Durability Study of Polymeric Ballistic Panels Used in Riverine Combat Boats Under Humidity-Aged and Impact Fatigue Conditions

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Abstract

Low Draft River Combat Boats are equipped with a set of armored panels on the deck and attached to the sides to protect the crew. These shields are composed of laminated panels made of ultra-high molecular weight polyethylene fibers with a polyurethane resin matrix. The use of these panels results in a weight reduction of approximately 50% compared to traditional armor. However, the polymeric nature of these panels makes them susceptible to degradation of their mechanical properties over time under operational environmental conditions.

This study evaluates the effect of moisture and temperature on the durability and crack propagation behavior of these ballistic panels under impact fatigue conditions through experimental procedures.

Key words: Ultra-high molecular weight polyethylene, crack propagation behavior, Low Draft River Combat Boats, effect of moisture, impact fatigue.

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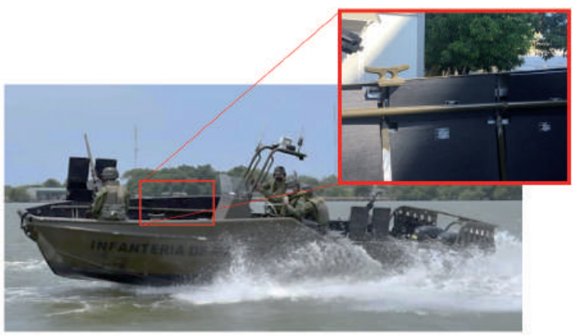
Introduction

The Colombian Navy, in fulfilling its institutional mission, requires access to shallow waters to conduct military surveillance, patrolling, and fluvial control operations in secondary and tertiary rivers across Colombian territory. To meet this need, Low Draft River Combat Boats were developed (see Fig. 1).

These vessels are equipped with polymeric armor composed of unidirectional ultra-high molecular weight polyethylene (UHMWPE) fibers, which are characterized by their high strength-to-weight ratio. This armor provides the crew with NIJ III-level protection, offering ballistic resistance to 7.62 x 51mm NATO ammunition (see Fig. 2).

Fig. 1. Ballistic panels on board the boat [1].



The lifespan of the ballistic polymer fiber panels (UHMWPE) with polyurethane resin is estimated to be five years. However, when exposed to environmental conditions such as high humidity and temperature—typical of maritime and fluvial operations—delamination may occur, potentially affecting the durability of the ballistic panels. Therefore, it is necessary to analyze how these conditions, over time, impact the material's ability to absorb energy.

UHMWPE composites are widely used in applications requiring lightweight, high-strength materials with favorable properties under high strain rates [2], such as protective armor, anchor ropes, and fishing nets [3]. The combination of UHMWPE thermoplastic fibers and a polyurethane-based liquid thermoplastic matrix forms a complete thermoplastic polymeric composite system. [4] This system plays a critical role in ballistic panel applications due to its high energy absorption capacity during impacts.

The ballistic limit of UHMWPE laminates is approximately 40–90% higher than that of Kevlar and E-glass composite laminates with the same areal density [5]. On a weight basis, UHMWPE laminates are up to 15 times stronger than steel and up to 40% stronger than aramid fibers. Additionally, these laminates are buoyant, highly durable, and resistant to moisture, ultraviolet light, and chemicals [6].

Composite materials in practical use are often subjected to mechanical stresses, such as low-speed impacts, and environmental factors, such as temperature variations, humidity, UV radiation, and chemical exposure. These factors contribute to the appearance of delamination or interlaminar cracks [7].

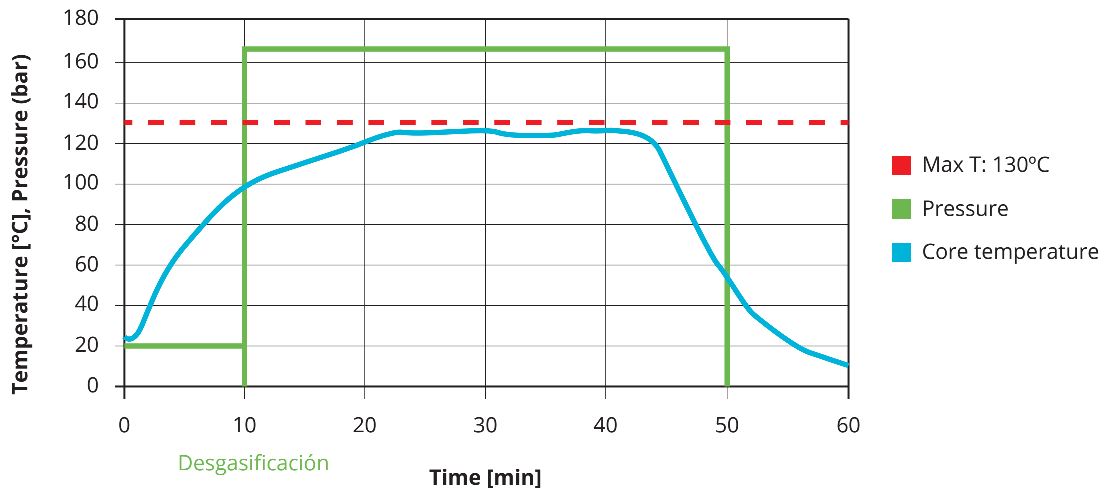
Although extensive research has been conducted on the effects of temperature, humidity, radiation, and chemical exposure on polymeric materials, the effects of aging on the failure modes of ultra-high molecular weight polyethylene under quasi-static and dynamic conditions have not been widely studied. The purpose of this project is to evaluate the effect of environmental conditions on the energy absorption capacity of UHMWPE ballistic panels. To achieve this, an experimental analysis of crack propagation in load modes I and II was conducted under quasi-static and low-velocity impact conditions in laminates subjected to different levels of aging due to temperature and humidity.

