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HEAT EXPOSURE AND ITS IMPLICATIONS ON THE LOW-VELOCITY IMPACT CHARACTERISTICS OF GFRP LAMINATES

This study investigates how prior heat exposure alters the low velocity impact response of glass fiber reinforced polymer laminates under a constant 16 J impact. Specimens were conditioned at 23.5°C, 50°C, 70°C, and 90°C and then tested. Peak load declined steadily with temperature from 2.040 kN at 23.5°C to 1.535 kN at 50°C to 1.52 kN at 70°C to 1.345 kN at 90°C. Contact duration showed a shallow rise followed by a drop, reported as 8.95 ms at 23.5°C, 9.10 ms at 50°C, 8.45 ms at 70°C, and 8.00 ms at 90°C. Absorbed energy decreased with heat, moving from 15.5 J at 23.5°C to 13.4 J at 50°C to 13.1 J at 70°C to 10.6 J at 90°C. Damage footprints expanded markedly with temperature, with top surface area growing from 152.36 mm^2 at 23.5°C to 185.22 mm^2 at 50°C to 202.47 mm^2 at 70°C to 255.58 mm^2 at 90°C, and bottom surface area from 100.24 mm^2 to 135.66 mm^2 to 155.08 mm^2 to 185.09 mm^2 over the same temperatures. The combined trends indicate thermally driven matrix softening and viscoelastic effects that reduce load bearing capacity and energy dissipation, shorten the effective contact window, and enlarge subsurface damage. Together these quantitative findings clarify how temperature weakens structural integrity under low velocity impact and provide design relevant guidance for material selection, allowable loads and operational safety margins in components expected to operate in elevated temperature environments, including mobility, aerospace, and energy applications.

Keywords: Heat exposure; characteristics; elevated temperature; low-velocity impact; Glass Fiber Reinforced Polymer

1. Introduction

Application of composites originated back in 1950 and since then they have been extensively used in several applications such as aerospace, automotive, consumer, construction industries. These are preferred mainly due to their high strength to weight ratio, GFRP composite laminates have found extensive usage due to their excellent characteristics such as high elastic modulus, low density, and resistance to corrosion [1]. With the usage of composites in the aerospace segment, they are a preferred choice in both primary and secondary structures namely wings, fuselage and other important areas. These structures can be subjected to varying temperatures between –1000C to +2700C [2]. Kara et al. [3] investigated damages of GFRP composite laminates under low-velocity impact at cryogenic temperatures and room temperature. They found that damage areas decrease as the temperature decreases, but the energy absorbed is slightly higher at low-temperature conditions compared to room temperature. Zhang et al. [4] analyzed the impact resistance of GFRP reinforced concrete slabs under elevated temperature. The investigation revealed significant degradation in impact resistance at high temperatures. Bălan et al. [5] investigated the effect of low-velocity multiple impacts at different temperatures on glass fiber reinforced plastic composites, finding temperature as a key factor in impact response with the epoxy matrix softening and delamination occurring as predominant failure modes. The temperature was revealed to play an important role in the impact response of composite material due its progressive softening of epoxy content. Sathvik et al. [6] used finite element modeling and analysis to predict damage in E-glass/Epoxy composite laminates induced by low velocity impact. The analysis was focused on force-time history, energy-time, displacement history, and impact-induced damage size and shape. Vieille and Coppalle [7] studied the impact energy required to induce damage in carbon and glass fibres reinforced Polyether Ether Ketone laminates at high temperatures. They noticed a significant decrease in im-

