Effect of Temperature on Impact Properties of Fiberglass and Fiberglass/Kevlar Sandwich Composites

Amin Salehi-Kojin	Graduate Student
Aaron Halvorsen	Graduate Student
Mohammad Mahinfalah	Associate Professor
Reza Nakhaei-Jazar	Assistant Professor

Email: M.Mahinfalah@ndsu.edu

Department of Mechanical Engineering and Applied Mechanics
North Dakota State University, Fargo, ND 58105, Fax: 701-231-8913

Introduction

Sandwich composites are widely used for their high strength to weight ratio as an alternative to homogenous load bearing materials such as wood and metals. These sandwich composites consist of two face-sheets and a core, typically the face-sheet materials are high strength and high stiffness and the core is a light weight and low strength. This composite structure maximizes the strength and stiffness of the faces and utilizes the light weight of the core to provide a good substitute to traditional structural materials. Depending on the application, these sandwich composites can potentially be subjected to high temperature ranges and are used in variable climatic regions (i.e. desert, arctic regions, space, high speed transportation).

Many studies have been done on the performance of sandwich composites during and after impact at room temperature, but impact behavior that varies over low and high temperatures is not as well known nor published. Temperature will alter the mechanical properties of the polymeric materials in the composite and effect impact loading [1] and is therefore important to understand.

Few studies have been conducted in temperature variation of composite impact performance. Dutta et al. [2] studied the energy absorption of graphite/epoxy plates and found small dependence on temperatures between -69C and 20C. Usami et al. [3] analyzed different epoxy resins at different temperatures and found that as temperature decreased the composite structures increased in strength and decreased in failure strain. Kwang-Hee et al. [4] investigated the damage area as a function of temperature and found that it increased as temperature decreased. Because no extensive work has been done on impact of sandwich composites over a temperature range, this study focuses on the impact properties of Fiberglass and Kevlar/Fiberglass sandwich composites over a range of -50C to 120C. As a direct result of the variation in different epoxy and/or fibers used in any given manufacturer or designer's process, this study of temperature dependence will be useful as a comparative procedure and does not represent every Fiberglass and Kevlar/Fiberglass sandwich composite. Rather, when used as a comparative procedure, general conclusions can be made as temperature is varied over the array of hybrid sandwich composites and impact energies.

Non-dimensional parameters were outlined in studies done by Torre and Kenny [5] to evaluate sandwich composite impact performance. “Absorbing Energy and Moment Parameter” (AEMP) and “Performance Parameter” (PI) were introduced as a reference scale for test comparison. However, Torre and Kenny impacted composites as a simple beam and did not study temperature effects. Other standard impact properties established in previously published works are face sheet stresses, maximum energy absorption, and compression after impact strength. These non-dimensional parameters along with these standard impact properties were used in this study to evaluate crash performance of the composites over the variable temperature range.

Three variations of a Fiberglass/Kevlar hybrid sandwich composite were tested:

1. 4 layered Fiberglass face-sheets (referred to in this paper as Fiberglass composite or FG)
2. 3 layered Fiberglass and 1 outer layer of Kevlar (referred to as energy Absorbing Kevlar or AKG)
3. 3 layered fiberglass and 1 inner layer of Kevlar (referred to as delamination reducing, Damage Kevlar or DKG)

The underlying goal in the testing of these sandwich composites is to (1) understand the performance of an array of sandwich composites undergoing temperature variation and (2) to work to develop cost effective composite structures that absorb the maximum amount of energy while still retaining the ability to withstand future loading [5].

Sample Construction

A hand-layup method was used to construct the samples. This process is done by hand and requires cutting the woven fabric to size, applying epoxy to the fabric layer by layer, and letting cure under vacuum. The major components required for this method are a vacuum pump, vacuum bagging, spiral tubing and sealant tape. The spiral tubing ensures a uniform vacuum across the sample and prevents epoxy from pooling on the sample side.

The core of the sandwich composite consisted of a polyurethane foam filled honeycomb. The honeycomb structure was constructed out of *kraft* paper. The foam filled honeycomb sheets, purchased from MGI, had the properties indicated in Table 1. The fiberglass and Kevlar properties are listed in Table 2. The epoxy consisted of F-82 resin and TP-41 hardener, which was allowed to cure under a 600 mm Hg vacuum for 9 hours. The cured properties of the epoxy, purchased from Eastpointe Fiberglass, are listed in Table 3.

