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Title: *Impact Damage and Failure Mechanisms of Hybrid Facesheet Sandwich Composites under Low Temperature Conditions*

Authors: Jason P. Mack
Faizan Mirza
Arnob Banik
M.H. Khan
K.T. Tan

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ABSTRACT

In this study, we experimentally investigate the impact damage and failure mechanisms of foam-core sandwich composites with carbon fiber reinforced polymer (CFRP) and/or glass fiber reinforced polymer (GFRP) face sheets. Specimens are conditioned and impacted over a wide temperature range (from room temperature of 23°C down to -70°C) using Instron CEAST 9350 impact test machine. This work also explores the use of hybrid composite face sheets, with various configurations of layering CFRP and GFRP in the face sheets of foam-core sandwich composites.

Results show that exposure to low temperature causes more severe damage, particularly in specimens with CFRP face sheets, due to their extreme brittleness. GFRP face sheet specimens are able to achieve larger deformation and absorb greater impact energy even at low temperature conditions. There is a significant benefit in using hybrid configurations, by striking a balance between brittle (CFRP) and ductile (GFRP) materials and harnessing their mechanical advantages of high strength and high fracture toughness, respectively. Results also demonstrate that hybridization is a solution to reduce temperature effects in impact deformation. Careful placement of CFRP and GFRP in layup order can harness the best impact performance. X-ray micro-computed tomography (μCT) images reveal substantial delamination at the interfaces between CFRP and GFRP layers. It is also observed that CFRP layers fail by brittle fracture, while delamination is the major damage mode within GFRP layers. Other complex failure mechanisms in the composite face sheets (such as matrix crack and fiber breakage) and foam core (core crushing, core shearing and interfacial debonding) are also presented.

Jason P. Mack, Department of Mechanical Engineering, The University of Akron, Akron, Ohio 44325-3903, U.S.A.
Faizan Mirza, Department of Mechanical Engineering, The University of Akron, Akron, Ohio 44325-3903, U.S.A.
Arnob Banik, Department of Mechanical Engineering, The University of Akron, Akron, Ohio 44325-3903, U.S.A.
M.H. Khan, Department of Mechanical Engineering, The University of Akron, Akron, Ohio 44325-3903, U.S.A.
K.T. Tan, Department of Mechanical Engineering, The University of Akron, Akron, Ohio 44325-3903, U.S.A.

INTRODUCTION

The topic on climate change has attracted tremendous attention in recent years. The effect of global warming, sea-level raising and arctic-ice melting have raised serious concerns. The reduction in Arctic sea ice region over the last three decades has opened new sailing routes which are more efficient and economical than the traditional ones [1]. This has resulted in the increased use of marine and naval vessels in extreme low-temperature arctic conditions. The fundamental challenge of operating in such a cold and harsh environment lies in the understanding of how materials and structures behave and perform in this challenging circumstance. Recently, the application of light-weight composite materials in the low-temperature domain is of great attention as they are hugely deployed in aerospace, automotive and marine transportation structures to achieve fuel efficiency and energy savings with high strength.

Research has shown that fiber-reinforced polymeric composite materials behave very differently at low temperature environment compared to the room temperature conditions for which they are typically designed [2, 3]. In particular, carbon fiber reinforced polymeric (CFRP) composite structures become extremely brittle at low temperatures, thereby causing tremendous damage during impact at low temperature [4].

One remedy to combat the inherent brittleness of CFRP is to employ the concept of hybridization to create greater ductility [5]. Wisnom and his group have specially designed fiber-reinforced polymeric composite materials by using CFRP and glass fiber reinforced polymer (GFRP) to achieve the concept of pseudo-ductility. This prevents sudden brittle failure of composites and allows progressive and gradual failure. With this as a motivation, the authors believe that hybridization can be a solution to avoid the extreme brittleness of CFRP in composite structures deployed in arctic conditions.