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pact bearing capabilities of the laminates exposed to a kerosene flame. Karakuzu et al. [8] explored the effect of temperature on the punch shear and low-velocity impact behavior of S2 glass fabric and Carbon-Kevlar hybrid fabric reinforced epoxy composites. The work concluded that absorbed energy and punch shear strength values show similar behavior for hybrid Carbon-Kevlar/epoxy at each temperature, with differences noted for S2 glass/epoxy at all temperatures. Lopresto et al. [9] provided an overview of low-velocity impact behavior of composite laminates at room and extreme temperatures. They compared results on different fibre-matrix combinations and investigated the influence of matrix and temperature on damage evolution. Giovanni Belingardi and Roberto Vadori [10] evaluated the kinetic energy dissipation in composite material during impact. impact behavior of the composite was considered with energy absorption parameters, impact force history and strain rate effect. The findings reveal the dependency of energy absorption parameters and force threshold values on impact velocity. However, the strain rate effect was not sensitive to the loading condition. Aktas et al. [11] investigated the impact behaviour of the laminated glass/epoxy composite at different temperatures ranging from 20°C to 100°C. The first fiber failure greatly influences the maximum contact force, which increases with temperature. The study also reveals the energy absorption capabilities of the laminate decreases with increase in temperature. López-Puente et al. [12] analysed the CFRP damage subjected to high and intermediate impact velocity at temperatures ranging from 25 to −150°C. The evidence shows that the damage greatly influenced temperature, impact velocity and type of laminate. Amin et al. [13] experimentally investigated the maximum energy, elastic energy, maximum deflection, impact force, ductility and compressive strength of fiberglass composite laminate subjected to a range of temperatures. The energy absorption was found to be an independent and dependent parameter at low and high temperatures respectively. Halvorsen et al. [14] conducted experiments on fiberglass composite laminates to investigate their performance under varying temperatures and impact energy levels. The study shows the impact performance changed over the range of temperatures. Suresh et al. [15] investigated the effect of low velocity impact and temperature on residual flexural strength in hemp-basalt/epoxy composites. The experimental evaluation provides the insight of impact and residual strength comparison in hybrid and non-hybrid composites, wherein the non-hybrid composites exhibit better performance than hybrid. Dhakal et al. [16] presented experimental work, focused on the influence of low velocity impact and temperature in jute fiber reinforced unsaturated polyester. The study reveals that the flexural strength decreases considerably with increase in temperature. The work also indicates the cause for the failure of composite is delamination. Daiyan et al. [17] evaluated the characteristics of the crack during low velocity impact at the temperature range between −60 to 20°C in different thickness of polypropylene plates. The central radial crack under the striker ran parallel to the flow direction for the most brittle fracture at low temperature and it ran perpendicular to the flow direction in other cases. Jaehyeong et al. [18] proposed the combination of shear thickness fluid layer in the carbon fiber reinforced polymer composite to enhance the impact resistance. They evaluated this requirement at different temperatures and found that the energy absorption was enhanced to 38.10% at 25°C. Indran et al. [19] discussed the adavance materials and their manufacturability for wide range of engineering applications. The discussion includes the challenges in the manufacturing of composistes contributing in reduction of cost, increased profitability, regulatory compliance and sustainability. Samuel Ibekwe et al. [20] identified that most existing research focuses on the impact behavior of composites at room temperature or within a narrow temperature range. Studies that explore the effects of both high and low temperatures on GFRP laminates are sparse.

In the present study, the influence of heat exposure on low velocity impact of GFRP/Epoxy composite laminate are investigated namely, ambient temperature (23.5°C), 50°C, 70°C and 90°C and a total of 4 trials are conducted for each temperature to ensure the average results are obtained. The values for the thermal performance are based on the glass transition temperature as determined by STA 449 F5 Jupiter, from Netzsch which was at 118°C.

2. Materials and methods

2.1. Fabrication

The construction of the composite laminate was skillfully executed using the Vacuum Bagging Technique, a method distinguished for its precision and effectiveness. In this modified process, a composite laminate consisting of six layers exclusively of Glass Fiber was developed. A meticulous hardener to epoxy ratio of 1:10 was accurately prepared to ensure the ideal resin composition for the fabrication process. The setup incorporated the use of 12 HP vacuum pumps, pivotal for achieving the desired composite configuration. The selection of materials was critical, with Glass Fiber Cloth sourced from MARKTECH COMPOSITES Pvt Ltd in Bengaluru, known for their superior quality offerings with an average thickness of 0.26 mm per layer. The Vacuum Bagging Technique, completed over a span of four hours, entailed the organization of the Glass Fiber layers in a specialized stacking sequence, denoted as [G+G+G+G+G+G], as depicted in Fig. 1.