Table 1: Properties of MGI Canada MIKOR honeycomb sheets

Density	112 kg / m^3
Compressive Strength	2.02MPa
Cell Size	12.7 mm
Shear Strength Perpendicular To Ribbon	1.65 MPa
Cell Thickness	0.3175 mm
Honeycomb Thickness	25.4 mm

Table 2: Fabric properties

	Fiberglass	**Kevlar 49**
Yarn Type	3 K	
Weave Type	Plain	4 HS
Area Density	193 g / m^2	169 g / m^2
Thickness	0.3048 mm	0.254 mm
Count (Rows/Tows Per Inch)	12.5 x 12.5	17 x 17

Table 3: Properties of Eastpointe Fiberglass epoxy

Density	1084 kg / m^3
Compressive Strength	131 MPa
Tensile Strength	63.6 MPa
Cure Time	9-12 Hours
Cure Temperature	75 F

Test Method

An Instron Dynatup drop tower, Model 9250HV, was used for impact testing. This machine is capable of impacting samples at energies of up to 826 J utilizing a spring-assist. For this study, all samples were impacted with a 7.25 kg drop weight and with a 12.7 mm (0.5in) diameter striker , constructed out of high strength steel. Impulse software was used to display and store the impact data.

Absorbed-Impact Energy

At higher energy levels (45 joules), where full penetration through the entire sandwich composite occurred, only a fraction of the kinetic impact energy was absorbed by the sandwich composite. Absorbed energy is defined as the amount of energy the sample absorbs from the impact, the energy absorbed reaches a maximum at the point the tup fully penetrates the sample and proceeds far enough to be stopped by the emergency brakes. At lower energy levels the percent of energy absorbed would be 100%. The amount of absorbed energy at full penetration was observed to be variable over the temperature range. At room temperature, nearly all of the impact energy was transferred to the composite. As the temperature deviated from room temperature the percent absorbed energy decreased in each situation.

Table 4: Percent absorbed energy of completely penetrating impacts

Temp C	Face-sheet Combination	Maximum Absorbed Energy (Joules)	Percent Absorbed Energy Relative to 45J (%)
-50	Fiberglass	34.6	78
-50	Absorbing Kevlar	36.7	82
-50	Damage Kevlar	35.0	78
20	Fiberglass	43.5	97
20	Absorbing Kevlar	43.6	97
20	Damage Kevlar	44.1	98
70	Fiberglass	32.8	73
70	Absorbing Kevlar	35.4	79
70	Damage Kevlar	40.7	90
120	Fiberglass	38.5	86
120	Absorbing Kevlar	33.6	75
120	Damage Kevlar	42.4	94

Table 4 illustrates that the energy absorption ability of these polymeric composites decreased when deviating from standard temperatures. This particular temperature characteristic would be applicable in armor design. A given composite at standard temperatures would be able to stop a projectile, whereas the same composite at non-standard temperatures might experience full penetration.

Figure 1 illustrates that energy absorption and back surface damage varied considerably with temperature. The -50 C resulted in the greatest amount of damage area and fiber breakage, as temperature increased damage area and fiber breakage decreased with a minimum occurring for 120 C. Temperature changes the primary modes of failure during impact, at lower temperatures the composites fail in a brittle manner and at higher temperatures the composites fail in a ductile manner.