Methodology

Specimens and materials

The experimental study was conducted

Fig. 2. Dyneema BHT compression molding cycle [9].



using a composite material consisting of four unidirectional layers of ultra-high molecular weight polyethylene fibers, consolidated with a polyurethane-based thermoplastic matrix. The layers were interlocked at 90-degree angles to each other.

The mechanical, physical, and thermal properties of the material are shown in Table 1. [8].

Table 1: UHMW-PE HB24T mechanical and thermal properties [8].

Properties	UHMW-PE
Tensile yield strength [MPa]	658.28 ± 65.81 MPa
Shear yield strength [MPa]	0.81 ± 0.034 MPa
Young's Modulus [GPa]	43.52 ± 4.55 GPa
Shear Modulus [MPa]	25.63 ± 0.414 MPa
Tensile ultimate strain [MPa]	1.59 ± 0.105%
Melting temperature	149.7 °C
Crystallinity	84%

The panels were fabricated using the compression molding method, following the Dyneema BHT compression molding cycle [see Fig. 2] [9]. The process involved 16 vents, with a venting time of 15 seconds between each cycle.

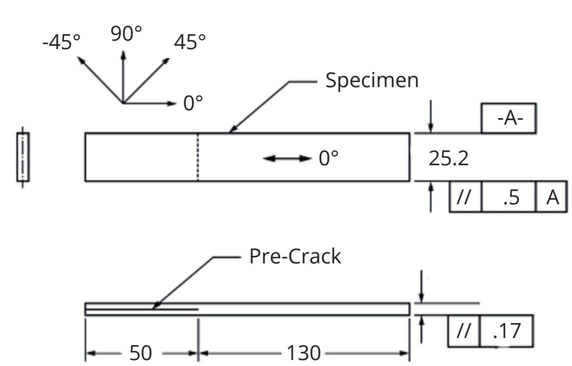
For specimen preparation, the guidelines of the ASTM D7905 standard were followed. Each panel was cut according to the dimensions shown in Fig. 3.

For the Mode I test under quasi-static conditions, two 1" x 1/8" steel plates were bonded to the specimen using Hysol Aero 934 EA epoxy adhesive. The adhesive was cured at 93°C for one hour in a conventional oven.

Quasi-Static Mode I crack propagation test

The double cantilever beam test is a standard method for measuring Mode I fracture

Fig. 3. Mode I specimens dimensions in mm.



toughness (GIC) [see Fig. 4]. The quasi-static crack propagation tests were conducted using an INSTRON 3367 universal testing machine equipped with a 500N load cell. The tests were performed at a constant speed of 1 mm/min, with a resolution of 0.00001, in accordance with the ASTM D5528-13 standard [10] [see Fig. 5].

Fig. 4. Crack opening in mode I crack propagation test.

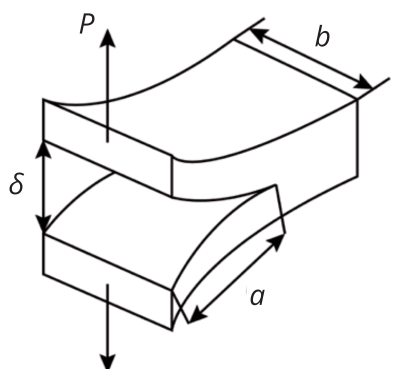
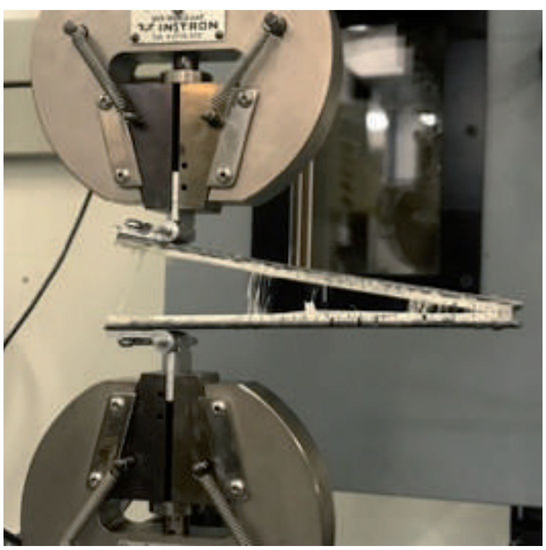


Fig. 5. Quasi-static Mode I test.



The critical energy release rate (G_{IC}) was calculated by the "Experimental compliance method (*ECM*)," based on the load results (P), jaw displacement (δ) and crack propagation length (a) [equation 1].

$$G_{IC} = \frac{nP\delta}{2Ba} \quad (1)$$

where *n* is the slope obtained from the logarithm graph of compliance vs the logarithm of crack length and *b* is the width of the specimen.

Quasi-Static Mode II Crack propagation test

This test method determines the Mode II interlaminar fracture toughness (GIIc) of composite laminates under shear loading [see Fig. 6]. The tests were conducted using the same INSTRON 3367 universal testing machine with a 500N load cell [see Fig. 7].

Fig. 6. Shear loading mode II test.

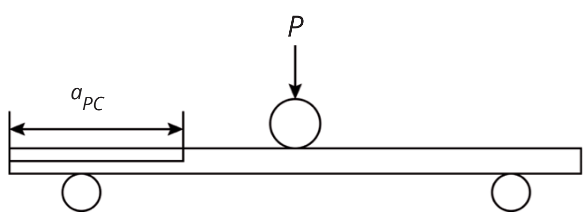
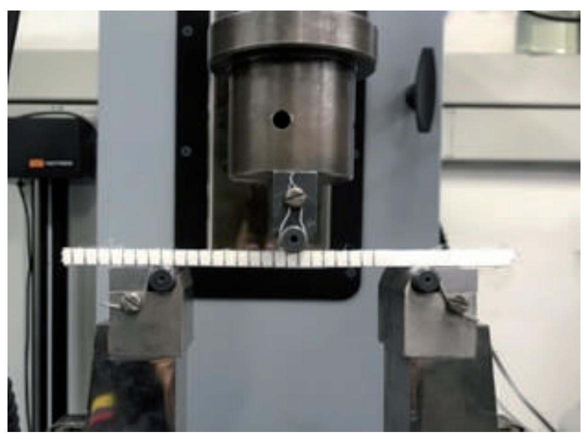


Fig. 7. Quasi-static Mode II test.



