CANCOM2024 – CANADIAN INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

INTERLAMINAR SHEAR STRENGTH OF CARBON/PEEK THERMOPLASTIC COMPOSITE LAMINATE IN-SITU CONSOLIDATED BY AUTOMATED FIBER PLACEMENT

Pourahmadi, E[1, 2, *], Shadmehri, F[1, 2], and Ganesan, R[1, 2]
[1] Concordia Center for Composites (CONCOM), Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, Montreal, Quebec, Canada
[2] Research Center for High-Performance Polymer and Composite Systems (CREPEC), Montreal, Quebec, Canada
* Corresponding author (emad.pourahmadi@mail.concordia.ca)

Keywords: *Carbon/PEEK thermoplastic composite; Short-Beam Shear (SBS) test; Automated Fiber Placement (AFP).*

ABSTRACT

Automated manufacturing methods, such as Automated Fiber Placement (AFP), provide cost and time-saving advantages over traditional manufacturing techniques, such as autoclave curing. However, achieving a comparable level of consolidation as in the autoclave consolidation proves to be challenging under certain constraints originating from the AFP process. The present research aims to evaluate the Interlaminar Shear Strength (ILSS) of Carbon/PEEK thermoplastic composite laminate manufactured using the AFP in-situ consolidation process based on the Short-Beam Shear (SBS) test. To this end, a thermoplastic laminate was fabricated using AFP in-situ consolidation technique. Baseline laminate was produced by re-consolidating another AFP-manufactured laminate inside the autoclave. The results revealed that the AFP in-situ consolidation process may cause the ILSS of Carbon/PEEK thermoplastic composite laminate to decrease by about 37% compared to that of autoclave-reconsolidated laminate. The Finite Element (FE) modeling of the SBS test sample is also carried out. The mechanical response of the laminates observed in the SBS test was distinguished in the simulation using the cohesive-element approach, wherein appropriate interface strength properties were numerically determined based on SBS test results.

1 INTRODUCTION

Owing to the superior properties of thermoplastic composite laminates, including high toughness and recyclability, their applications are ever-increasing, particularly in the aerospace industry, despite manufacturing challenges. In-situ manufacturing of thermoplastic composites using the AFP process offers significant time and cost benefits over conventional manufacturing methods, such as autoclave curing. However, due to certain limitations arising from the short AFP processing time, such as high cooling rate, incomplete healing process, and intimate contact, it is challenging to achieve comparable bonding quality to that of the autoclave technique [1].

Typically, the Short-Beam Shear (SBS) test serves as a prevalent quality control measure to explore the impact of several factors, including consolidation techniques, on the Interlaminar Shear Strength (ILSS). Numerous investigations [2–5] have focused on identifying optimal Hot Gas Torch (HGT)-assisted AFP processing parameters for manufacturing Carbon/PEEK thermoplastic composite material, relying on ILSS values. These studies carefully examined four key processing variables: process temperature, torch positioning, deposition rate, and compaction force, meticulously determining ideal conditions through extensive experimental trials. Findings from these studies indicated that while the ILSS value of in-situ consolidated Carbon/PEEK thermoplastic composite samples ranges between 55 to 60 MPa, autoclave re-consolidation can elevate it to nearly 90 MPa. Moreover, delamination, primarily influenced by matrix characteristics, emerges as the dominant failure mode in the short-beam shear test. To simulate the layer separation phenomenon in composite laminate in finite element modeling, researchers frequently employ the cohesive zone model, as documented in the literature [6,7].

The present research work aims to introduce a novel methodology to distinguish between the mechanical performance of in-situ-consolidated and autoclave-reconsolidated thermoplastic composite specimens in finite element modeling. This is achieved by determining suitable interface strength properties using the results of short-beam shear experiments. To this end, a Carbon/PEEK thermoplastic composite laminate was produced through the AFP in-situ consolidation technique. Subsequently, half of the AFP-manufactured laminate underwent re-consolidation inside an autoclave to serve as the baseline laminate. The Short-Beam Shear (SBS) test, following the ASTM D2344 standard [8], was used to assess the quality of specimens resulting from each manufacturing process. Furthermore, finite element analysis was conducted to predict the initiation and evolution of composite damage, integrating a VUMAT subroutine along with the cohesive-element approach within the ABAQUS software for intralaminar and interlaminar (delamination) damage simulation, which is the primary failure mode observed during the SBS test. A comparative analysis between the numerical and experimental results was performed to assess the effectiveness of the proposed FE model in estimating the ILSS values. These interfacial strength properties can be utilized as input in the finite element analyses of in-situ-consolidated Carbon/PEEK composite laminates in further investigations on their response and behavior.