In this study, we experimentally investigate the impact damage and failure mechanisms of foam-core sandwich composites with CFRP and GFRP face sheets. Specimens are conditioned and impacted over a wide temperature range (from room temperature of 23°C down to -70°C) using Instron CEAST 9350 impact test machine. This work also explores the use of hybrid composite face sheets, with various configurations of layering CFRP and GFRP in the face sheets of foam-core sandwich composites. History data of force-time, energy-time and force-displacement curves are analysed to understand the effects of CFRP/GFRP face sheets on damage mechanisms with varying temperatures. Post-mortem inspection using X-ray micro-computed tomography (μCT) is performed to observe complex damage modes, particularly the interaction between CFRP and GFRP hybrid face sheets.

EXPERIMENTAL METHODOLOGY

Material Configurations

The composite sandwich panels consist of two different face sheet materials: CFRP and GFRP. Four different configurations are prepared by altering the sequence of CFRP and GFRP in each face sheet, as shown in Figure 1. Carbon fibers of 3K Twill standard modulus (AS-4) are used for the CFRP face sheet, whilst 7781 glass fibers are used for the GFRP face sheet. Each face sheet is 2mm thick, sandwiching a 6.35 mm thick

Divinycell PVC H-100 foam core for all specimens. The specimens are fabricated by wet lay-up method and co-cured in an oven. The sandwich panel is then cut into 150 mm x 100 mm specimen size for impact testing. For low-temperature testing, specimens are conditioned in a freezer at -70 °C for 24 hours to achieve thermal equilibrium.

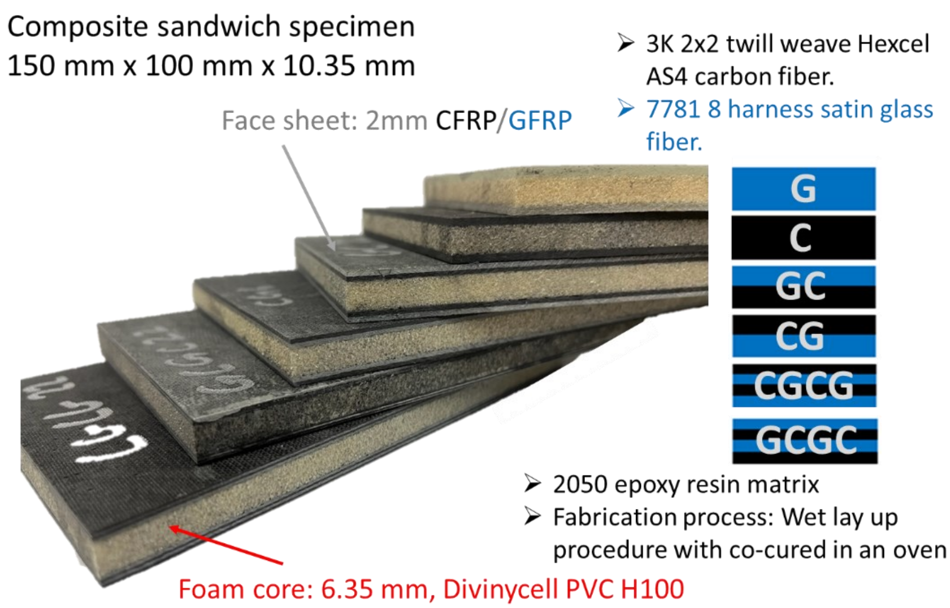

Figure 1. Sandwich composite specimens and layup configurations used in this study.

Impact Test and X-Ray Micro-Computed Tomography Analysis

The impact tests are conducted with Instron CEAST 9350 drop tower using a 16 mm diameter hemispherical striker, as displayed in Figure 2. The samples are placed on a round support frame with a cut-out window of 76 mm diameter. 2.482 kg impactor is dropped from various heights to generate 15 J, 30 J and 45 J of impact energy. Specimens are tested either at room temperature (RT) of 23 °C or low-temperature (LT) of -70 °C. The thermostatic chamber cooled by liquid nitrogen is used for LT testing. Test repeatability is confirmed with at least two specimens tested for each impact energy.

