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Title: *Investigation of Bending After Impact Failure Behavior in Foam-Core Hybrid Sandwich Composites at Extreme Low Temperature*

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ABSTRACT

In this study, we investigate the behaviour of foam-core sandwich composites, specifically with regards to bending after impact (BAI), in the presence of carbon fibre reinforced polymer (CFRP) and/or glass fibre reinforced polymer (GFRP) facesheets. To accomplish this, we utilize an Instron 5582 universal testing machine to conduct 3-point bend test on specimens that have previously undergone impact testing. The 3-point bend tests are conducted at both room temperature (23°C) and low temperature (-70°C) to evaluate the effect of low temperature (LT) on the BAI behaviour of the composite materials. Moreover, we explore the effect of different stacking sequence and layup configuration of GFRP and CFRP layers on sandwich composites under flexural loading. We analyse the force-displacement curves and compare peak stress values to gain insight into the influence of the CFRP and GFRP hybrid face sheets.

Results suggest that altering the arrangement of CFRP and GFRP layers has a significant impact on the flexural strength of the hybrid composite. At LT, the specimens experience more flexural damage due to increase in brittleness. However, the peak stress at LT increases due to the increase in the compressive strength of the CFRP/GFRP layers. Specimens featuring a GFRP layer on the outside (referred to as 'glass first' specimens) and specimens with alternating CFRP/GFRP layers, with CFRP positioned on the outermost layers (referred to as 'CGCG'), when impacted at 15J, experience core shear and core debonding at LT flexural test. Overall, GC is found to be the optimal configuration. This configuration provides excellent strength from the inner CFRP layer and while the outer GFRP layer offers damage resistance during impact test.

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INTRODUCTION

The decline of Arctic Sea ice in recent years has led to the emergence of new sailing routes, resulting in an increased presence of marine and naval vessels in the challenging arctic conditions [1]. To effectively operate in this environment, the use of advanced materials is crucial, and hybrid sandwich composites have gained significant attention for their unique properties and versatility. Hybrid sandwich composites consist of alternating layers of stiff face sheets made from different materials, separated by a lightweight and shear-resistant core. Hybridization combines different fibres to create a composite material with improved properties by leveraging the unique characteristics of each constituent, leading to a more customized behaviour for the composite [2]. Hybrid sandwich composites have various applications in industries such as aircraft manufacturing, shipbuilding, wind energy, and infrastructure, offering advantages such as increased bending stiffness, reduced weight, excellent thermal insulation, and effective acoustic damping.

While sandwich composites offer many benefits, they encounter a significant issue regarding their susceptibility to damage from impacts and catastrophic failure due to low compressive strength especially under LT environment. Extensive research has been conducted to investigate the factors affecting impact tolerance, flexural tolerance, and damage resistance in sandwich composites. Dhakal et al. [3] investigated the influence of temperature on the post-impact flexural response of composite laminates, noting a significant influence on post-impact damage characteristics, but their work focused on high temperatures. Jia et al. [4] examined the flexural performance of composites at LT, but their study was limited to composite laminates. Erickson et al. [5] analysed the post-impact bending behaviour of foam core sandwich structures through impact tests conducted at LT, but their bending tests were performed at room temperature (RT). This has led to an unclear understanding of the relationship between LT and post-impact flexural behaviour in hybrid composite sandwich structures.

Therefore, this study aims to investigate the post-impact flexural behaviour of foam-core hybrid sandwich composites made of Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) at both RT & LT by providing valuable insights into the flexural response of hybrid sandwich composite structures in extreme Arctic environments.

EXPERIMENTAL METHODOLOGY

Material Configurations

The sandwich composite, manufactured by Rock West Composites, consists of a 6.35 mm thick Divinycell Type H100 foam core, along with face sheets composed of different configurations of woven carbon fibre and fiberglass reinforced polymers. Each face sheet comprises of 8 plies, resulting in a combined thickness of 2 mm. This arrangement creates a sandwich composite with a total thickness of 10.35 mm. The