The mode II interlaminar fracture toughness, GIIc, was calculated using the following relation:

Where P_{max} is the maximum value of the recorded load, a_{PC} is the delamination length, and *m* is the slope between compliance and the length of the crack; this value is obtained experimentally [equation 2].

$$G_{IIC} = \frac{3mP_{max}^{2} a_{PC}^{2}}{2B} \qquad (2)$$

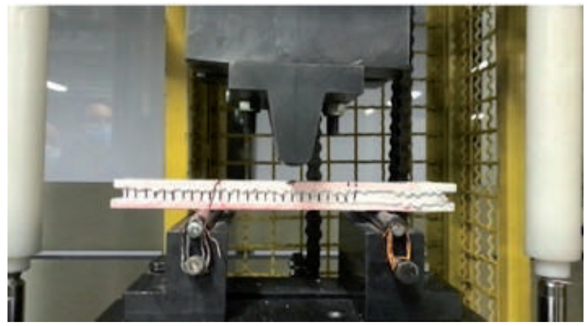
Crack Propagation test at dynamic conditions

Dynamic crack propagation tests were conducted using the low-energy impact machine at Universidad de los Andes (DWIT). The impact force was measured using three Kistler 9212 load cells in a delta configuration, while hammer displacement was recorded using an LSD 90/40-M laser position sensor. For Mode I failure, a 6.78 kg aluminum hammer was used at an average height of 26 mm. For Mode II failure, a 13.5 kg hammer was dropped from an average height of 26 mm, with a load cell calibration factor of 49.93 and debounce time of 90 [see Fig. 8].

Fig. 8. Mode I crack propagation impact test.

For failure mode II, a distance between supports of 100 mm was used, dropping a weight of 13.5 kg (hammer weight plus flexion assembly) at an average height of 50 mm, with a load cell calibration factor of 201.16 and debounce time of 110 ms [see Fig. 9].

Fig. 9. Mode I crack propagation impact test.



Aging of the specimens

The specimens were aged in a DISCOVERY/ FLOWER DY110 climatic chamber, which operates within a temperature range of -40°C to +180°C and a humidity range of up to 98%. [11]. The material was exposed to a temperature of 50ºC and 80% relative humidity for 500 and 1000 hours, considering the operating conditions and recommendations of [12] since when using a temperature higher than 60°C, there is a risk of damaging the material or causing a permanent change in the properties of the material. The experimental model for obtaining the critical energy release rate was calculated by the "Experimental compliance method".

Results and Discussion

Crack propagation at mode I Quasi-Static regime

The results of maximum load versus jaw extension for different crack sizes are shown in Figs. 10–12. Specimens aged for 1000 hours exhibited stable crack growth with more increments compared to unaged and 500-hour-aged samples. [see Fig. 10, Fig. 11, Fig. 12].

To obtain the energy release rate (GIC), an average obtained from the "Experimental

Fig. 10. Mode I crack propagation non-aging samples.