Internal damage observation of the impacted specimens is acquired using Nikon Metrology XTH 320 LC X-ray micro-computed tomography system. Numerous projection images are captured, as the sample rotates a complete 360° revolution. 3D reconstruction is done using software CT Pro provided by Nikon Metrology. The X-ray source is a 178 kV microfocus reflection target. X-ray emission parameters for the scans are 35 µA with an exposure time of 500 ms. Each single rotational position image is averaged twice and total of 6200 scans for each specimen is collected. The voxel size for the received data is 41.7 µm. After reconstruction of the 3D virtual object, an analysis of the reconstructed volumes is performed using VG Studio Max 2.0 software.

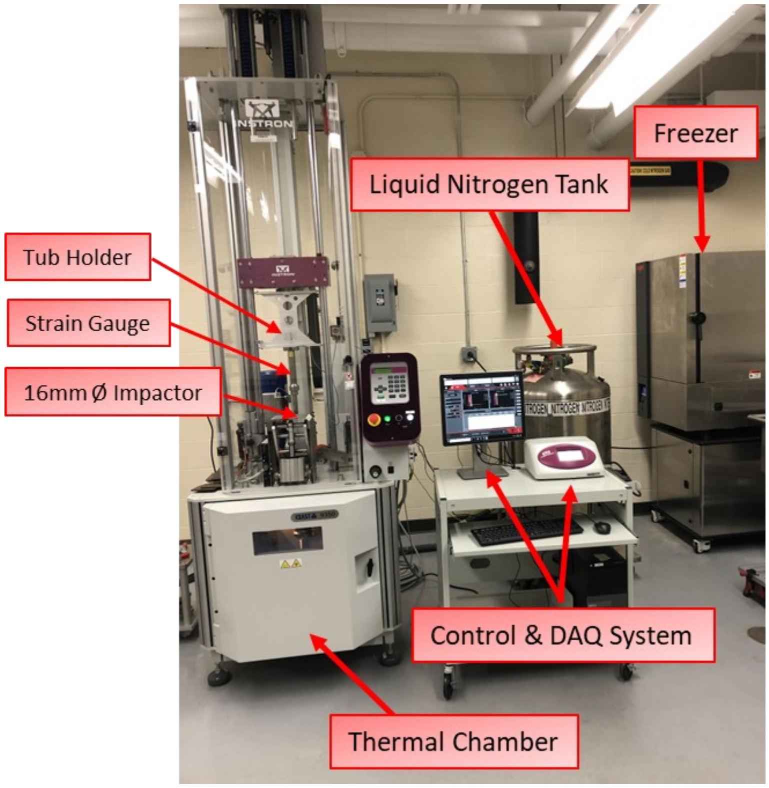

Figure 2. Impact test setup.

RESULTS AND DISCUSSION

Impact Damage Response

The impact force-time graphs are presented in Figures 3-5. The specimen with CFRP face sheet has unique behavior (Figure 3b) compared to the other specimens. The low first peak force and higher second peak force indicate front and back face sheet penetration at RT. There are drastically low force values at LT for both front and back face sheet damage.

Generally, it is observed that LT specimens have higher stiffness and larger force values compared to RT specimens. The load drop is also large for LT specimens, signifying brittle failure in both CFRP and GFRP face sheets in cold conditions. A greater load drop typically means sudden failure and larger damage during impact.

From Figure 4, the CG and GC curves seem similar. But CG has relatively larger load drop, due to CFRP layer having brittle failure for both RT and LT. For GC, the impact layer is the GFRP layer. This results in a smaller load drop at RT, but greater load drop at LT. This implies that GFRP layer transits from ductile at RT to brittle failure behavior at LT.

It is obvious from Figure 5 that there are larger load drops for GCGC and CGCG compared to GC and CG. This is due to more delamination damage at multiple interfaces. CGCG can withstand higher impact force than GCGC, due to outer CFRP layer, but the load drop is also greater when outer CFRP layer is damaged.