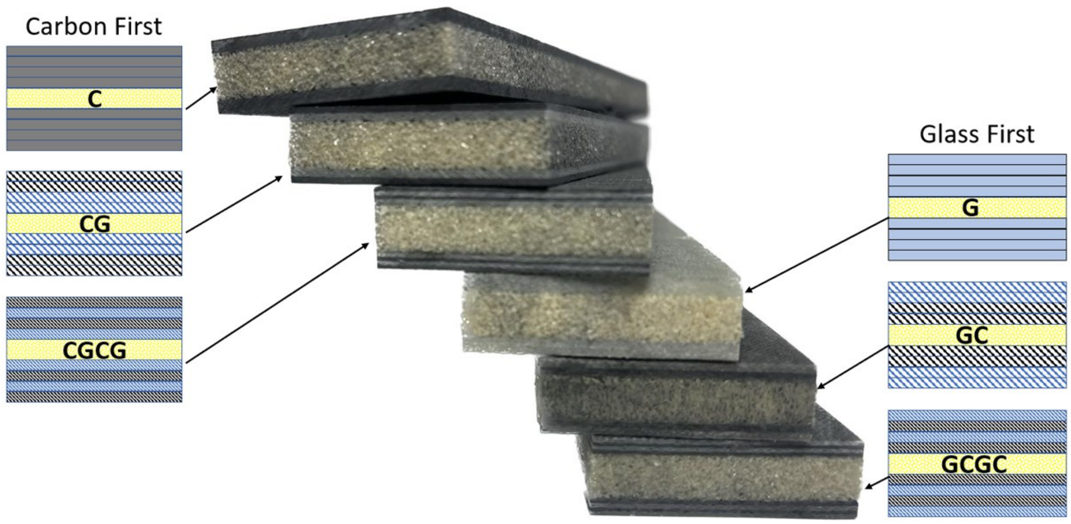

Figure 1. Hybrid sandwich composite layup configurations used in this study: Carbon First (C, CG & CGCG) and Glass First (G, GC & GCGC)

fabrication process involved a wet layup technique, wherein dry carbon fiber and fiberglass fabrics were manually infused with epoxy resin and applied in specified sequences to achieve hybridization. The entire lamination was then carefully enclosed in a vacuum bag and cured in an oven to ensure optimal consolidation of the plies.

The impact test was conducted with 15J and 30J impact energy at RT & LT conditions using Instron CEAST 9350 machine with a hemispherical impactor. To conduct impact testing, the composite panels were cut into specimens measuring 150 mm x 100 mm using a diamond bladed saw. After the impact tests were carried out, the specimens were further trimmed to dimensions of 150 mm x 25 mm for flexural testing. For the low-temperature flexural test, specific samples were conditioned in a freezer for a day at -70°C to attain thermal equilibrium.

In this study, specimens C, CG and CGCG which have CFRP as outer layer are referred to as carbon first specimens, whereas G, GC and GCGC which have GFRP as outer layer are referred to as glass first specimens, as illustrated in Figure 1.

Bending After Impact (BAI) Test

The three-point bend test is conducted utilizing an Instron 5582 universal testing machine equipped with a 10kN load cell. To facilitate low-temperature testing at -70°C, an environmental chamber is employed, which is cooled using liquid nitrogen, as depicted in Figure 2(a). The test configuration involves setting the test span, denoted as L, to 100 mm, while the crosshead displacement rate is maintained at 0.5 mm/min.

During the test, the impacted specimen is carefully positioned on the bending fixture, ensuring that the impacted face sheet experiences compression (inward bending), as illustrated in Figure 2(b). To ensure reliable and consistent results, a minimum of two specimens are tested in each scenario to verify repeatability, following the guidelines outlined in ASTM C393 Standard Test Method.