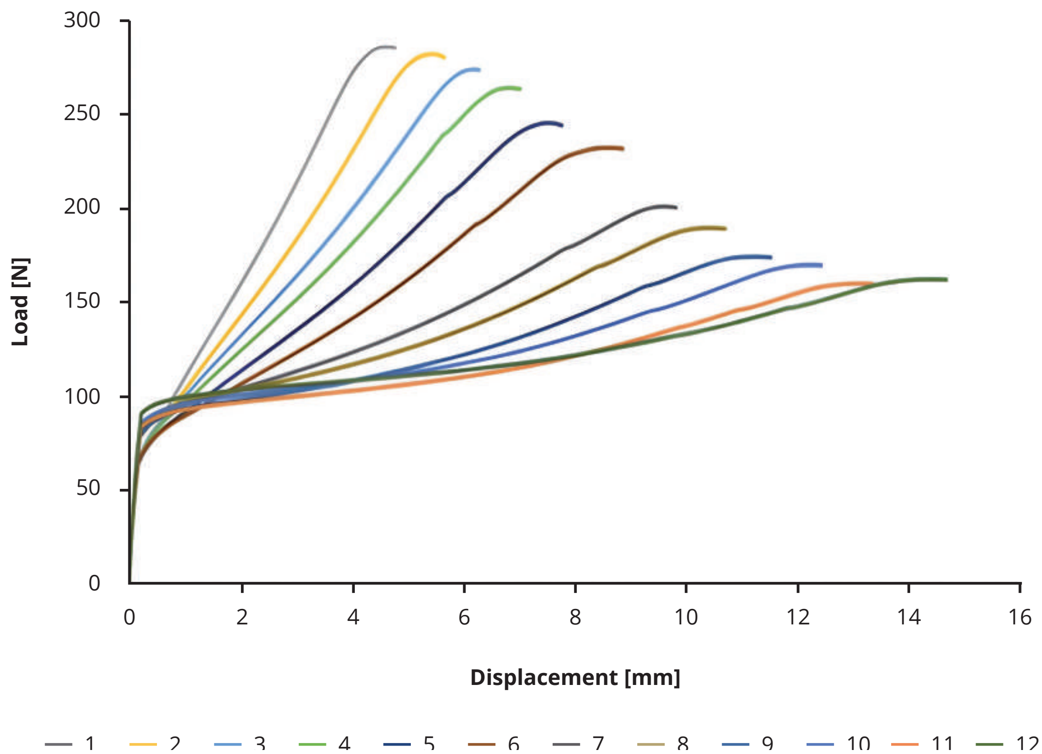
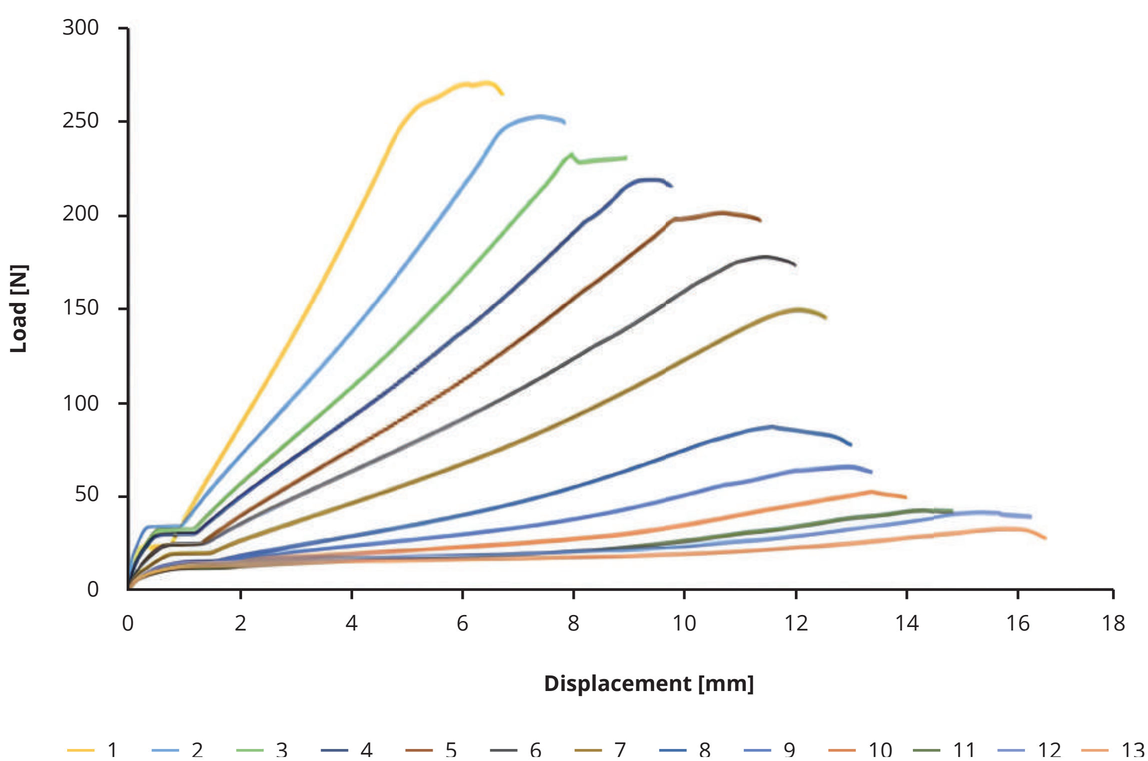


Fig. 11. Mode I crack propagation 500 hours aging.



compliance method" was calculated, considering that they are characteristic values of and independent of the size of the crack.

The value of (GIC) for the unaged specimens was 126.76 ± 9.28 J/m², for the specimens aged at 500 hours it was 116.06 ± 13.55 J/m², and for

Fig. 12. Mode I crack propagation 1000 hours aging.

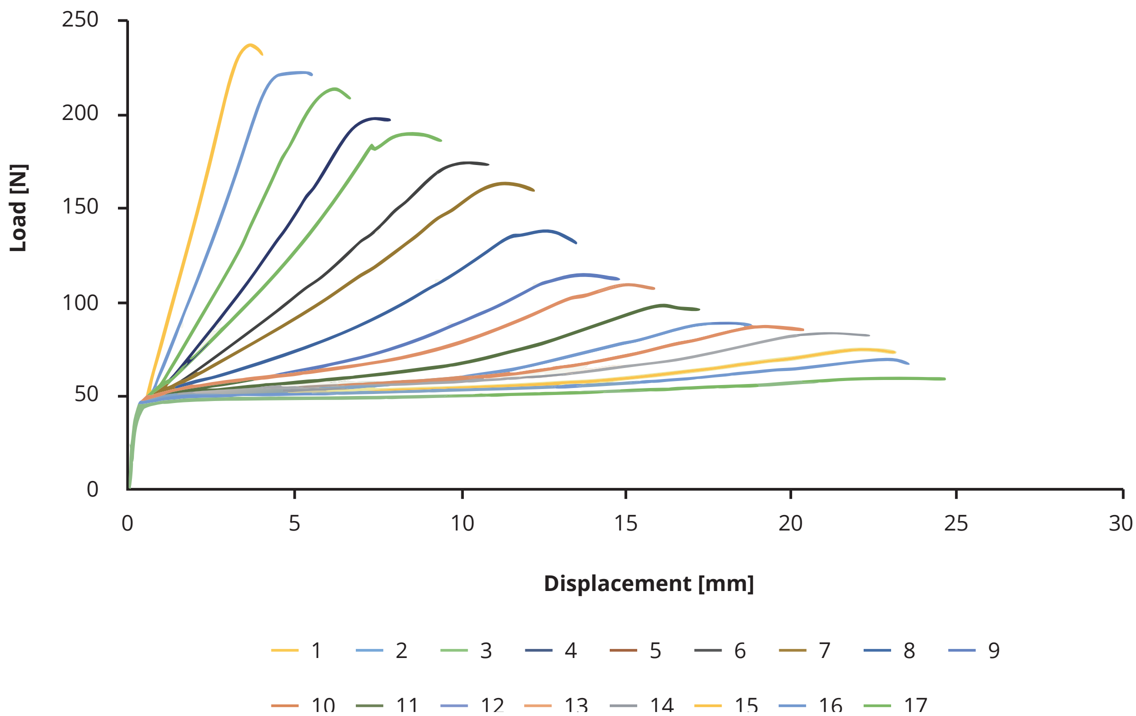


Fig. 13. Critical energy release rate at non-aging conditions.