This arrangement was chosen to assess the laminate's resistance to damage across both surfaces comprehensively, with each Glass Fiber layer having a weight of 200 gsm. A bubble burster played a key role in eliminating any surplus resin and air pockets, ensuring a smooth, defect-free laminate. Following the vacuum bagging, the laminate underwent a meticulous drying phase in a hot air oven at 60 degrees Celsius for two hours, significantly enhancing its mechanical strength. After drying, the laminate was cut to specifications based on ASTM Standard D7136/D7136M, yielding samples of 150 mm by 100 mm, each with a thickness of 2.0 ±0.2 mm. To refine the edges and adhere to precise standards,

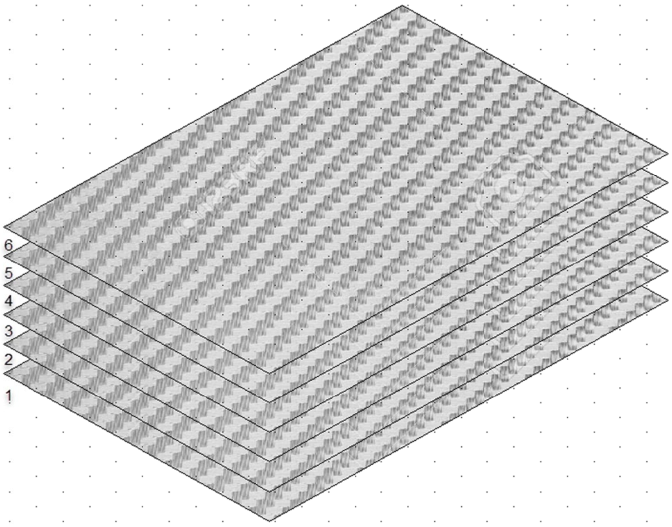

Fig. 1. Glass fiber cloth stacking

the cut laminates were subjected to an additional drying session for 30 minutes at 40 degrees Celsius, after being shaped using waterjet cutting technology as shown in Fig. 2.


Fig. 2. Waterjet cutting of laminates

2.2. Drop Weight Impact Testing

Low-velocity Impact Testing is critical for analysing the durability and impact resistance of materials when exposed to varied ambient temperatures prior to testing. This approach employs a specific protocol with a maximum drop height of 1.5 meters, targeting an impact energy of 16J at a drop height of 397 mm on samples made from six layers of Glass Fiber cloth. Unlike tests conducted within a heating chamber, the specimens here are pre-conditioned to different temperatures and then subjected to impact testing. The temperature of each specimen at the time of impact is accurately measured using a non-contact temperature gun, ensuring precise and consistent thermal data. This method allows for an in-depth examination of how pre-exposure to different temperatures influences the Glass Fiber composite's capacity to absorb and distribute impact energy. By documenting the temperature of each specimen with the non-contact temperature gun immediately before the impact, the correlation effects of thermal conditioning on the material's performance can be determined. The specifications of test specimens are detailed in TABLE 1. The temperature was maintained within a climatic chamber.

TABLE 1

Specimen code for low velocity impact at different temperatures

Specimen Code	**Impact Energy, (J)**	**Temperature in (°C)**	**Experimental Velocity, (m/sec)**
T1	16	23.5 (Ambient Temp)	2.801
T2		50	
T3		70	
T4		90	

Within the low-velocity impact testing setup, an anti-rebound mechanism is incorporated to prevent secondary impacts, ensuring each test measures only the initial strike. Specimens, sized at 150 mm by 100 mm, are firmly held in place using toggle clamps, adhering to ASTM D7136 standards, to maintain a consistent and reliable test environment. The system utilizes a pair of sensors to accurately capture the velocity at impact, tracking both initial and final speeds, which is vital for experimental accuracy. A 4.1 kg Total Unitary Projectile (TUP) is employed to apply uniform impact forces across tests. Impact force and timing are precisely recorded with an NI 6210 Data Acquisition Card from National Instruments, while a high-accuracy 50 kN impact load cell measures peak forces, providing critical data for analysis, as illustrated in Fig. 3.


Fig. 3. Low velocity impact testing machine

2.3. Damage Area Assessment

In the present study, to evaluate the extent of damage incurred by GFRP laminate after exposure to low-velocity impacts under varying temperature conditions, a meticulous damage area analysis was performed. The utilization of Image J software, a powerful tool in the realm of image processing and analysis facilitated this analysis. The methodology involved the conversion of pixels, as captured in the digital images of the impacted materials, into measurable units (millimetres) to accurately quantify the area affected by damage. This conversion process is crucial as it bridges the gap between digital image representations and tangible, real-world measurements, thereby enabling a precise calculation of the damage area in square millimetres (mm^2). The approach adopted in this study not only underscores the importance of leveraging digital tools for material damage assessment but also highlights the software's capability in providing detailed insights into the scale of impact-induced damage, offering valuable data for further analysis and material improvement strategies.

