore, for each type of mechanical test, 0.5 × 0.5 m panels were initially produced, with layups corresponding to ASTM standards. Individual test specimens were then machined from these panels.

The panels were fabricated in three process parameter variants, referred to as Set 1, Set 2, and Set 3. Each parameter set was intentionally designed to maximize differences in mechanical test outcomes by varying three key AFP process parameters: layup speed, compaction force, and process temperature. Each of these parameters were adjusted across three levels, while tool temperature was kept constant throughout all experiments. The parameter ranges were selected based on the authors' previous experimental research and optimization studies. These parameter sets were designated as follows: Set 1, Set 2, and Set 3.

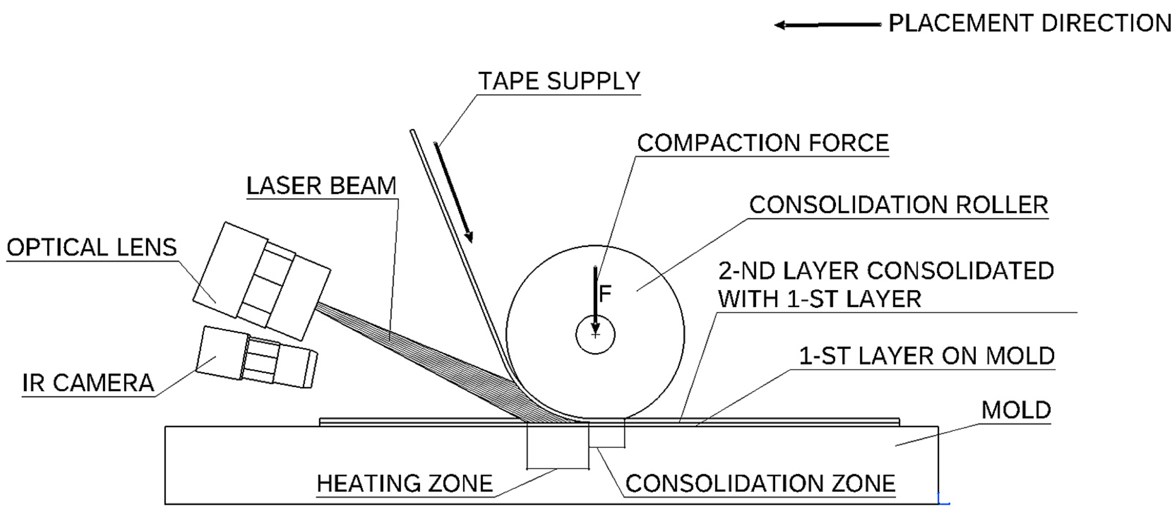


**Figure 1.** Automated fibre placement idea

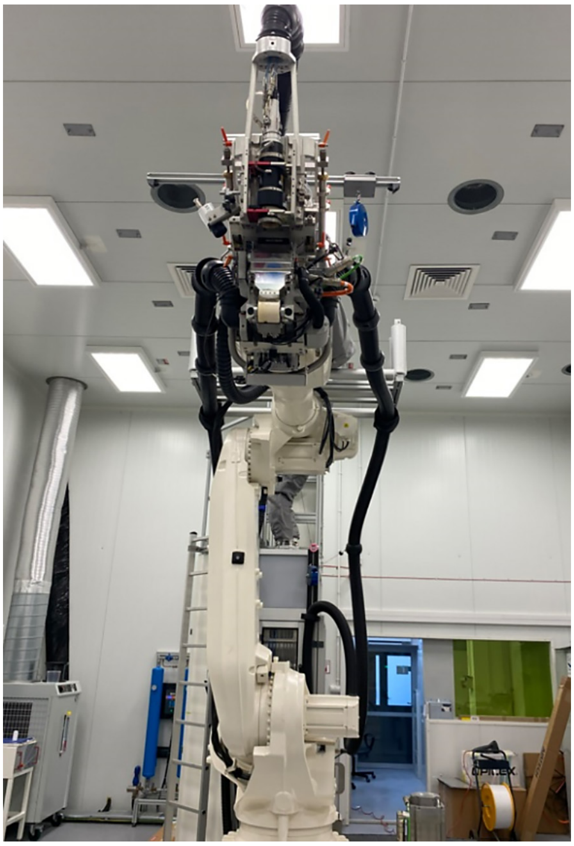

**Figure 2.** Automated fiber placement cell

- Set 1 parameters were optimized to yield the highest quality panels.
- Set 2 parameters were selected to produce intermediate quality panels.
- Set 3 parameters were deliberately set to produce panels of the lowest expected quality.

For each test method, including Short beam strength, In-plane shear, Compression at 0°, and Compression at 0–90°, two panels were manufactured per parameter set. The specimens were then tested in accordance with the relevant ASTM standards and the results were compared and analyzed.