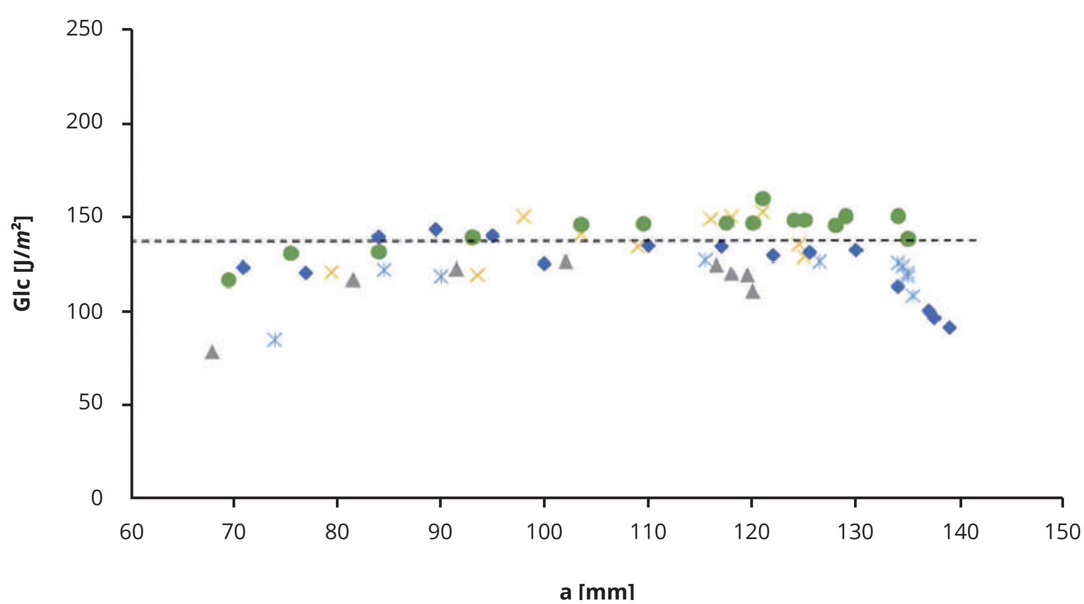


Fig. 14. Critical energy release rate at 500 hours aging.

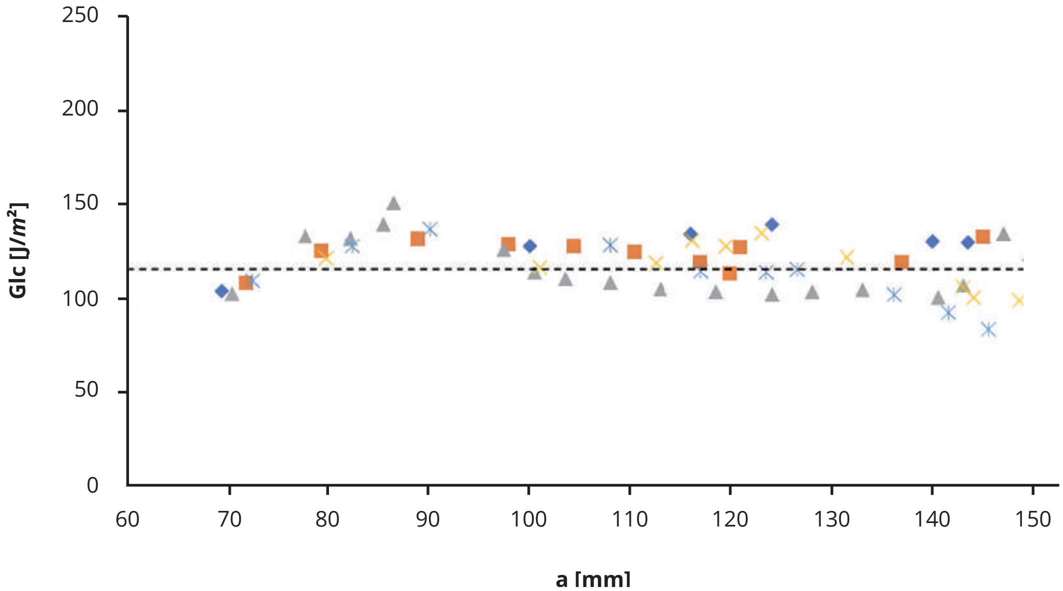
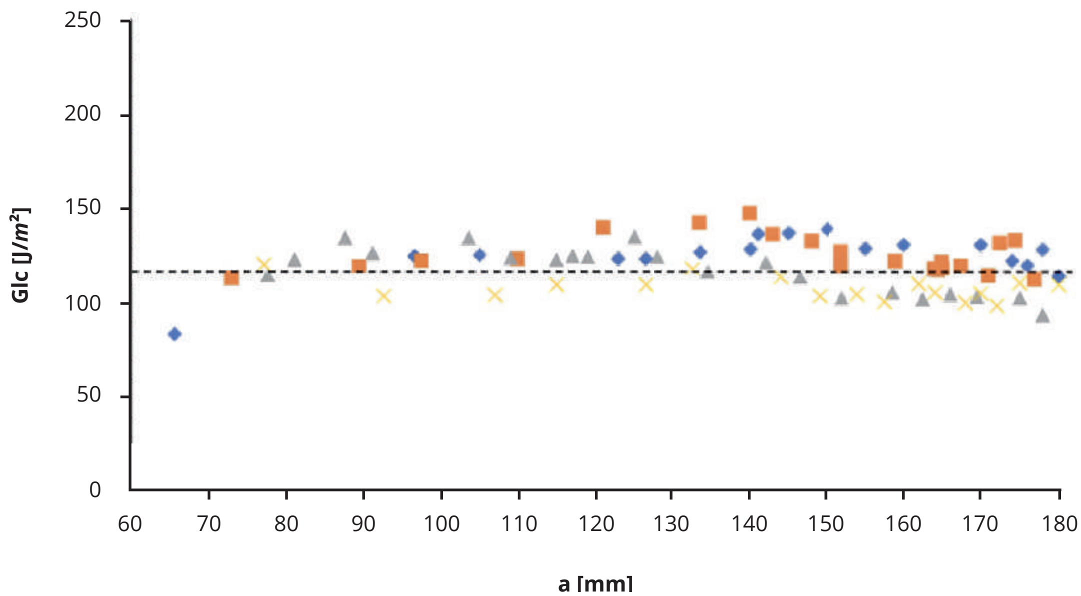


Fig. 15. Critical energy release rate at 1000 hours aging.



the specimens aged at 1000 hours was 117.44 ± 10.04 J/m^2. When an ANOVA statistical analysis was performed, no significant difference in mode I loadings was found among the three conditions.