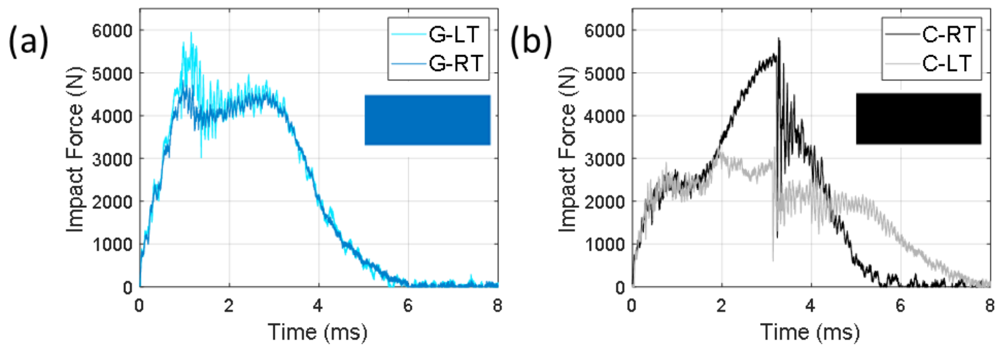

Figure 3. Force-time graphs of (a) GFRP face sheet and (b) CFRP face sheet sandwich composites.

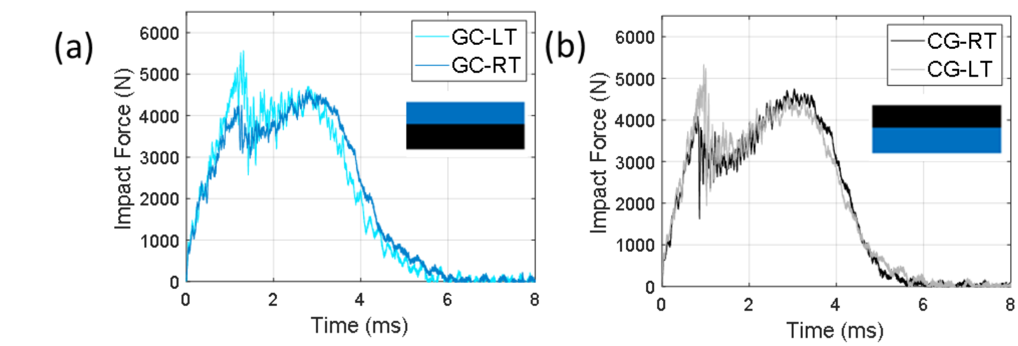

Figure 4. Force-time graphs of hybrid face sheet sandwich composites with (a) GFRP at outer layer and (b) CFRP at outer layer.

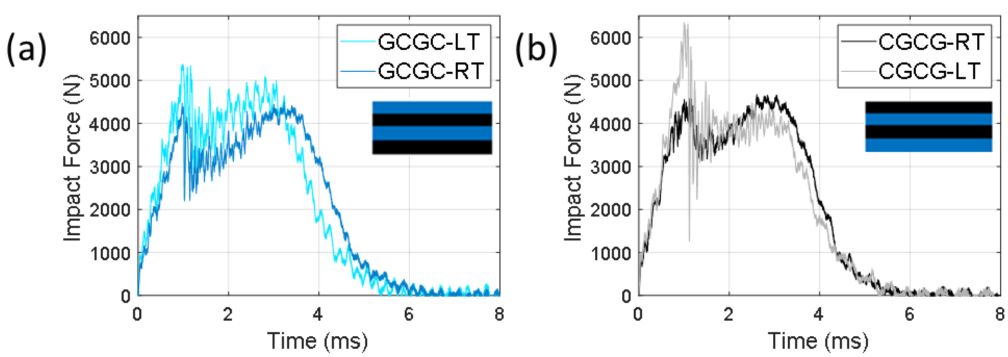

Figure 5. Force-time graphs of alternating hybrid face sheet sandwich composites with (a) GFRP at outer layer and (b) CFRP at outer layer.