The AFP process parameter sets used for fabricating test panels are summarized in Table 2.

Using each of the parameter sets (Set 1, Set 2, and Set 3), two panels were manufactured per test method, resulting in a total of six panels for each method. Panels for the Short beam strength test were fabricated using 16 plies with a $[0_{16}]$ layup, resulting in a total laminate thickness of 1.56 mm. Specimens were machined from these panels to final dimensions of 25.4 ± 2.5 mm in length and 6.35 ± 2.5 mm in width.

Panels for the In-plane shear test were fabricated using 8 plies with a $[45/\text{-}45]_{2s}$ layup, resulting in a laminate thickness of 1.04 mm. Specimens were subsequently cut to dimensions of 250 ± 2 mm in length and 25 ± 0.5 mm in width.

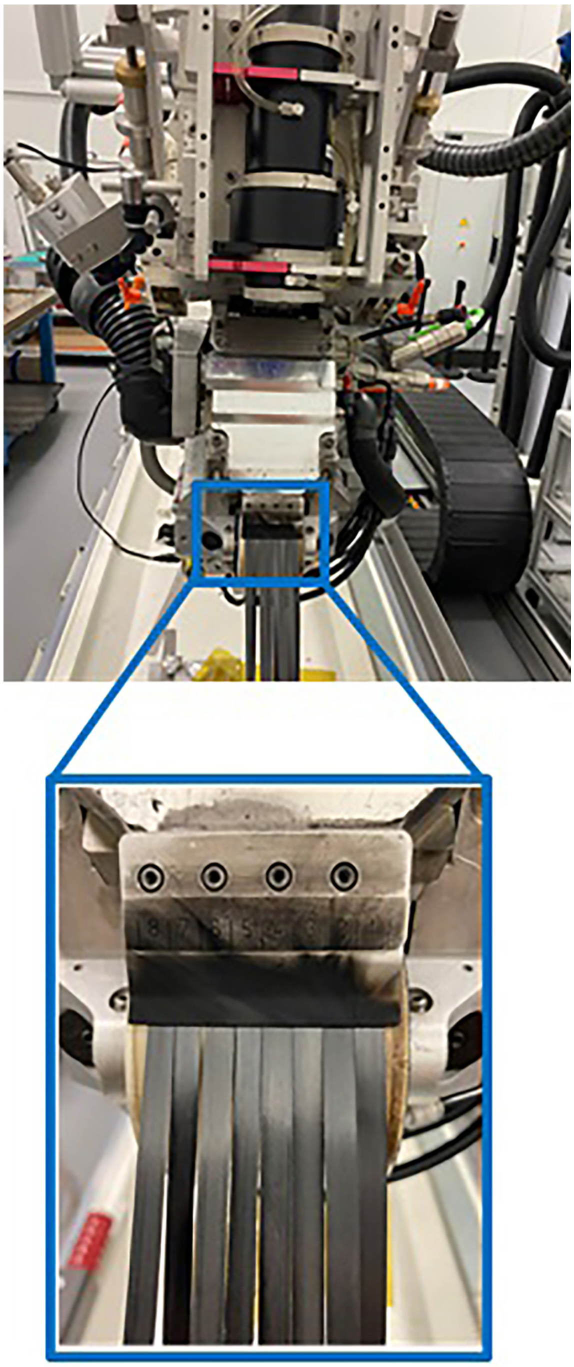

**Figure 3.** AFP head with eight visible tapes

Panels for the Compression 0° and Compression 0–90° tests were fabricated using 16 plies with stacking sequences of $[0_{16}]$ and $[0\text{–}90]_{4s}$, respectively, both resulting in a total thickness of 2.08 mm. For both configurations, specimens were cut to dimensions of 140 ± 0.5 mm in length and 12.7 ± 0.125 mm in width. Additionally,


**Figure 4.** Material container with tape

symmetrical 63.5 mm long grip tabs were bonded to the ends of each specimen, leaving a 12.7 mm gauge section.

From each panel, six specimens were extracted, yielding a total of 36 specimens per test method. This resulted in a cumulative total of 516 specimens. A summary of the number of panels, specimens, and corresponding process parameters used for each test is provided in Table 3.