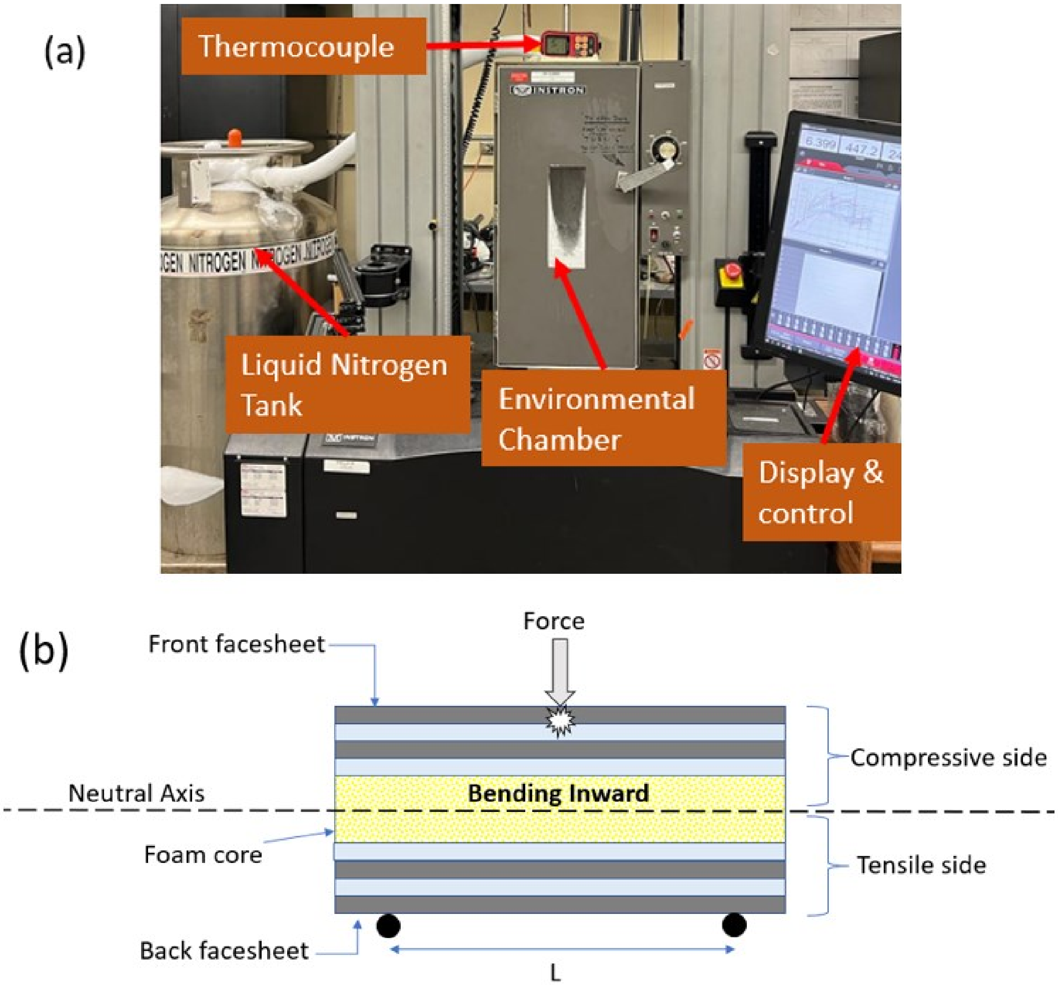

Figure 2. (a) Low temperature three-point bend test setup using Instron 5582. (b) Schematic illustrating three-point inward bend test case: where impact damage is at top.

RESULTS AND DISCUSSION

Force-Displacement curves

Figures 3(a-b) presents force-displacement curves for specimens subjected to inward bending at RT, with impact energies of 15J and 30J. Notably, these curves show no significant load drops at both 15J and 30J. This absence of load drop at RT can be attributed to the prior damage sustained by the front face sheet during impact testing. Consequently, the flexural test at RT does not induce significant damage, resulting in eliminated load drops. The curves display linear increases until reaching a saturation point, beyond which the increase in the flexural force becomes gradual.

Specimen C demonstrates the lowest flexural load carrying capacity among all the tested specimens, whereas the load carrying capacity increases as we move to CG and CGCG. This difference can be attributed to the stacking sequence of the CFRP/GFRP layers. Specimen C, which has only CFRP layers, exhibits higher brittleness, resulting in a lower load carrying capacity. On the other hand, CG and CGCG specimens gain ductility through the inclusion of GFRP layers, enabling them to withstand higher loads and providing increased resistance to compressive stress. The flexural load carrying capacity of all the glass first specimens is similar and higher than that of C and CG. This is because the outer GFRP layers being ductile not only mitigate the damage during impact test but also reduces the compressive stress on the inner CFRP layers during flexural test enabling the specimen to carry high flexural load.

Figure 3(c) illustrates force-displacement curves for specimens impacted at LT with impact energy of 15J. Significant load drops are evident in the 15J specimens due to increase in brittleness at LT, leading to catastrophic failure. In C and CG, the peak force linearly increases until reaching a maximum value, after which it drops due to the breaking of the compression-side CFRP layer. Both C and CG show no signs of core shear or debonding and exhibit only one load drop. Besides, CGCG specimens resemble glass first specimens by showcasing a higher flexural force in comparison to C and CG specimens. Moreover, they demonstrate two noticeable load drops during testing. The first load drop occurs due to the breaking of the brittle CFRP face sheet, followed by an increase in flexural force resulting from the contribution of the ductile GFRP layer. This flexural force continues to rise until reaching the second peak. The load drop following the second peak indicates core shear and debonding of the core from the GFRP/CFRP layers on the tensile side of the specimen as shown in Figure 4(a-d). This core shear and debonding occurs due to the PVC core undergoing embrittlement at LT. Similarly, for GC and GCGC, the first load drops signify the breaking of the compression-side CFRP layer, while the second drops mark core shear and debonding from the GFRP/CFRP layers.