2 MANUFACTURING PROCESS

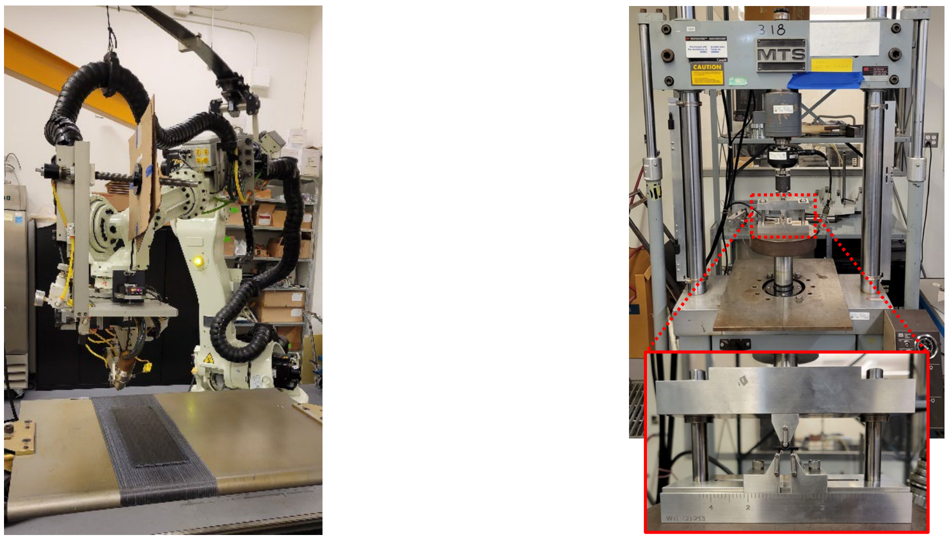
The Concordia Centre for Composites (CONCOM) offers researchers access to an HGT-assisted AFP machine featuring a 6-axis Kawasaki articulated robot arm with a 125 kg payload, equipped with a thermoplastic head provided by Trelleborg. A unidirectional Carbon/PEEK tape supplied by the Solvay Group, measuring 6.35 mm (0.25 in) in width and 0.140 mm (0.0055 in) in thickness, was utilized in the present research work to fabricate a Carbon/PEEK (AS4/APC-2) laminate with $[0]_{17}$ layup using AFP in-situ consolidation and a flat aluminum mandrel, as shown in Figure 1 (a). Throughout the manufacturing process, the settings for the hot gas torch temperature, Nitrogen flow rate, compaction force, and deposition rate were established at 875°C, 80 SLPM, 60 lbf, and 50.8 mm/s (2 in/s), respectively. To assess the impact of the AFP in-situ consolidation manufacturing technique on the interlaminar shear strength of Carbon/PEEK thermoplastic composite material, the in-situ consolidated plate was halved, vacuum bagged, and re-consolidated in an autoclave using the cure cycle specified in the CYTEC technical data sheet [9], serving as a baseline laminate for comparison.

3 SHORT-BEAM SHEAR TEST

In the present research, flat coupon specimens measuring 19 mm × 6 mm × 2.4 mm, as per ASTM D2344 [8], were obtained from both AFP and autoclave-manufactured laminates using a circular diamond saw. It is important to highlight that the thickness of the samples re-consolidated in the autoclave was reduced from 2.4 ± 0.037 mm to 2.3 ± 0.024 mm due to void elimination and excess resin removal. To conduct the experiment, as shown in Figure 1 (b), an SBS test fixture provided by Wyoming Test Fixtures Inc. (WTF) was utilized, featuring a loading nose and supports with diameters of 6 mm and 3 mm, respectively. Each laminate underwent testing with five samples to determine the interlaminar shear strength (ILSS), with the fixture's span length to thickness ratio set at 4.0. The test was carried out under displacement control mode at a crosshead movement rate of 1.0 mm/min using a universal hydraulic testing system. The ILSS value, F^{sbs}, for each sample was computed using the following equation:

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \tag{1}$$

where P_m, b and h denote maximum applied load, specimen width and specimen thickness, respectively.



(a) (b)

Figure 1. (a) AFP machine available at CONCOM and (b) short-beam shear testing with WTF fixture.