## EXPERIMENTAL PROGRAM

The objective of this study was to determine the optimal mechanical test method for the efficient development of process parameters in AFP technology using thermoplastic composites. The experimental program was structured to provide a clear and objective comparison of four standardized mechanical test methods for AFP manufactured laminates: Short beam strength (ASTM D2344), In-plane shear (ASTM D3518), Compression 0° (ASTM D6641), and Compression 0–90° (ASTM D6641). For each test method, composite panels were fabricated using three distinct sets of AFP process parameters, designated as Set 1, Set 2, and Set 3 corresponding respectively to the expected laminate quality at high, intermediate, and low level. This strategy was implemented to systematically evaluate how process parameter variations influence the mechanical properties of the laminates. Panel fabrication was adhered to the stacking sequences specified by the relevant ASTM standards. Specimens were subsequently prepared from each panel by precision cutting and finishing, ensuring conformity with the requirements of each of the test method. Mechanical testing were conducted at room temperature in accordance with the referenced ASTM standards. Results were collected for all specimens produced with each set of process parameters, allowing for a robust comparison across different testing approaches and process conditions.

Each test method was rigorously assessed based on four key evaluation criteria:

1. Method sensitivity – the ability of the method to distinguish between panels fabricated with different process parameters, quantified by the knock down factor (KDF).

Method sensitivity was quantified using an indicator termed KDF. The KDF, expressed as a percentage, represents the arithmetic average of percentage drops in performance between specimens produced using parameter sets Set 1 and Set 2 as well as Set 1 and Set 3.

$$KDF = \left( \frac{\left( \frac{(\bar{X}_{Set\,1} - \bar{X}_{Set\,2})}{|\bar{X}_{Set\,1}|} + \frac{(\bar{X}_{Set\,1} - \bar{X}_{Set\,3})}{|\bar{X}_{Set\,1}|} \right)}{2} \right) \cdot 100\% \quad (1)$$

**Table 2.** AFP process parameter sets used for test panel manufacturing

| Set no. | Process temperature [°C] | Layup speed [m/s] | Compaction force [N] | Tool temperature [°C] |
|---|---|---|---|---|
| Set 1 | 410 | 0,050 | 1200 | 250 |
| Set 2 | 410 | 0,20 | 1200 | 250 |
| Set 3 | 360 | 0,40 | 500 | 250 |

**Table 3.** Summary of the number of panels, specimens, and corresponding process parameter sets used for each test

| Test type | Test method | Stacking sequence | Process parameters | Panels quantity | Total coupons quantity |
|---|---|---|---|---|---|
| Short beam strength | ASTM D2344 | $[0_{16}]$ | Set 1 | 2 | 12 |
| | | | Set 2 | 2 | 12 |
| | | | Set 3 | 2 | 12 |
| In-plane shear | ASTM D3518 | $[45/-45]_{2s}$ | Set 1 | 2 | 12 |
| | | | Set 2 | 2 | 12 |
| | | | Set 3 | 2 | 12 |
| Compression 0° | ASTM D6641 | $[0_{16}]$ | Set 1 | 2 | 12 |
| | | | Set 2 | 2 | 12 |
| | | | Set 3 | 2 | 12 |
| Compression 0–90° | ASTM D6641 | $[0/90]4_{s}$ | Set 1 | 2 | 12 |
| | | | Set 2 | 2 | 12 |
| | | | Set 3 | 2 | 12 |
| | | | Total | 24 | 516 |

where: KDF – Knock down factor; Set 1, Set 2, Set 3 – the respective parameter stes used to manufacture test specimens

The scoring rules for method sensitivity were defined as: KDF ≤ 40% – low sensitivity, score "0", KDF > 40% – high sensitivity, score "1"

2. Result variation – repeatability and consistency of results, measured by the coefficient of variation (CV).

Result variation was quantified using the CV, defined as the average coefficient of variation across the three parameter sets:

$$CV = \left( \frac{\frac{S_{Set\,1}}{\bar{X}_{Set\,1}} + \frac{S_{Set\,2}}{\bar{X}_{Set\,2}} + \frac{S_{Set\,3}}{\bar{X}_{Set\,3}}}{3} \right) \cdot 100\% \quad (2)$$

where: $CV$ – coefficient of variation;
$S_{set\ 1,\ set\ 2,\ set\ 3}$ – standard deviation of results obtained using each parameter set;
$X_{set\ 1,\ set\ 2,\ set\ 3}$ – aritmetic mean of test results for each parameter set;

The scoring rules for result variation were defined as:
- CV ≥ 5% – high variability, score "0"
- CV < 5% – low variability, score "1"

3. Quality and manufacturability of panel and specimen fabrication – determined by the absence or presence of technological difficulties such as panel deformation, specimen distortion, or excessive labour requirements.

Quality and manufacturability of fabrication were assessed based on the absence or presence of technological difficulties encountered during manufacturing and sample preparation.
The scoring rules were defined as:
- Score "1": No significant issues during panel and specimen manufacturing - stable process, efficient, and with specimens meeting ASTM dimensional tolerances.
- Score "0": Occurrence of difficulties, such as panel deformation, specimen distortion, excessive labor intensity, machining difficulties.

4. Interpretation of the results – clarity of outcome analysis and compliance with the relevant ASTM standard, including failure mechanism.

