Development and Delamination Behavior of Adhesive Joints in Composite Structures under Extreme Environmental Conditions

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4TH INTERNATIONAL CONFERENCE ON ADVANCED JOINING PROCESSES
16-17 October 2025 - Coimbra, Portugal

Introduction

Polymer matrix composites reinforced with continuous fibers are typically formed by stacked laminated layers bonded with adhesives. This structure makes them prone to delamination, the separation of adjacent layers that reduces mechanical performance and can lead to structural failure. Understanding this phenomenon requires analyzing mechanical, thermal, and environmental effects through fracture mechanics.

It has explored how temperature, humidity and saline exposure influence delamination and adhesive joint behavior, as well as the development of models to predict structural performance.

This work focuses on studying the combined effect of temperature, moisture and saline environment on delamination in a unidirectional carbon fiber–reinforced composite under static loading, within a temperature range of 20–90 °C.

Experimental

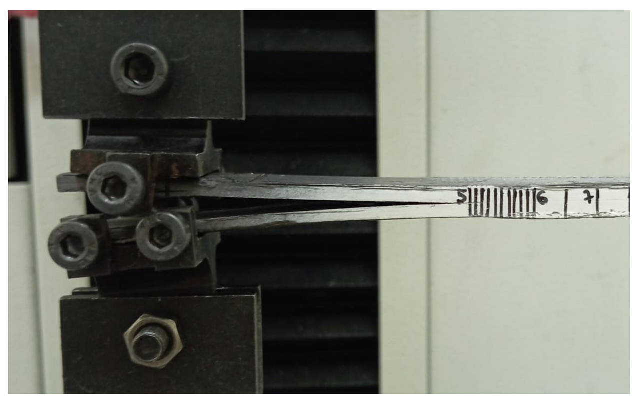
MECHANICAL PROPERTIES

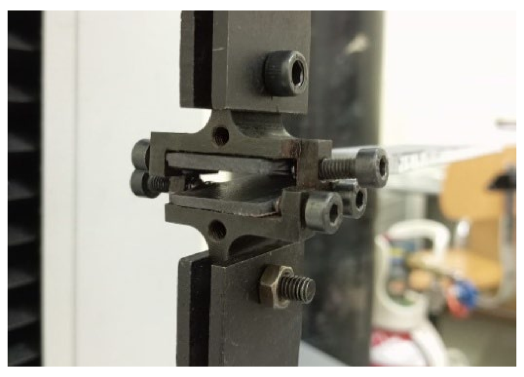
Composite Substrate (MTC510-UD300-HS)

	Elastic modulus [a]		Tensile strength [a]		Shear modulus [b]	Shear strength [b]
T (ºC)	E_{11} (GPa)	E_{22} (GPa)	σ_{11} (MPa)	σ_{22} (MPa)	G_{12} (GPa)	$\tau_{máx}$ (MPa)
20	122 CV= 8 %	8.5 CV= 8%	1156 CV=12 %	28 CV= 12%	5.2 CV= 10%	37 CV=2%
50	139 CV=12%	8.16 CV= 2%	1361.6 CV=4%	27 CV=9%	5.3 CV=11%	36 CV=2%
90	129 CV=14%	8.8 CV= 9%	1261 CV=12%	25 CV=6%	4.9 CV=12%	34 CV=13%

[a] ASTM D 3039M [34]
[b] ASTM D 3518M [35]

SPECIMEN CLAMPING SYSTEM





Methodology

SURFACE PREPARATION

Manual abrasion with P220 Al_2O_3 sandpaper

Cleaning and degreasing before bonding

EXPOSURE CONDITIONS

Saline

35 °C ± 2 °C, 89% RH, 50 g/L NaCl for 12 weeks

Hygrothermal

60 °C and 70% RH for 12 weeks

Thermal loading

Tests at 20 °C (room) 50 °C, and 90 °C

TESTING PROCEDURE

Modified Beam Theory (MBT)

$$G_{IC} = 3P\delta/2b(a+|\Delta|)$$

Compliance Calibration (CC)