X-ray Micro-Computed Tomography Observation

Figure 6 shows the X-ray μCT images of impacted specimens at RT and LT. It is observed that damage is significantly increased from RT to LT for CFRP face sheet specimens. When GFRP is added to the second layer, the extent of impact damage is drastically reduced, especially at LT. When alternating hybrid layers (CGCG) are incorporated in the sandwich composite face sheet, the damage is similarly reduced. The damage mode is seen to switch from fiber damage to more delamination failure due to multiple interfaces in the CGCG specimens.

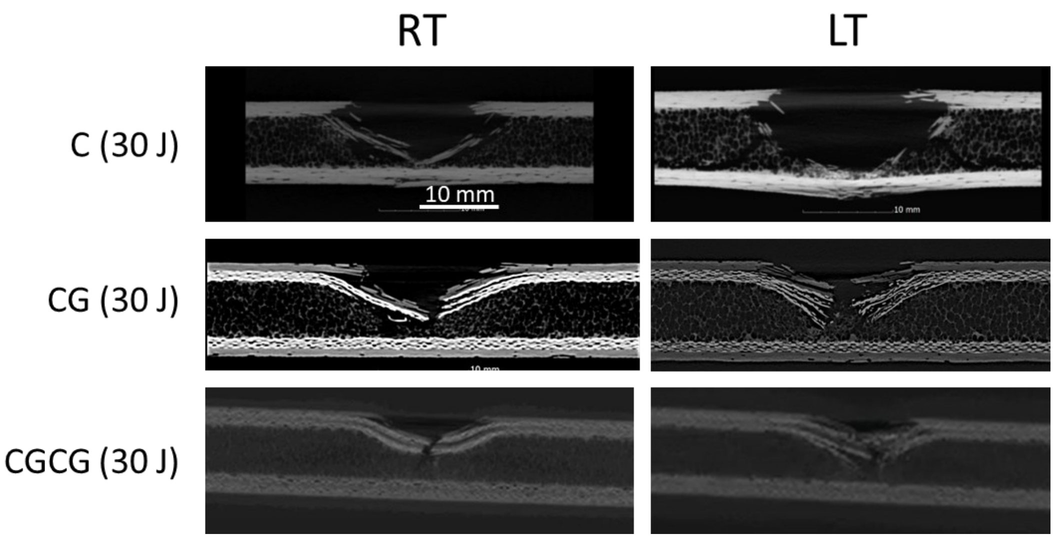

Figure 6. X-ray μCT images showing comparison of damage mechanisms at room temperature and low temperature for sandwich composites with CFRP face sheet and CFRP outer layer face sheets.

CONCLUSIONS

In this study, the impact performance of hybrid face sheet composite sandwich structures in arctic conditions is investigated. CFRP face sheet sandwich composites perform poorly in arctic temperature, due to the inherent brittleness of CFRP, which is dominantly exhibited at low-temperature. This work demonstrates that hybridization can harness the strength of CFRP and ductility of GFRP, posing a solution to reduce temperature effect in impact damage. Careful placement of CFRP and GFRP in various layup order can harness the best impact performance. However, hybridization generates more interfaces that will lead to significant delamination failure.

REFERENCES

1. Vihma, T. 2014. "Effects of Arctic Sea Ice Decline on Weather and Climate: A Review," *Surv. Geophys.*, 35(5):1175-1214.
2. Sápi, Z., R. Butler. 2020. "Properties of Cryogenic and Low Temperature Composite Materials – A Review," *Cryog.*, 111:103190.

3. Khan, M.H., K.T. Tan. 2020. "Post-Impact Flexural Collapse Modes of Composite Sandwich Structures in Arctic Conditions: Analytical Prediction and Experimental Validation," *Compos. Sci. Technol.*, 195:108187.
4. Elamin, M., B. Li, K.T. Tan. 2018. "Impact Damage of Composite Sandwich Structures in Arctic Condition," *Compos. Struct.*, 192:422-433.
5. Czél, G., M.R. Wisnom. 2013. "Demonstration of Pseudo-Ductility in High Performance Glass/Epoxy Composites by Hybridisation with Thin-Ply Carbon Prepreg," *Compos. Part A,* 52:23-30.