Ease of result interpretation was assessed based on the presence or absence of difficulties in evaluating the test outcomes in accordance with the applicable ASTM standard. The evaluation considered whether the failure mechanism observed during testing was consistent with the expected mode described in the standard, and whether the results could be interpreted clearly and unambiguously.
The scoring rules were defined as:
- Score "1": Full compliance with the ASTM standard, a correct failure mechanism and no difficulties encountered in interpretation of test results.
- Score "0": Non-compliance with the standard or difficulty in interpretation, such as incorrect failure mode or unexpected specimen behavior.

- Each criterion was scored on a binary (0–1) scale, with 1 indicating the criterion was met and 0 indicating it was not. All criteria were assigned equal weight. The cumulative score for each test method was calculated, by summing the scores across all criteria. The method with the highest total score was considered optimal for process parameter development in AFP-manufactured thermoplastic composites. This approach ensures a balanced assessment, taking into account not only sensitivity and reproducibility, but also practical aspects of specimen preparation and result interpretation. The structure and workflow of the experimental program are graphically illustrated on the Figure 5. This systematic approach ensures the reliable identification of the optimal test method to support the development and quality assurance of thermoplastic composite laminates manufactured by AFP technology.

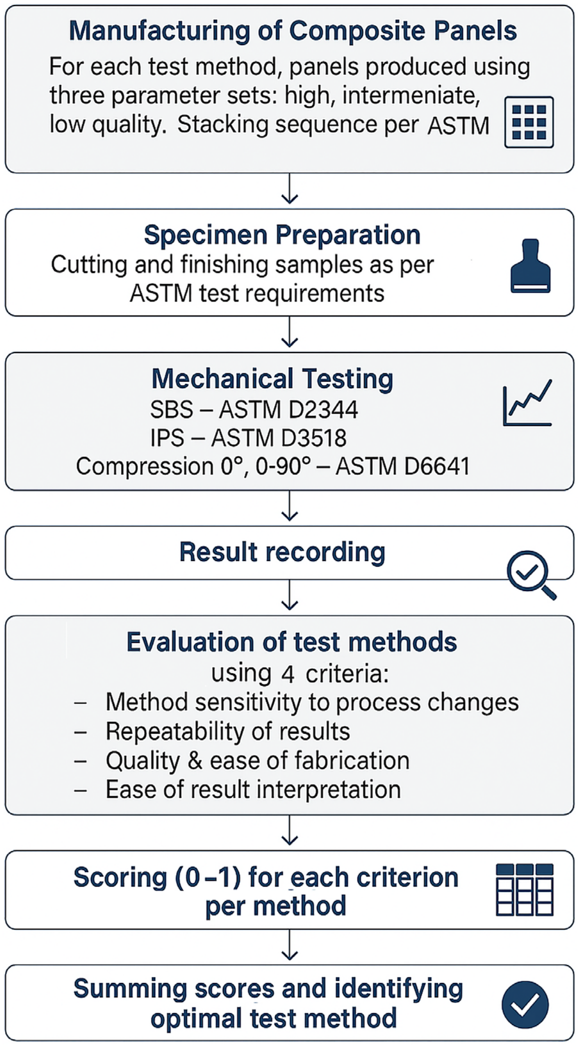


**Figure 5.** Flowchart of the composite panel testing procedure: production with three parameter sets, specimen preparation, mechanical testing according to ASTM standards, and evaluation with scoring of test methods

## TESTS

### Short beam strength test

Short beam strength tests were conducted according to ASTM D2344 at room temperature. Three AFP parameter sets (Set 1, Set 2, and Set 3) were employed to manufacture the test panels. Panels were fabricated using a stacking sequence of $[0_{16}]$ from unidirectional tapes. However, this particular laminate configuration induced an unfavorable residual stress distribution, leading to panel deformation. The deformation issue is illustrated in Figure 6 and this problem persisted across all tested parameter sets.

The highest average interlaminar shear strength (ILSS) value obtained was 100.3 MPa for parameter Set 1, while the lowest was 52.9 MPa for parameter Set 3. Standard deviations obtained from Short beam strength tests were relatively small, ranging from 0.8 to 1.4, resulting in consistent CV values between 1.4% and 1.5% across all tests. The average SBS test results, along with standard deviations and CV values, are presented at Figure 7.

The test results differed by 15% between Set1 and Set 2, and by 43% between Set 1 and Set 3, resulting in a KDF of approximately 29%. Such differences indicate moderate sensitivity of the SBS test method to variations in AFP process parameters. However, difficulties arose during the interpretation of the test results. For thermoset composites, the primary design and expected failure mode during Short beam strength testing is interlaminar shear-induced delamination (Figure 8a). Such failure mechanism was anticipated for thermoplastic composites. Nevertheless, due to the significantly higher ductility of thermoplastic composites compared to thermoset materials, the actual observed failure mode for all specimens was plastic deformation (Figure 8b). This deformation prevents the accurate quantitative determination of ILSS and allows only for establishing a threshold below which no interlaminar shear-induced damage occurs.