3. Results

The study focused on assessing the impact of varying temperatures namely ambient, 50°C, 70°C and 90°C on laminate materials under a specific Low Velocity Impact (LVI) scenario, with an impact energy set at 16 J. A key feature of the experimental setup was the implementation of an advanced anti-rebound system, designed to eliminate secondary impacts and ensure the integrity of the impact data. The experiment utilized a high-frequency data acquisition system, operating at 50 kHz, equipped with an optical sensor for precise measurement of the impactor's velocity at the moment of contact with the laminate. Additionally, a load cell with a capacity of 50 kN was utilized to accurately measure the forces exerted during the impact, providing critical insights into the LVI dynamics on laminate materials, especially those incorporating carbon. The experimental protocol included testing multiple samples to ensure the findings' consistency and reliability, and carefully examining the role of temperature in influencing the material's behavior under LVI conditions.

3.1. Force vs Contact Duration

In a low-velocity impact test, the Force vs. Time graph, as shown in the Fig. 5, is crucial for understanding the material response under impact conditions. Such a graph typically displays the force experienced by the material throughout the impact event. The force-time graph usually exhibits an initial peak followed by oscillations and drop-off in the load scenario. Since the GFRP showed pronounced oscillations, the peak load decreased for an increase in temperature.

At ambient temperature (T1), the peak load was found to be 2.040 kN and for T4 the load was 1.345 kN as shown in Fig. 4 and TABLE 2, this gave a clear understanding of the effect of temperature on low-velocity impact, wherein the peak force decreased with increasing exposure to heat, the oscillations are mainly due to damage phenomenon being carried out during the impact test. Thermal softening increases indentation depth and changes the effective Hertzian/contact stiffness during the hit. As the contact radius and subsurface state evolve (and delaminate), the instantaneous $k(t)$ varies, modulating the measured force.

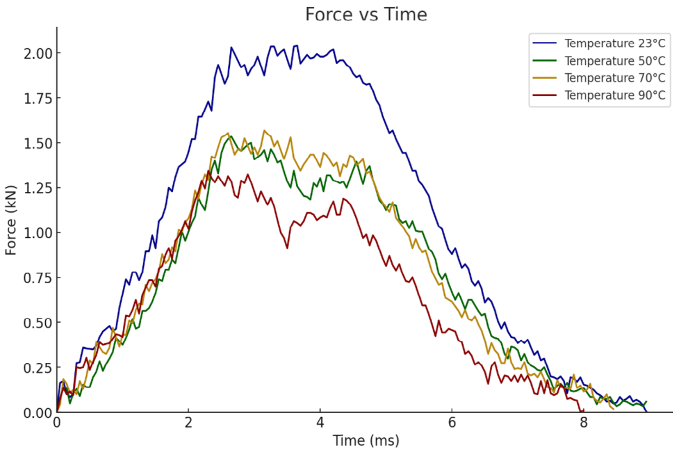

Fig. 4. Force – Time plot

The peak force almost remained constant between T2 and T3 this was because at elevated temperatures a phenomenon of softening and plasticization was being carried out at the matrix level and similar trends were observed by C Suresh Kumar et al. [15].

3.2. Velocity vs Time

The velocity-time plot in the context of low-velocity impact gives the dynamic response of the material or structure. From the time of the plot to the cessation of motion, the initial

TABLE 2

Low velocity impact test results for different temperature

Specimen Code	Impact Energy (J)	Temperature (°C)	Peak Force (kN)	Contact Duration (ms)	Absorbed Energy (J)	Damage Area (mm^2) Top	Damage Area (mm^2) Bottom
T1	16	23.5	2.04	8.95	15.5	152.36	100.24
T2		50	1.535	9.10	13.4	185.22	135.66
T3		70	1.52	8.45	13.1	202.47	155.08
T4		90	1.345	8.00	10.6	255.58	185.09

impact velocity in the present study involved the speed at which the tup moved and till the impactor struck the material. Upon striking the material, velocity drastically dropped down. This deceleration can provide a better understanding of the material performance for different applications. As per Fig. 5, it is noted that the contact duration initially raised and then reduced with an increase in temperature. This can be due to the matrix fiber interface being soft and leading to increased contact duration. The highest contact duration was noted in T2 which accounts for more ductility of the material thereby absorbing more energy before falling while in T4 the duration was the least as shown in TABLE 2, this was due to severe plastic deformation leading to quick failure of the matrix and fiber interface. The initial velocities for all temperatures start at approximately the same value, but as time progresses, the curves begin to diverge slightly