Crack propagation test at mode II Quasi-Static regime

The results for Mode II crack propagation are shown in Fig. 16. Unlike Mode I, the load reached a maximum value before falling instantly as the crack propagated, obtaining a single characteristic curve for each test piece. In Fig. 16 the more the aging, the lesser stiffness of the sample is shown. Since the stiffness is a function of second moment of area and elastic modulus, and the first remains the same, this leads to a degradation of the matrix elastic modulus.

On the other hand, the value of the critical energy release rate at mode II conditions (G_{IIC}) in the non-aging specimens was 68.75 ± 2.38 J/m, for the specimens aged at 500 hours it was 25 .70 ± 2.86 J/m^2, and for the specimens aged at 1000 hours it was 10.12 ± 1.40 J/m^2. The non-aging samples show a G_{IIC} 6.8 times higher than 500 hours aging specimens [see Fig.17]. When the ANOVA statistical analysis

Fig. 16. Characteristic quasi-static mode II crack propagation curve.

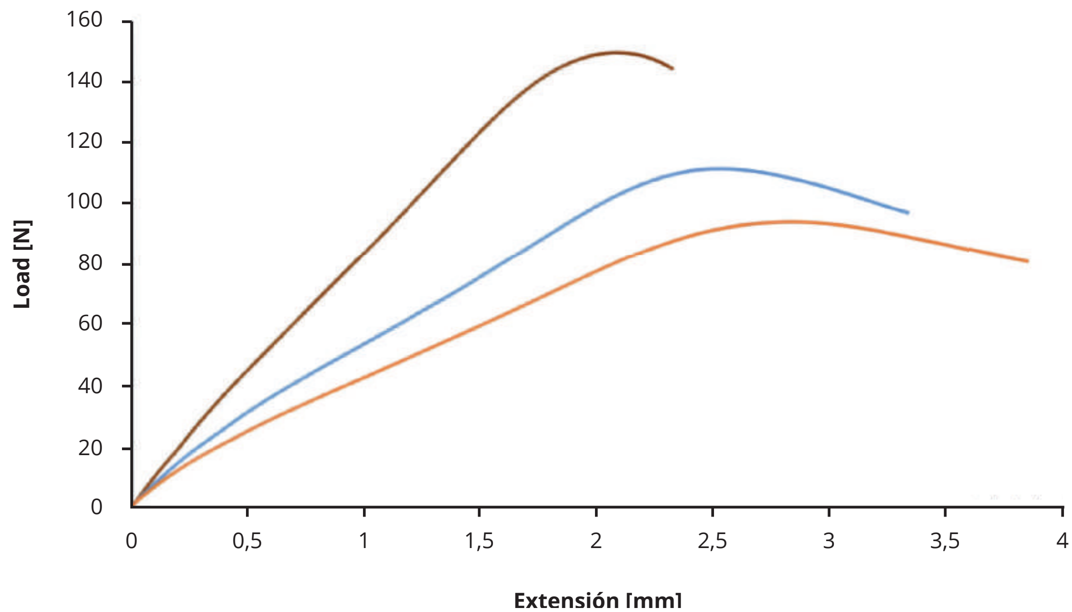
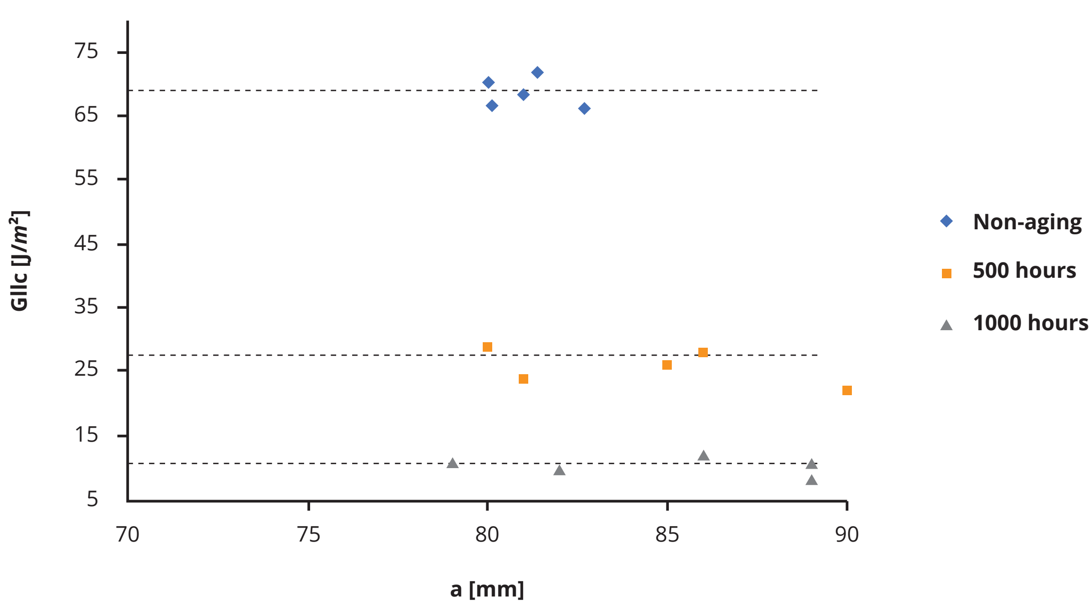


Fig. 17. Critical energy release rate at mode II conditions.



was done, a significant difference in G_{IIC} among the three conditions was found. Therefore, the required energy to crack growth at mode II loading decreases with aging.