4 FINITE ELEMENT MODELING

In the present study, the finite element modeling was carried out to predict the distinct mechanical behavior of Carbon/PEEK thermoplastic composite material resulting from in-situ consolidation and autoclave re-consolidation techniques. To achieve this, a three-dimensional model was developed using ABAQUS/Explicit software to simulate the short-beam shear test, as shown in Figure 2 (a). Discrete rigid shell elements were used for the simulation of the loading nose and supports. To avoid roller penetration into the simulated composite specimen, a general contact interaction was established between them. Normal behavior was set to hard contact mode, while a friction coefficient of 0.3 was applied for metal-laminate tangential interaction.

A VUMAT subroutine was written in FORTRAN programming language to perform the composite damage (intralaminar damage) modeling. The 3D Hashin failure criteria and linear softening damage model [10] were employed to predict the damage initiation and propagation, respectively, in conjunction with the one-parameter plasticity model to consider the nonlinear behaviour of thermoplastic composite material during the simulation. Moreover, since delamination is the primary failure mode in the SBS test, the cohesive elements with a thickness of 0.01 mm were placed between layers to model the separation of layers (interlaminar damage). This was achieved by considering traction-separation response along with the quadratic-stress failure criterion for the cohesive zone damage model (for more information on how to implement intralaminar and interlaminar damage models, see Ref. [10]).

5 RESULTS

Numerous scholars explored the effect of processing conditions on the fracture toughness in Carbon/PEEK thermoplastic composite material, including variables such as degree of crystallinity and fiber-matrix adhesion. The influence of cooling rate on the interlaminar fracture toughness was examined by Gao and Kim [11]. Their findings revealed that higher cooling rates lead to an increase in Modes I and II interlaminar fracture toughness, highly likely due to a reduction in the degree of crystallinity. They claimed that the cooling rate's influence on fracture toughness arises from intricate interplays between matrix ductility and fiber-matrix interfacial bonding strength. In another research work, Gao and Kim [12] assessed the bonding strength between fibers and matrix in Carbon/PEEK thermoplastic composite material. They observed a significant decrease in bonding strength with accelerated cooling rates. Additionally, tests conducted on neat PEEK resin revealed that high cooling rates can lead the elastic modulus and tensile strength of thermoplastic resin to decrease, a phenomenon attributed to the reduced degree of crystallinity. In conclusion, their findings showed that although a high cooling rate leads the matrix ductility to increase, fiber-matrix bonding and material properties of neat PEEK resin are negatively affected due to the reduction in the degree of crystallinity.

The primary limitation of the AFP in-situ consolidation manufacturing process, in contrast to autoclave treatment, is its short processing time, resulting in a high cooling rate and an incomplete healing process. Consequently, while fracture toughness may increase, bonding strength and matrix properties are diminished, as elaborated previously. Mode II delamination energy is more reliant on fiber-matrix adhesion than Mode I delamination energy, which is mainly governed by matrix characteristics. As a result, significant variations in ILSS values obtained from the SBS test are anticipated depending on each manufacturing method. AFP processing parameters, namely deposition rate, compaction force and process temperature, are mainly responsible for the quality of the final composite part. Ray et al. [13] reported that fracture toughness can be increased by up to 80% by the AFP process in comparison with the autoclave consolidation. Numerous studies [4,5] conducted extensive SBS tests on in-situ-consolidated Carbon/PEEK thermoplastic composite specimens, demonstrating ILSS values ranging from 30 to 60 MPa depending on AFP processing parameters. Despite efforts to identify optimum AFP processing conditions, a notable discrepancy persists between ILSS values obtained from AFP in-situ consolidation and those (≈ 90 MPa) from autoclave treatment.

To capture this difference in ILSS values during the finite element modeling, a parametric study was performed on the fracture toughness and interfacial strength values, as shown in Figure 2 (b) and (c), to have a better understanding of how the load-displacement curve may change. According to Figure 2 (b) and (c), an increase in the fracture toughness does not have a considerable effect on the delamination onset; rather, it holds greater influence on the measured ultimate strength or failure strain. However, because delamination is the dominant mode of failure in the SBS test, any decline in the interface strength can affect the ILSS values substantially. The mechanical properties of the unidirectional Carbon/PEEK lamina used in the finite element modeling are presented in Table 1.

Table 1. Mechanical properties of unidirectional Carbon/PEEK thermoplastic composite ply [9,10].