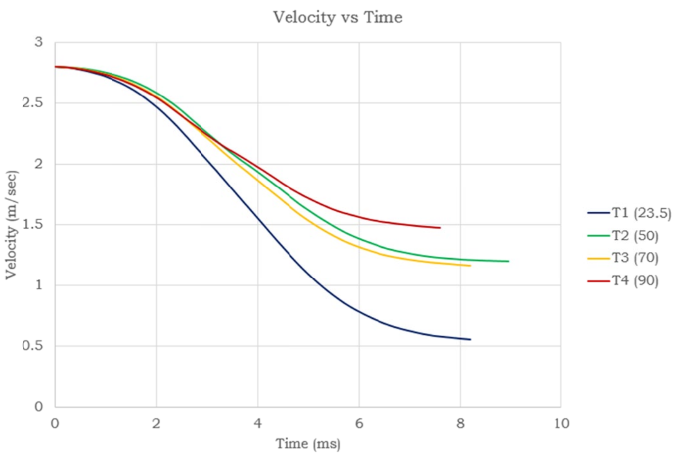

Fig. 5. Velocity vs Time plot

Trend on contact duration shows a general decrease in contact duration as temperature increases from 23.5°C to 90°C, with a slight increase at 50°C before decreasing again. This suggests that temperature affects the material's ability to absorb or dissipate energy, possibly due to changes in its viscoelastic properties. This divergence implies that temperature has an impact on the velocity. These studies enable users to make informed decisions on the selection of materials for aerospace, automotive and defense applications.

3.3. Absorbed Energy Studies

In the context of evaluating the efficiency of energy absorption over time with an imposed impact energy of 16 Joules, the experiment aims to delineate how different temperatures affect the absorption characteristics of a given material or system. Fig. 6 depict the energy absorbed vs time plot. At T1 (23.5°C), the system underwent a contact duration of 8.2 ms and absorbed 15.5 Joules of energy. This high level of energy absorption, closely approaching the total impact energy, indicates that the material or system is highly efficient in energy dissipation at this moderate temperature. The effectiveness in energy absorption could be attributed to the material's optimal resilience and ductility at room temperature, facilitating significant energy dissipation over a short duration. At T2 (50°C), the contact duration increased slightly to 8.95 ms, with the energy absorbed decreasing to 13.4 Joules. The increased temperature leading to a reduced energy absorption capacity suggests that the material's ability to absorb energy diminishes as the temperature rises. This behavior can be due to alterations in the material's structural properties at elevated temperatures, possibly reducing its ability to deform elastically and absorb energy efficiently.

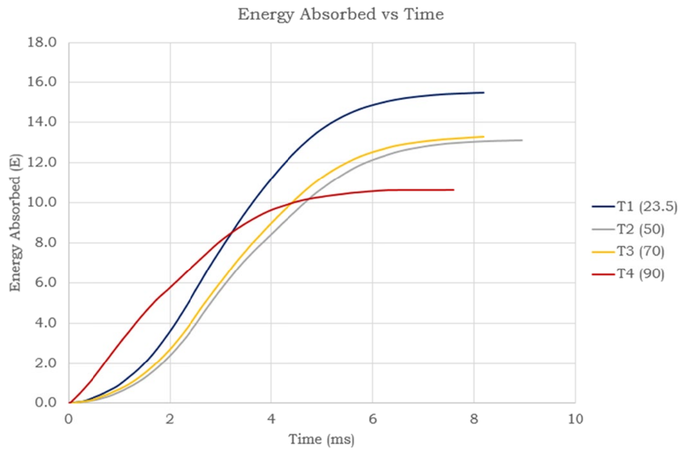

Fig. 6. Energy absorbed vs Time plot

For T3 (70°C), the system's contact duration was 8.2 ms, with an absorbed energy of 13.1 Joules. A similar trend was observed for T4 (90°C), there was a notable decrease in both contact duration (7.6 ms) and energy absorbed (10.6 Joules) as shown in TABLE 2. This indicates that as the temperature continues to increase, the system or material becomes less efficient at absorbing energy. The decreased contact duration alongside lower energy absorption could reflect a more brittle material behavior at higher temperatures, where the material is less capable of undergoing deformation to dissipate energy.