Crack propagation test at dynamic impact loadings

To determine the limit energy release rate, the maximum release rate vs. propagation velocity was plotted [See Fig. 18], which shows the slope of the graph decreasing as the effect of aging increases. The values found for the limit energy release rate without aging were 85.71 ± 6.89; at 500 hours, 57, 09 ± 5.59 [See Fig. 19] and at 1000 hours it was 43.66 ± 4.03 [See Fig. 20]. This means that the minimum energy required to propagate a crack decreases with aging. From this graph, the values of the Paris law C and m of the region with linear behavior are also obtained [See Table 3]; the exponent m refers to the sensitivity of the stress at the tip of the crack, which was higher in the specimens without aging; while the constant C refers to the sensitivity to the environment, which was higher in the specimens aged at 1000 hours.

The critical energy release rate in failure mode II (GIIC) in the unaged specimens was 44.12 ± 3.61 J/m^2, for the specimens aged 500 hours it was 29.47 ± 1.71 J/m^2, and for the specimens aged at 1000 hours it was 17.65 ± 0.90 J/m^2 [See Fig.21].

The limit energy release rate GIth obtained under dynamic conditions corresponds on average to 66% of the GIC under quasi-static conditions. On the other hand, the energy release rate GIIC obtained under dynamic conditions corresponds on average to 62 % of the GIIC under quasi-static conditions.

Table 2. Energy release rate at quasi- static conditions.

Properties	Non-aging	500 hours	1000 hours
(G_{IC})	126.76 ± 9.28 [J/m²]	116.06 ± 13.55 [J/m²]	117.44 ± 10.04 [J/m²]
(G_{IIC})	68.75 2.38 [J/m²]	25.70 2.86 [J/m²]	10.125 1.40 [J/m²]

Fig. 18. Crack growth rate at mode I impact fatigue conditions. Non aging specimens.

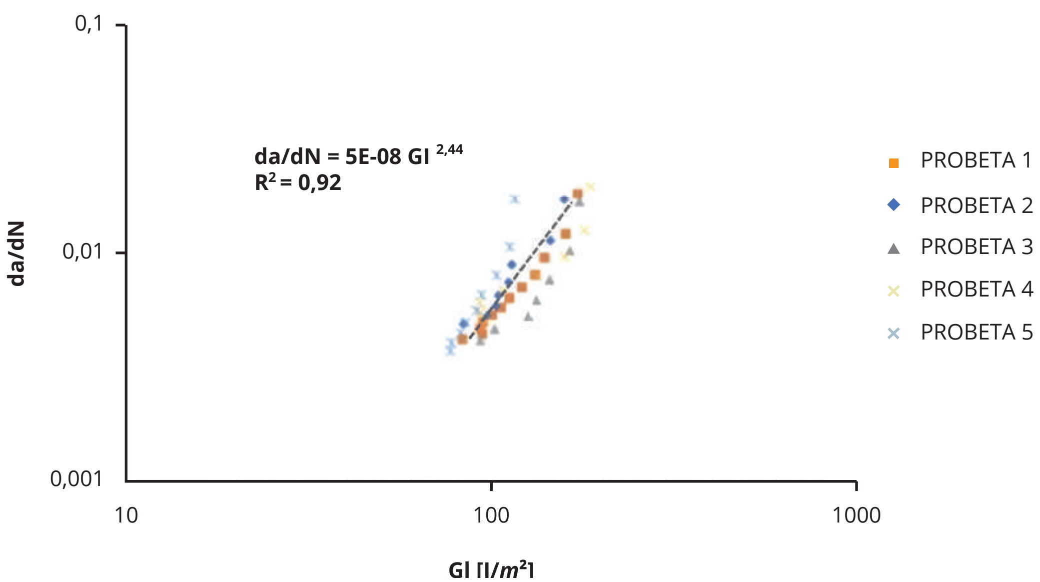


Fig. 19. Crack growth rate at mode I impact fatigue conditions. 500 hours aging specimens.

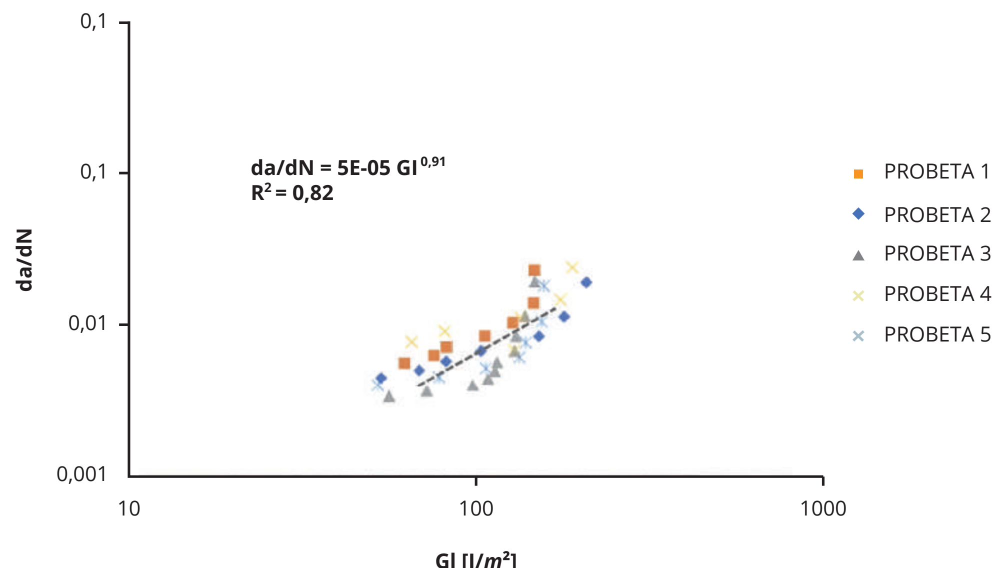


Fig. 20. Crack growth rate at mode I impact fatigue conditions. 1000 hours aging specimens.