Stiffness (MPa)	E_{11}	$E_{22}=E_{33}$	$G_{12}=G_{13}$	G_{23}	$\nu_{12}=\nu_{13}$	ν_{23}
	138,000	10,300	5700	3700	0.3	0.45
Strength (MPa)	X_T	X_C	Y_T	Y_C	$S_{12}=S_{13}$	S_{23}
	2070	1360	86	176	186	86

Regarding the interfacial strength, there exists no standardized technique for quantifying them. Furthermore, while Linear Elastic Fracture Mechanics (LEFM) offers a means to calculate the interface strength, the rapid onset and evolution of delamination in reality make it extremely challenging to accurately measure the crack-tip opening displacement. Another approach involves iteratively adjusting interface strength values until numerical results align with experimental findings. To this end, in the present research, interfacial strength values resulting from AFP in-situ consolidation and autoclave re-consolidation manufacturing methods were determined based on the ILSS values measured during the SBS tests, as shown in Figure 2 (d). According to the interlaminar shear strength (ILSS) values provided in Table 2, it is evident that AFP in-situ consolidation can result in an ILSS of 54.52 MPa for the Carbon/PEEK thermoplastic composite samples, representing a 37% decrease compared to that of specimens re-consolidated within an autoclave. It is important to emphasize the significance of the interface strength values (denoted as N and S) listed in Table 2, found based on the SBS experimental data. These values hold considerable importance as they serve as crucial inputs for further numerical analyses of in-situ-consolidated Carbon/PEEK thermoplastic composite materials.

Table 2. Interlaminar Shear Strength (ILSS) values obtained experimentally and numerically.

	FEM (MPa)	N (MPa)	S (MPa)	Experiment (MPa)	SD[1] (MPa)	CV[2] (%)
Autoclave re-consolidation	87.76	56	70	86.16	1.12	1.30
AFP in-situ consolidation	56.51	36	45	54.52	1.31	2.41

[1] Standard deviation

[2] Coefficient of variation

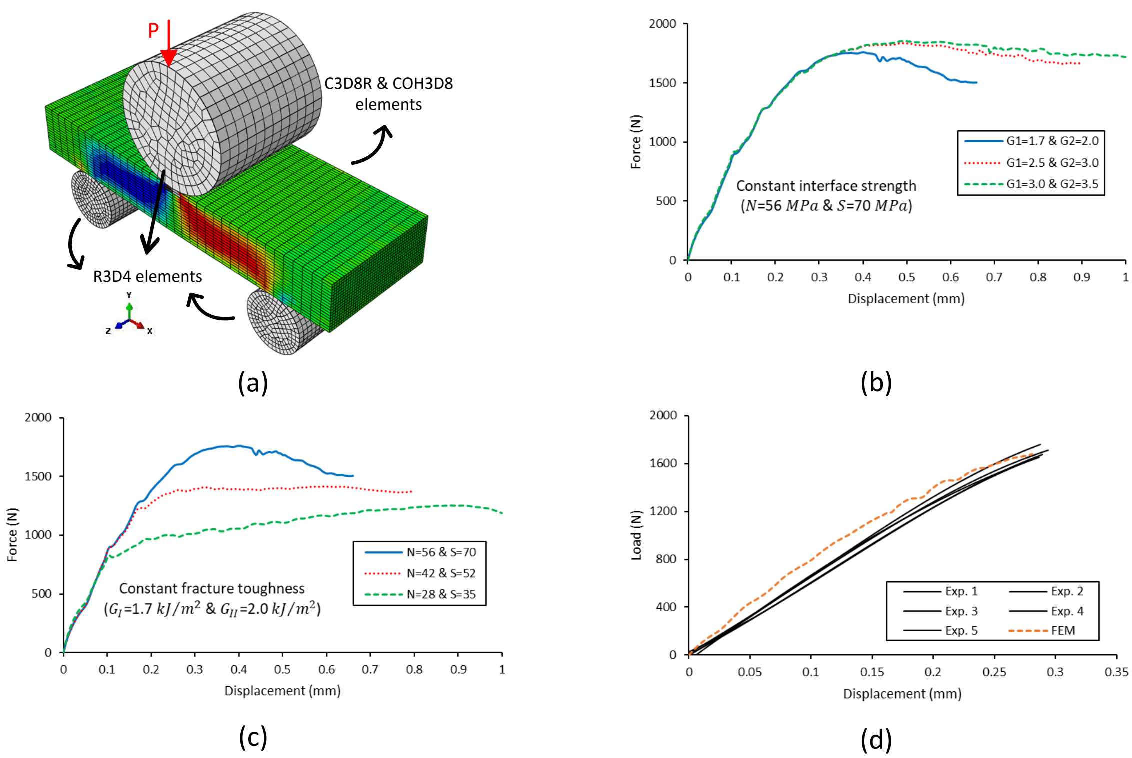


Figure 2. (a) SBS test simulation in ABAQUS software. Effects of variations in (b) fracture toughness and (c) interface strength values on the load-displacement curve of Carbon/PEEK thermoplastic composite sample. (d) Comparison of the response obtained by numerical analysis and experiments for ILSS calculation of reference samples.