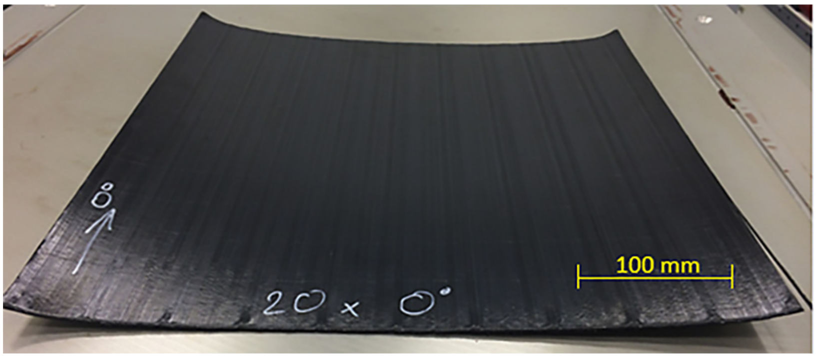


**Figure 6.** Unidirectional panel deformation

## In-plane shear test

In-plane shear tests were conducted according to ASTM D3518 at room temperature, using the same three AFP parameter sets (Set 1, Set 2, and Set 3). Panels were manufactured with a stacking sequence of $[45/-45]_{2s}$ from unidirectional tapes. This stacking sequence provided a favorable residual stress distribution, resulting in flat panels. Test specimens were cut from these panels and subjected to mechanical testing.

The best IPS test results were achieved with parameter Set 1, yielding a maximum average shear stress of 164.8 MPa. The lowest average shear stress was 123.8 MPa, obtained with parameter Set 3. Standard deviations for IPS tests ranged from 1.2 to 3.5, resulting in CV values between 0.9% and 2.8%. Average values of in-plane shear test results, along with standard deviations and coefficients of variation, are presented at Figure 9.

Observed discrepancies in test outcomes amounted to a 22% difference between parameter Set 1 and Set 2, and 25% between Set 1 and Set 3, averaging to approximately 23%. Such relatively small differences indicate a low sensitivity of the IPS method to changes in AFP process parameters.

Interpretation of the test results proved challenging. According to ASTM D3518, the maximum load is typically defined at 5% strain. However, specimens fabricated from thermoplastic composites exhibited strain levels of up to 20% at maximum load, together with substantial deformation. The ASTM D3518 standard was originally developed for thermoset composites, which are significantly less ductile. The discrepancy between the strain occurred int the test specified by