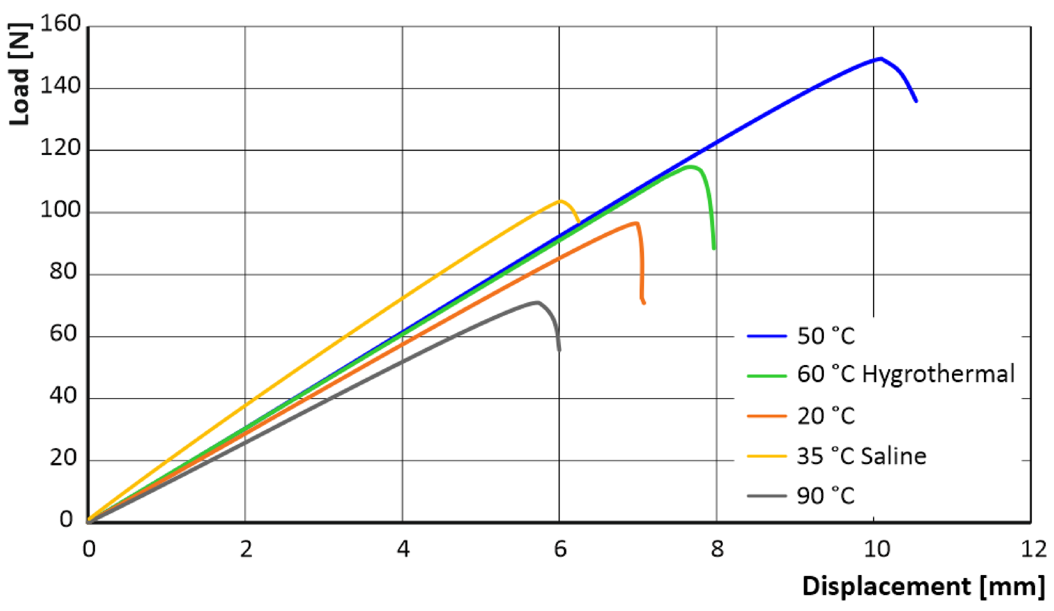
$$G_{IC} = nP\delta/2ba$$

Modified Compliance Calibration (MCC)

$$G_{IC} = 3P^2C^{2/3}/2A_1bh$$

Results

LOAD - DISPLACEMENT

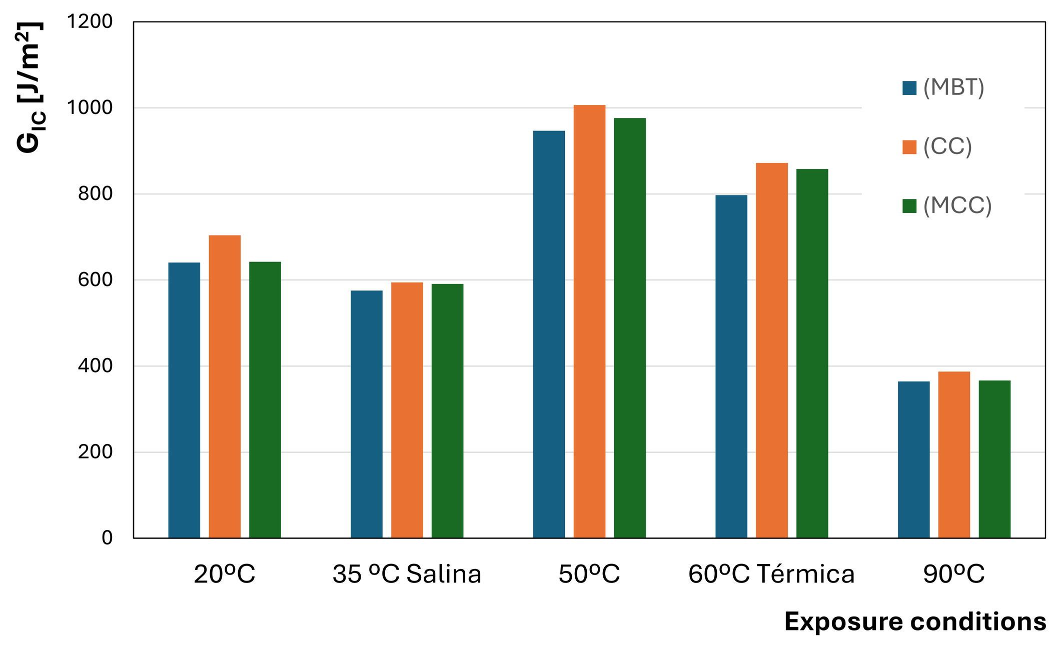


The curves display a similar initial slope, indicating that the stiffness of the adhesive joints remains almost unchanged for moderate temperature variations.

However, a notable variation appears in the maximum load and displacement values. Compared to room temperature (**20 °C**), higher loads and displacements are recorded at **50 °C** and after hygrothermal exposure (**60 °C**–70% RH), which suggests a beneficial post-curing effect of the adhesive.