3.4. Damage Area Analysis

In any low-velocity impact test, one of the most important analyses is the damage area assessment, this allows engineers to make necessary decisions before the material is fabricated and later sent for its applications. In the realm of assessment, several techniques can be used to identify the damaged area. One of the simple and easy ways to assess is by utilizing the ImageJ software tool which is an open source entity. The damage area after identifying them is tabulated in TABLE 2. The damage area of the laminate impacted at room temperature (RT) measured using ImageJ software is shown in Fig. 7. The temperature can significantly impact the structural performance of the composite laminate causing changes in matrix softening, delamination and fiber matrix failure. In any low velocity impact studies, surface interaction damage is the first type and this further propagates to the bottom layer. The first type of damage during an impact is matrix cracking, which arises at the damage threshold [19]. Matrix microcracking, fibre–matrix debonding, and delamination initiate and grow intermittently. Each damage burst locally unloads and then restiffens the contact zone, creating serrated up–down steps in the force trace. Higher temperatures lower the thresholds for these events, so serrations intensify.

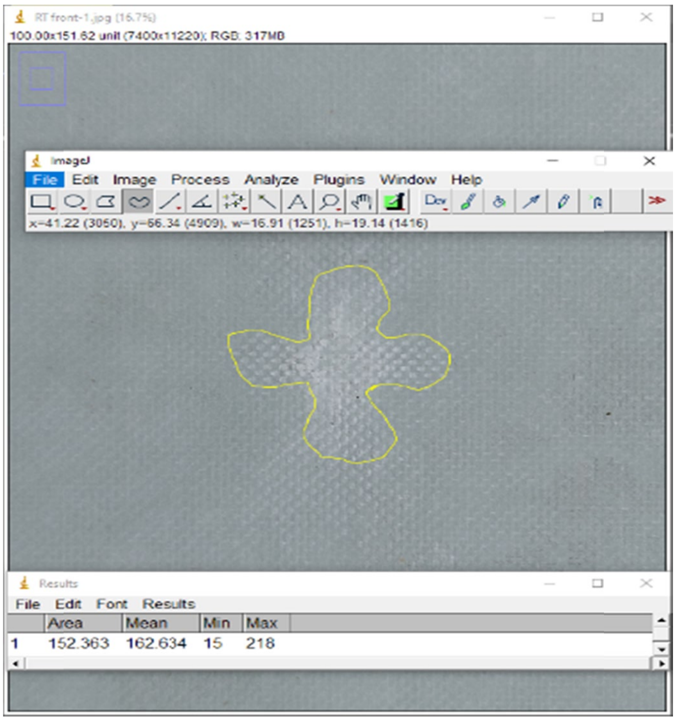

Fig. 7. Damage area assessment using ImageJ software

A similar trend was observed in the present studies, where damage to the matrix in the neighbouring areas was extended and then propagated to the bottom layers. All the specimens displayed hemispherical impact damage on the top layer while the rear surface displayed a different pattern based on the variations of the temperature. With increase in temperature, the damage area also increased considerably. Damage area and its influence due to temperature changes from brittle to ductile nature with increased temperature and a viscoelastic response was noted which resulted in higher damage area from 23.5°C to 90°C. The damage area increased with increase temperature. Fig. 8 dipicts the damage area for different impact temperatures.

4. Conclusions

Based on the findings from the study on the impact of heat exposure on the low-velocity impact characteristics of Glass Fiber Reinforced Polymer (GFRP) laminates, the results can be summarized with the specified points as follows:

Temperature – The study investigated the behavior of GFRP laminates at various temperatures: ambient (23.5°C), 50°C, 70°C, and 90°C. It was observed that as temperature increases, the mechanical properties and impact resistance of GFRP laminates are significantly affected, demonstrating a decrease in peak load and absorbed energy, with an increase in damaged area.