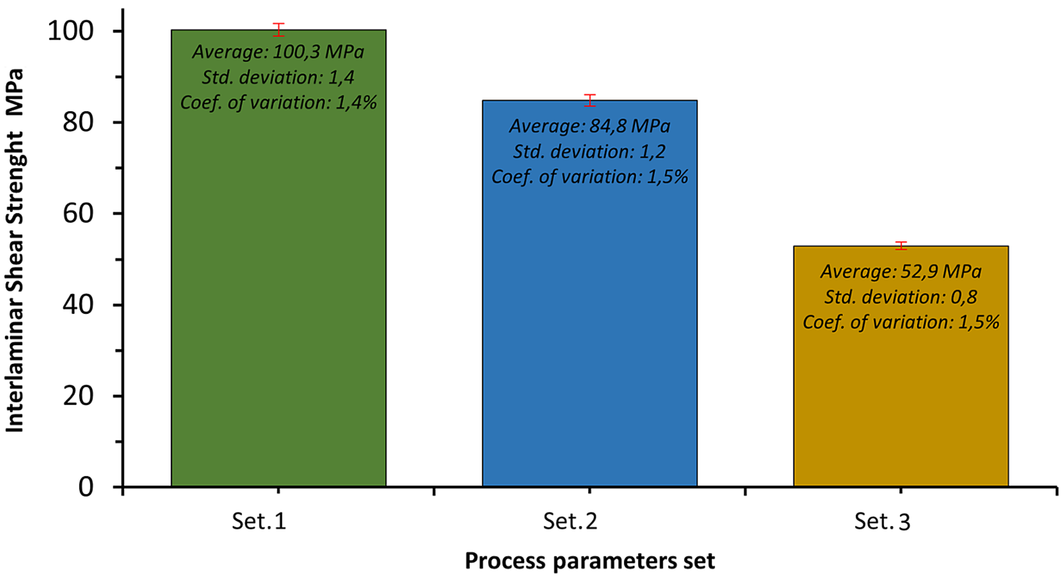


**Figure 7.** Average short beam strength test results with various process parameters – mean values and std. deviation

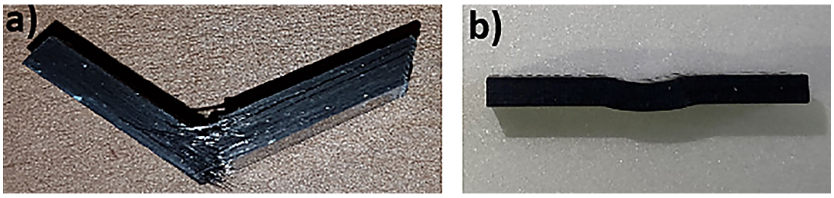


**Figure 8.** a) Thermoset composite – interlaminar shear failure, b) Thermoplastic composite – plastic deformation

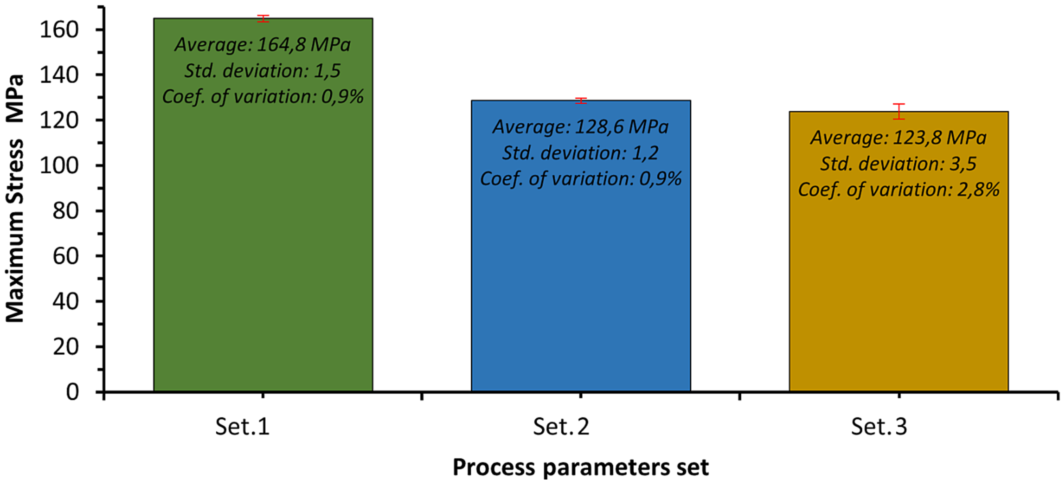


**Figure 9.** Average in-plane shear test results with various process parameters – mean values and std. deviation

**Figure 10.** Break at 40 mm elongation and 8 mm necking

the standard and the actual observed strain, arises from the significantly greater ductility of thermoplastic composites compared to thermosets.

This interpretative issue is illustrated in Figure 10 and corresponding stress-strain curves are shown in Figure 11.

## Compression 0° test

Compression 0° tests were conducted according to ASTM D6641 at room temperature. Panels were fabricated using the same three parameter sets (Set 1, Set 2, and Set 3) with a stacking sequence of $[0_{16}]$ from unidirectional tapes. Similar to the Short beam strength test configuration, this laminate sequence resulted in an unfavorable residual stress distribution causing panel deformation. This deformation occurred consistently across all parameter sets. Specimens were cut from the manufactured panels, and symmetrical patches (illustrated in Figure 12) were bonded outside the gauge section, to reinforce and stabilize the specimens. The requirement for bonded patches significantly increased the labor intensity of specimen preparation, compared to other test methods.

The highest average compressive strength was 1419.5 MPa, achieved with parameter Set 1, while the lowest was 647.6 MPa, corresponding to parameter Set 3. Standard deviations for Compression 0° tests were substantial, ranging from 64.7 to 82.8, with CV spanning 5.8–10%.

Average compressive strength values, along with standard deviations and CV, are presented on the chart at Figure 13.

The sensitivity of the test, quantified as differences between parameter sets, amounted to 22% between Set 1 and Set 2, and 54% between Set 1