Figure 3(d) demonstrates force-displacement curves for LT specimens impacted with 30J energy. The intensity of load drop is considerably reduced due to pre-existing damage on the facesheet caused by the high impact energy at LT. Among the carbon first specimens, C exhibits the lowest load carrying capacity due to severe impact damage. CG & CGCG experiences a small load drop corresponding to the damage of the brittle CFRP layer, while the flexural force increases gradually, supported by the strength provided by the ductile GFRP layer. Among the glass first specimens, the peak force of G and GC increases steadily without any load drop, as the less brittle glass fibers allow for continued deflection of specimen without significant drops in load. GCGC exhibits small load drops associated with the flexural damage of the compression-side CFRP layers.

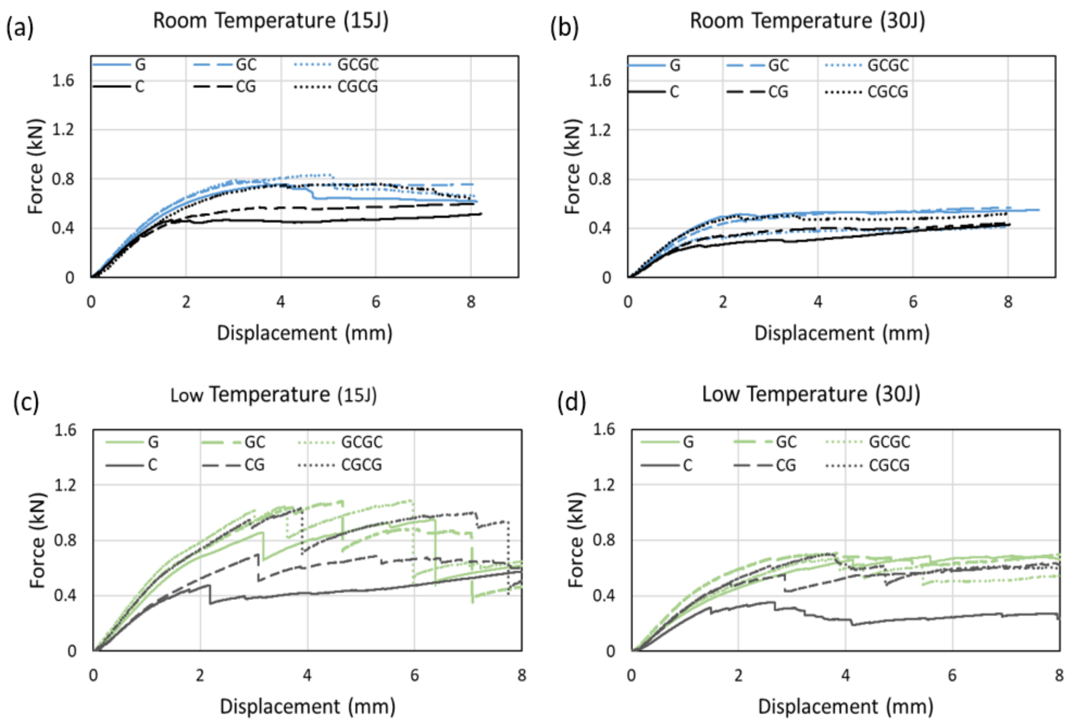

Figure 3. Force-displacement graphs of (a) 15J at RT. (b) 30J at RT. (c) 15J at LT. (d) 30J at LT.