Damage Area – With the increase in temperature, the damage area induced by low-velocity impacts on GFRP laminates also increases. At higher temperatures, the material exhibits

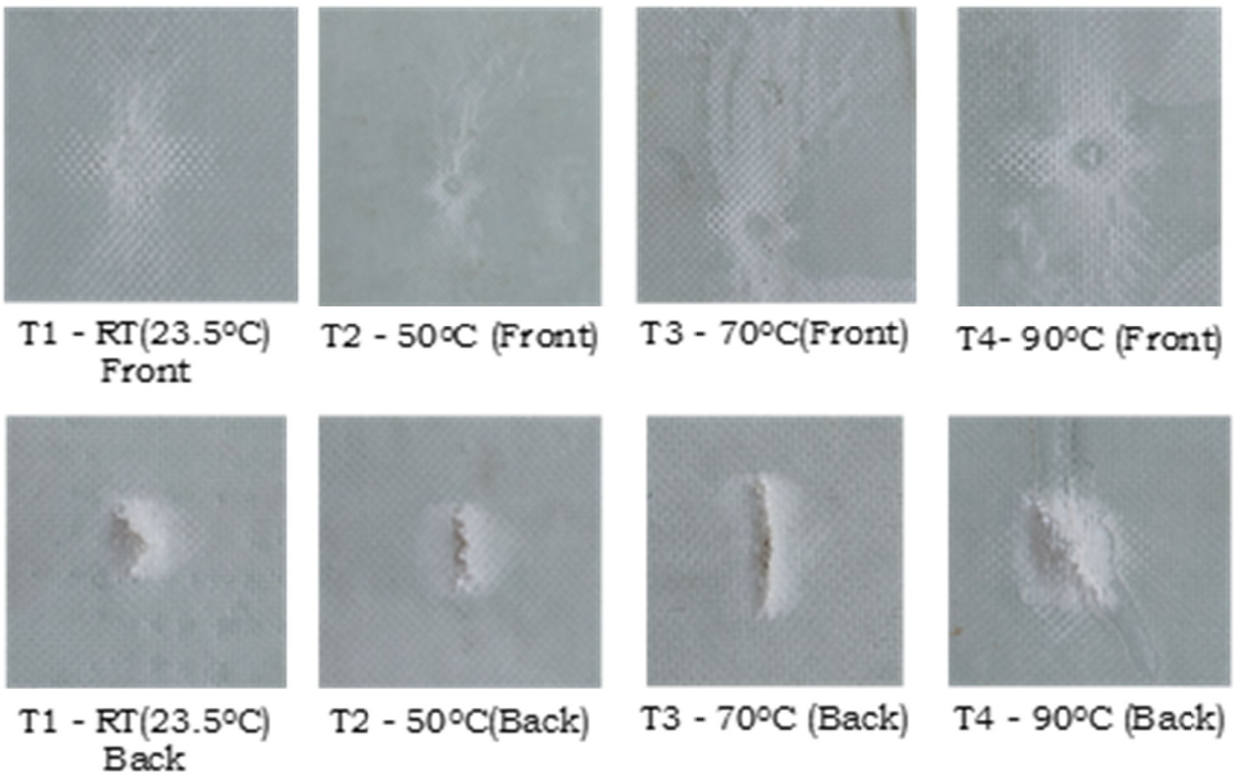

Fig. 8. Damaged area for different impact temperatures

greater damage extents, highlighting the temperature's influence on the composite's structural integrity. This suggests that the matrix becomes softer and less capable of distributing the impact energy, leading to larger areas of damage.

Peak Load – The peak load observed during the impact tests decreases as the temperature increases. At ambient temperature, the peak load is higher compared to that at 90°C. This indicates that GFRP laminates can withstand greater forces without significant deformation or damage at lower temperatures, whereas at elevated temperatures, their ability to withstand such forces diminishes.

Absorbed Energy – Absorbed energy decreases with an increase in temperature. At ambient temperature, GFRP laminates exhibit higher energy absorption capabilities, which reduce as the temperature rises. This trend suggests that the laminates' ability to absorb and dissipate energy from impacts is compromised at higher temperatures, leading to more pronounced damage and reduced impact resistance.

Velocity – The velocity at impact was controlled to deliver a consistent impact energy of 16J across all temperature conditions. However, the study's findings on velocity-time behavior suggest that temperature affects the laminate's response to impact. The material's response, in terms of deceleration and contact duration, indicates that higher temperatures may lead to quicker energy transfer and potentially faster velocity reductions post-impact, correlating with the observed reductions in absorbed energy and increased damage areas.

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