6 CONCLUSION

The use of an automated fiber placement (AFP) machine for in-situ consolidation presents a cost and time-efficient alternative to autoclave curing. However, the shorter processing time with AFP adversely affects the quality of thermoplastic composite laminates compared to those treated in an autoclave. In the present study, Carbon/PEEK thermoplastic composite laminates were manufactured by AFP in-situ consolidation and autoclave re-consolidation processes. Findings revealed about 37% reduction in the Interlaminar Shear Strength (ILSS) values of samples manufactured by AFP in-situ consolidation when compared to those re-consolidated in an autoclave. Moreover, a numerical simulation was conducted using a VUMAT subroutine and cohesive-element approach to analyse the onset and evolution of intralaminar and interlaminar (delamination) damages. The distinction in mechanical behavior was achieved by computationally determining suitable interface strength properties in accordance with the SBS test data. These findings can be utilized in subsequent numerical investigations concerning the in-situ-consolidated Carbon/PEEK thermoplastic composite materials.

7 REFERENCES

[1] A. Khodaei and F. Shadmehri. "Intimate contact development for automated fiber placement of thermoplastic composites". *Composites Part C: Open Access*, Vol. 8, pp 100290, 2022.

[2] J. Tierney and J. W. Gillespie. "Modeling of in situ strength development for the thermoplastic composite tow placement process". *Journal of Composite Materials*, Vol. 40, No. 16, pp 1487-1506, 2006.

[3] Z. Qureshi, T. Swait, R. Scaife and H. M. El-Dessouky. "In situ consolidation of thermoplastic prepreg tape using automated tape placement technology: Potential and possibilities". *Composites Part B: Engineering*, Vol. 66, pp 255-267, 2014.

[4] X. Cai, F. Shadmehri, M. Hojjati, J. Chen and SV. Hoa. "Determination of optimum process conditions for processing AS4/APC-2 thermoplastic composites by automated fiber placement". *The Society for the Advancement of Material and Process Engineering (SAMPE) conference*, 2012.

[5] E. Oromiehie, A. K. Gain and B. G. Prusty. "Processing parameter optimisation for automated fibre placement (AFP) manufactured thermoplastic composites". *Composite Structures*, Vol. 272, pp 114223, 2021.

[6] P. P. Camanho, C. G. Davila and M. F. de Moura. "Numerical Simulation of Mixed-Mode Progressive Delamination in Composite Materials". *Journal of Composite Materials*, Vol. 37, No. 16, pp 1415-1438, 2003.

[7] M. Ghayour, R. Ganesan and M. Hojjati. "Flexural response of composite beams made by Automated Fiber Placement process: Effect of fiber tow gaps". *Composites Part B: Engineering*, Vol. 201, pp 108368, 2020.

[8] ASTM D2344 / D2344M. "*Standard test method for short-beam strength of polymer matrix composite materials and their laminates*". ASTM International, West Conshohocken, PA, 2016.

[9] CYTEC. "*APC-2-PEEK Thermoplastic Polymer*". www.cytec.com, 2012.

[10] E. Pourahmadi, F. Shadmehri and R. Ganesan. "Interlaminar shear strength of Carbon/PEEK thermoplastic composite laminate: Effects of in-situ consolidation by automated fiber placement and autoclave re-consolidation". *Composites Part B: Engineering*, Vol. 269, pp 111104, 2024.

[11] S.-L. Gao and J.-K. Kim. "Cooling rate influences in carbon fibre/PEEK composites. Part II: interlaminar fracture toughness". *Composites Part A: Applied Science and Manufacturing*, Vol. 32, No. 6, pp 763-774, 2001.

[12] S.-L. Gao and J.-K. Kim. "Cooling rate influences in carbon fibre/PEEK composites. Part 1. Crystallinity and interface adhesion". *Composites Part A: Applied Science and Manufacturing*, Vol. 31, No. 6, pp 517-530, 2000.

[13] D. Ray et al. "Fracture toughness of carbon fiber/polyether ether ketone composites manufactured by autoclave and laser-assisted automated tape placement". *Journal of Applied Polymer Science*, Vol. 132, 2014.