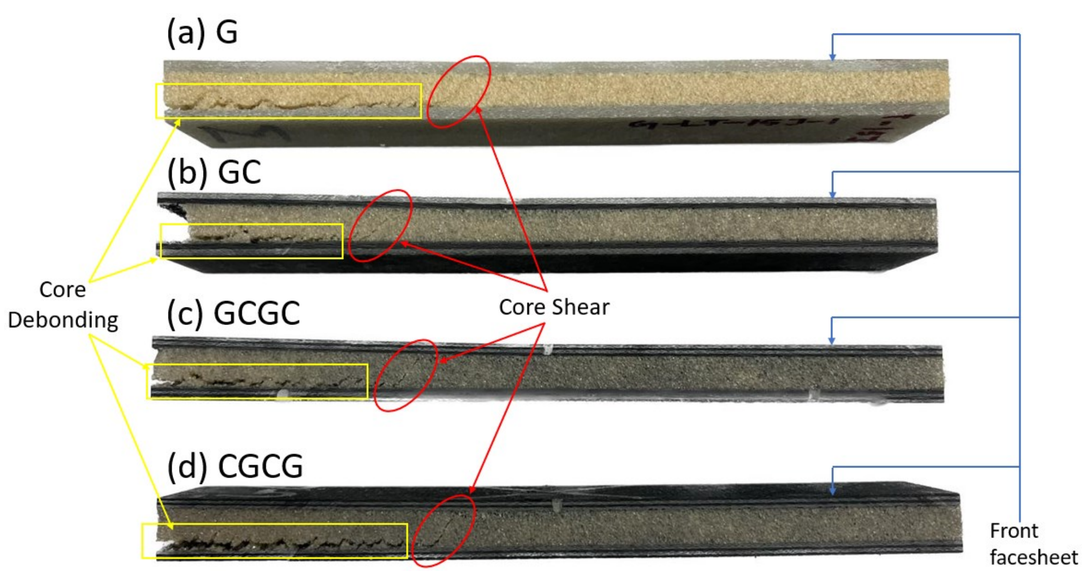

Figure 4. Picture of LT samples impacted at 15J which experienced core shear and core debonding during inward bend test.

Peak Stress

Figure 5(a-b) presents the peak flexural stress graph for specimens subjected to inward bending at RT and LT. It is observed that for both 15J and 30J impact energies,

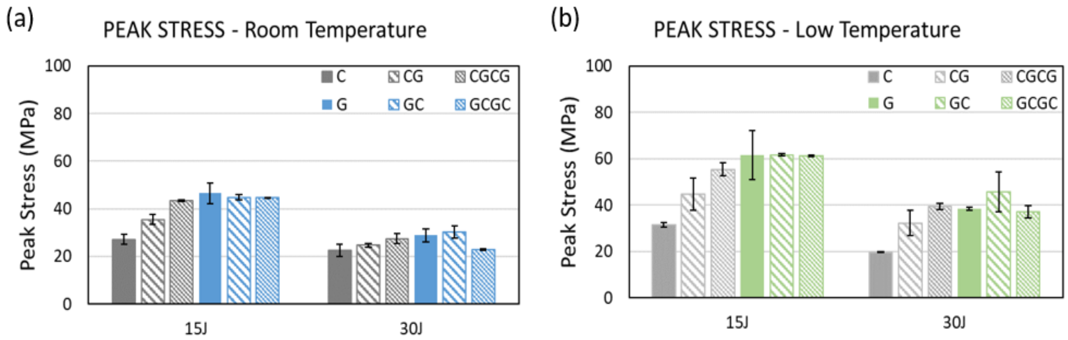

Figure 5. Peak stress graph of (a) 15J and 30J at RT. (b) 15J and 30J at LT.

the peak flexural stress of carbon first specimens increases as the number of alternate GFRP layers in the specimen increases. This is because the compressive strength of GFRP is higher than that of CFRP, so having more alternate GFRP layers on the compressive side leads to an increase in peak flexural stress. Conversely, increasing the number of CFRP layers results in a decrease in peak flexural stress.

At an impact energy of 15J, the peak stress of all glass first specimens remains consistent. The peak stress value for RT is 45MPa, while at LT it is 60MPa. However, when the impact energy is increased to 30J, the specimen GCGC, which has more alternate CFRP layers, exhibits a decrease in peak stress. This decrease can be attributed to the extensive damage suffered by the brittle CFRP fibers in GCGC at the higher impact energy, leaving the ductile glass layers to bear the flexural load. Moreover, all the LT specimens have higher flexural peak stress compared to RT specimens. This rise in flexural stress can be attributed to the increased compressive strength of the CFRP/GFRP layers at LT, resulting in improved performance under flexural load [6].

It can also be observed from Figure 5(a-b) that as the impact energy increases from 15J to 30J, the peak force of GC becomes the highest among all the specimens. This is because the outer GFRP layer mitigates impact damage, while the inner CFRP layer provides superior strength to the composite. Therefore, GC configuration exhibits lower load drop and higher peak stress, making it a preferable choice.

CONCLUSIONS

This research investigated the flexural behavior of hybrid composite specimens subjected to inward bending under different impact energies and temperatures. The research findings indicate that the flexural behavior of specimens under different impact energies and temperatures varies based on the stacking sequence of GFRP and CFRP layers. Specimens with prior impact damage showed no load drops at RT. At LT, significant load drops occurred indicating high damage due to increased brittleness. The GC configuration showed the highest peak stress and lower load drop, making it a preferable choice. This study illustrates the potential of combining CFRP and GFRP to address the flexural damage caused by temperature effects. By strategically arranging layers of CFRP and GFRP, the hybrid material can leverage the strength of CFRP and the ductility of GFRP, resulting in improved BAI performance.

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