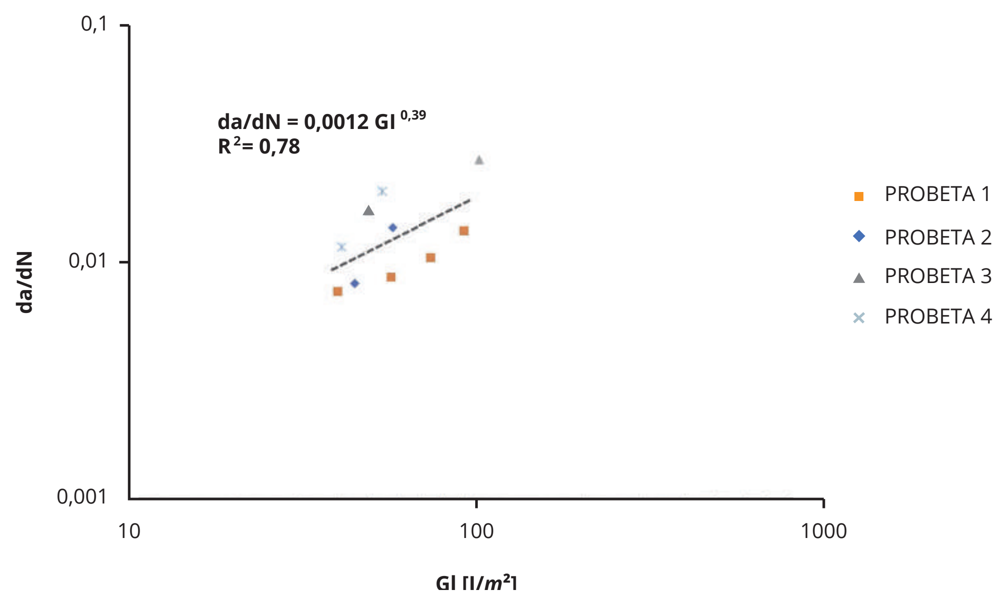
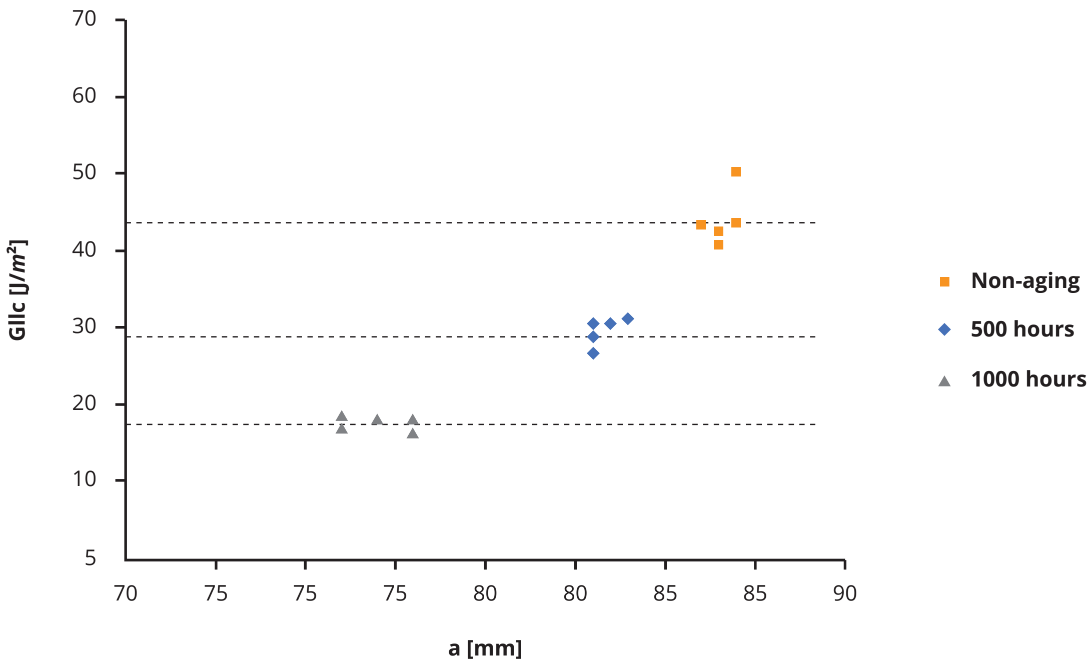


Table 3. Paris law coefficients at mode I impact fatigue conditions.

	m	C [(mm/cycles)/(J/m²)]	G_{Ith} [J/m²]
Non-aging	2.44	$5x10^{-8}$	85.7 ± 6.89
500 hours	0.91	$5x10^{-5}$	57 ± 5.59
1000 hours	0.39	$12x10^{-4}$	43.6 ± 4.03

Fig. 21. Energy release rate at mode II conditions.



Conclusions

No significant changes in the energy absorption capacity in failure mode I are reported under quasi-static conditions due to temperature and humidity at 500 and 1000 hours of aging.

In mode II loading and under the studied conditions, the energy absorption capacity, and therefore the resistance of crack propagation, decreases as the aging time increases.

Non-aged laminates of ultra-high molecular weight polyethylene fibers with polyurethane resin required less energy to propagate cracks under impact loads compared to quasi-static conditions.

The energy required to propagate cracks in mode II was lower than in mode I, under both dynamic and quasi-static conditions; this is related to matrix degradation due to aging and load mode.

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About this article

Author Contribution

- Nohora Alejandra Jiménez Abril: Conceptualization, methodology, data analysis, drafting of the manuscript.
- David Ricardo Alvarado Carvajal: Data analysis, validation, revision of the manuscript.
- Juan Pablo Casas Rodríguez: Data analysis, manuscript review.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest that may have influenced the results or interpretation of the data presented in this article.

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