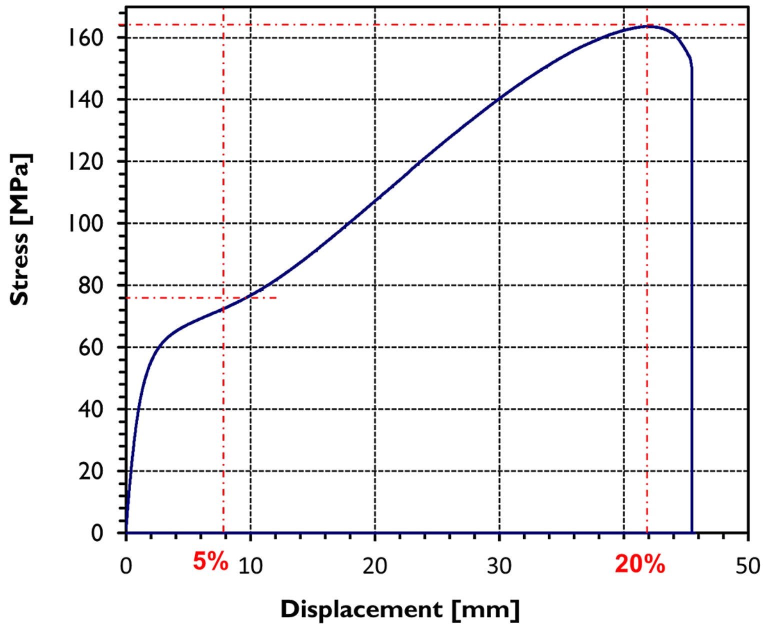


**Figure 11.** Stress at 5% and 20% strain

and Set 3, resulting in a KDF of approximately 38%. Such substantial differences clearly demonstrate high sensitivity of the Compression 0° method to variations in AFP process parameters.

### Compression 0–90° test

Compression 0–90° tests were performed according to ASTM D6641 at room temperature. Panels were manufactured with the three previously defined parameter sets (Set 1, Set 2, and Set 3) using a stacking sequence of $[0–90]_{4s}$ from unidirectional tapes. This particular stacking sequence resulted in a favorable residual stress distribution, yielding flat panels. Specimens cut from these panels were then subjected to mechanical testing. The highest average compressive strength recorded was 647.6 MPa, corresponding to parameter Set 1, whereas the lowest average strength was 264.8 MPa, achieved with parameter Set 3. Standard deviations for the Compression 0–90° tests ranged between 5.6 and 10.1, resulting in low CV from 1.6% to 2.1%. Average test results, standard deviations, and CV are summarized graphically in Figure 14.

**Figure 12.** Compression 0° samples with tabs

Differences in test results were significant, with 32% between Set 1 and Set 2, and 59% between Set 1 and Set 3, resulting in a KDF of 46%. Such pronounced differences indicate very high sensitivity of the Compression 0–90° method to changes in AFP process parameters.

## RESULTS

A complete summary of the test results for each test method, evaluated according to the defined criteria, is presented in Table 4.

All criteria were evaluated using a binary (0–1) scale, with assigned equal weight. The selection of the optimal method was determined by the total number of scored points across all criteria. The highest score 4 points was obtained by the Compression 0–90° method. The second best result was 2 points for the in-plane shear