Conversely, at **90 °C**, a pronounced reduction in both load and displacement is observed, evidencing thermal degradation of the adhesive and loss of structural integrity of the joint.

EFFECT OF TEMPERATURE AND ENVIRONMENT ON G_{IC}



Critical energy release rate (G_{IC}) calculated using the three formulations recommended by ASTM D5528:
Modified Beam Theory (MBT), Compliance Calibration (CC), and Modified Compliance Calibration (MCC).
All three methods show a consistent trend.

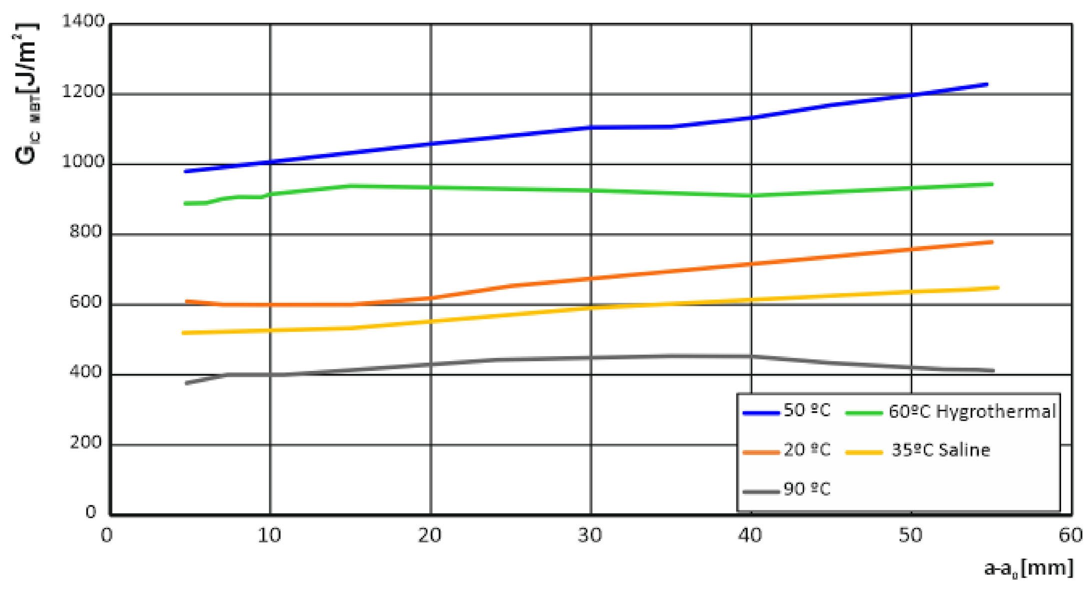
At **20 °C** (reference, room temperature) and **35 °C** (saline exposure), the results are of similar magnitude.

At **50 °C** and **60 °C** (hygrothermal exposure), the fracture energy values increase noticeably, confirming that moderate heat exposure can enhance the adhesive network's crosslinking and improve delamination resistance.

At **90 °C**, the energy release rate decreases sharply, exceeding a 40% reduction with respect to **20 °C**.

Among the methods, MBT consistently provides the most conservative estimates of fracture toughness.

G_{IC} – CRACK LENTH



The evolution of the Mode I fracture energy with crack length also follows a temperature-dependent pattern.

At room temperature **20 °C**, **35 °C** and **50 °C**, the energy required for crack propagation increases progressively as the crack advances, indicating stable crack growth and effective energy absorption.

After hygrothermal conditioning, this trend is maintained, confirming that moisture and moderate temperature do not critically impair the adhesive–composite interface.

At **90 °C**, however, the G_{IC} values remain practically constant throughout crack propagation, indicating a loss of cohesive strength and a transition toward unstable delamination behavior.

Conclusions

The experimental investigation demonstrated that **temperature is the dominant factor** influencing the delamination behavior of adhesive joints in reinforced composites. At moderate temperatures (**50–60 °C**), both the load capacity and fracture energy increased due to a post-curing effect of the epoxy adhesive, which enhances stiffness and resistance to crack initiation and propagation.

However, at high temperature (**90 °C**), a significant degradation of the adhesive was observed, with a reduction of more than 40% in fracture toughness, indicating a loss of cohesive and interfacial strength. In contrast, saline and hygrothermal exposures produced only minor variations, not critically affecting structural integrity. The MBT method provided the most conservative and reliable estimates of fracture toughness.

Overall, the study concludes that moderate environmental exposure can improve adhesive joint, while excessive temperature severely compromises mechanical properties. These findings support the design and durability assessment of bonded composite structures used in aerospace, automotive, and marine environments.

Bibliography