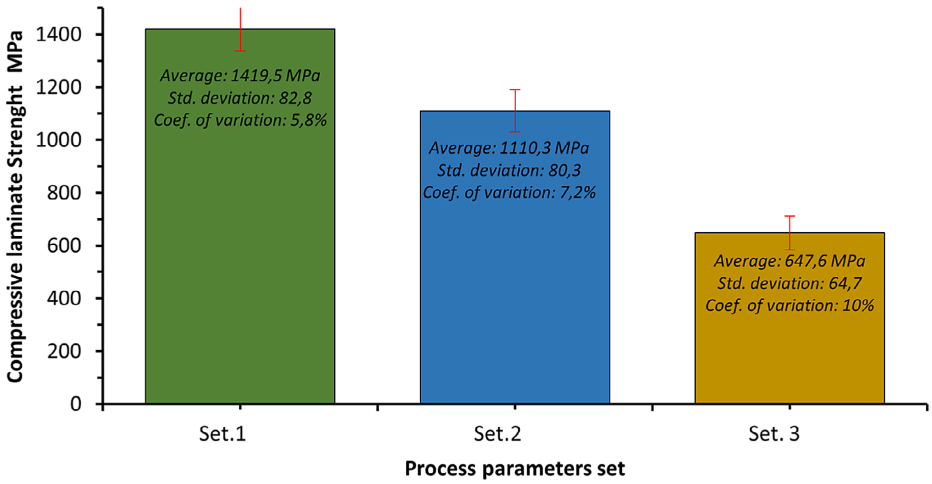


**Figure 13.** Average compression 0° test results with various process parameters – mean values and std. deviation

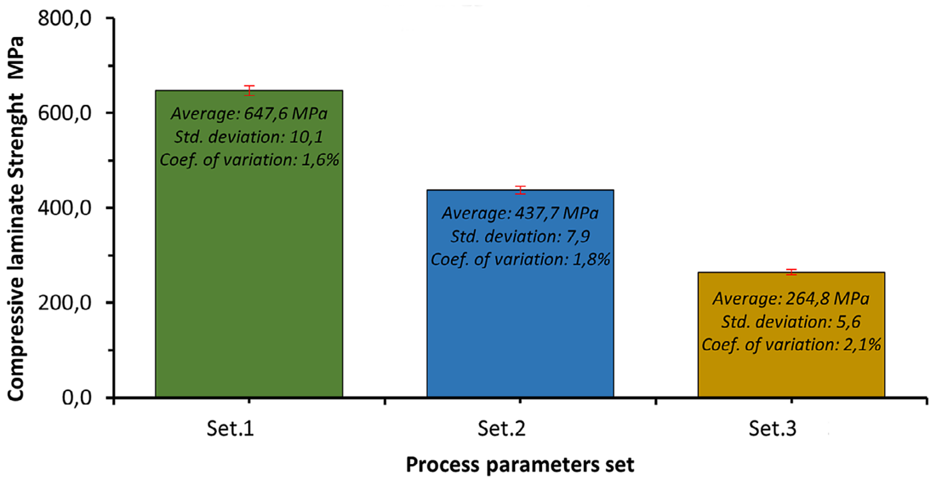


**Figure 14.** Average compression 0–90° test results with various process parameters – mean values and std. deviation

**Table 4.** Test results by evaluation criterion

| Test type | Short beam strength test | In-plane shear test | Compression 0° test | Compression 0–90° test |
|---|---|---|---|---|
| Method sensitivity (KDF) | 29% | 23% | 38% | 46% |
| Result variation (CV) | 1.46% | 1.55% | 7.67% | 1.82% |
| Panel and specimen producibility | Poor | Good | Good | Poor |
| Interpretation of the results | Difficult | Difficult | Easy | Easy |

**Table 5.** Test method score card

| Evaluation criterion | Short beam strength test | In-plane shear test | Compression 0° test | Compression 0–90° test |
|---|---|---|---|---|
| Method sensitivity | 0 | 0 | 0 | 1 |
| Result variation | 1 | 1 | 0 | 1 |
| Panel and specimen producibility | 0 | 1 | 0 | 1 |
| Ease of result interpretation | 0 | 0 | 1 | 1 |
| Summary | 1 | 2 | 1 | 4 |

test method. The remaining methods received 1 point each. Such a significant difference in the final scores confirms the validity of the multicriteria analysis approach, for identifying the optimal mechanical testing methodology for thermoplastic composite structures manufactured using AFP technology. The detailed scoring card for all test methods is presented in Table 5.

## CONCLUSIONS

In this paper, a multi-criteria evaluation of four popular mechanical test methods for composite materials was performed: Short beam shear, in-plane shear, compression 0°, and compression 0–90°. Each test was assessed according to four key criteria: sensitivity to changes in process parameters, variability of results, specimen manufacturability, and ease of result interpretation. Based on the conducted experiments, authors observe the following conclusion:

- The short beam shear test demonstrated high sensitivity and low result variability; however, the producibility of unidirectional panels proved problematic due to significant deformation and the unexpected plastic deformation failure mode resulting from the high ductility of thermoplastic composites.
- The in-plane shear test showed relatively low sensitivity to parameter variations and good producibility. Nevertheless, difficulties were encountered in interpreting test results due to the significantly higher strain levels exhibited by thermoplastic composites compared to thermoset composites for which the ASTM standard was originally developed.
- The compression 0° test exhibited low sensitivity, substantial result variability, and problematic producibility associated with panel deformation. Additionally, the requirement for bonded tabs significantly increased the labor intensity of specimen preparation.

The compression 0–90° test method demonstrated the highest overall sensitivity to variations in AFP process parameters. This superior sensitivity was primarily attributed to the balanced laminate stacking sequence ($[0–90]_{4s}$), favorable stress distribution preventing unwanted deformations, and straightforward interpretation of results, all contributing to clear differentiation between parameter sets.

The primary conclusion from this investigation is the identification of the Compression 0–90° test method as the most suitable for effectively evaluating thermoplastic composite structures fabricated by AFP. The balanced stacking sequence of the $[0–90]_{4s}$ laminate, providing an optimal combination of mechanical behavior under compressive loading conditions, was decisive in achieving a high sensitivity to variations in process parameters. Furthermore, the specimen geometry and its deformation characteristics under load facilitated clear differentiation of mechanical properties linked to specific AFP process parameters. An important limitation identified during the study was the exclusive use of ASTM standards, originally developed for thermoset composites. The absence of evaluations based on European norms represents a gap in the current research and should be addressed in subsequent studies. Additionally, the significantly higher ductility of thermoplastic composites compared to thermosets resulted in challenges related to test interpretation and specimen behavior, highlighting a critical need for developing dedicated standards specifically tailored to AFP-manufactured thermoplastic composites.

The Compression 0–90° test method is recommended for future AFP process parameter optimization studies, enabling faster and more reliable parameter development.

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