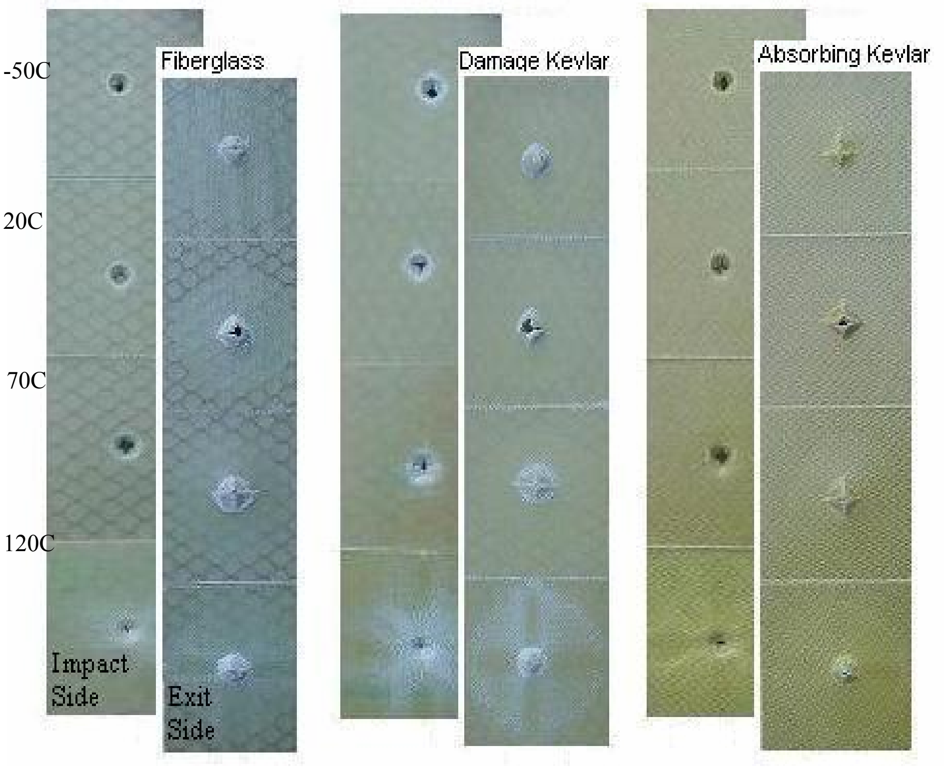

Figure 1: Photos of impacted 4in x 4in samples

Crash Performance Non-Dimensional Parameters

Kenny and Torre [5] introduced two non-dimensional parameters for crash performance for a simply supported composite beam. They showed that these non-dimensional parameters are important where sandwich composites are used in civil transportation applications. These are important because they show how much moment load is transferred to the rest of the structure (AEMP) and how much transverse deflection is generated during impact. In our study, these parameters as well as facing stress and core shear stress were developed for the impact model of edge clamped (cantilevered) circular plate composite.

The following equations express non-dimensional parameters introduced to evaluate the crash performance [5].

$$A.E.M.P. = \frac{E_{\max}}{M_{r\max}}$$

$$P.I. = \frac{A.E.M.P.)_r}{(R.D.)^2} \quad where: R.D. = \frac{Def_{\max}}{D_{span}}$$

Where: Def_{max} = Applied Force of Impact

D_{span} = Radius of Clamped Circular Plate

A.E.M.P. is the ratio between the maximum energy absorbed by the plate (E_{max}) and the maximum moment (M_{rmax}) of the impact load on the supports. A high A.E.M.P. ratio indicates a low amount of load transfer to the supports compared to impact energy. The performance parameter (PI), which essentially relates the impact energy absorbed to the deflection, is the ratio between A.E.M.P. and a deformation ratio (R.D.). A high PI value indicates that the plate is able to absorb high amounts of energy without transferring excessive deformation to the inner structure.

Several trends were seen as temperature and energy varied for the non dimensional parameter AEMP. In Figure 2, it is observed for the low energy that there is very little variation in AEMP as temperature changes. The data indicates that at this energy level AEMP is nearly independent of temperature. At the intermediate energy level (Figure 3), all face sheet combinations show similar behavior, with a local minimum occurring at 120C. Finally, for high energy impact (Figure 4), different combinations show different behavior. FG shows a constant value over the temperature range, AKG outperforms the rest at high temperatures, and DKG outperforms the rest at low temperatures. Overall data demonstrates that there is inconsistent behavior for variations of temperature, face sheet material, and energy levels. This indicates that in designing for specific cases AEMP tests over the predicted temperature conditions is important.

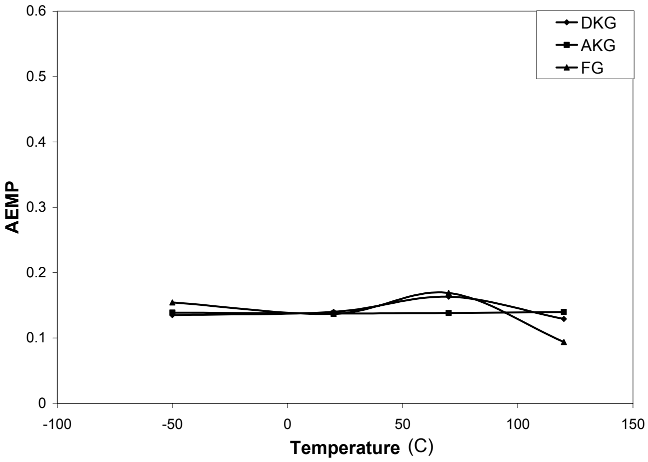

Figure 2: AEMP results for 15 Joule impact

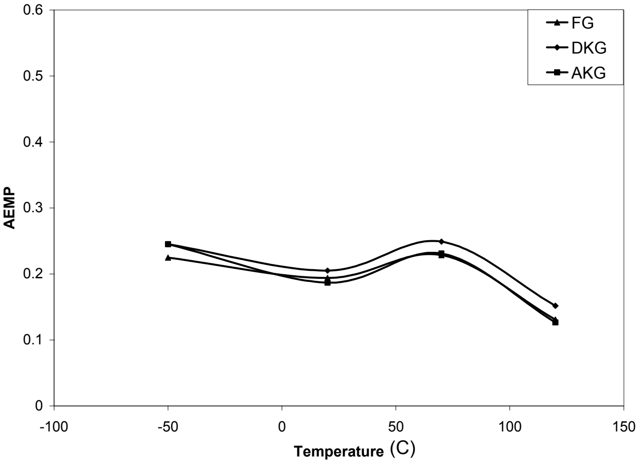

Figure 3: AEMP results for 25 Joule impact

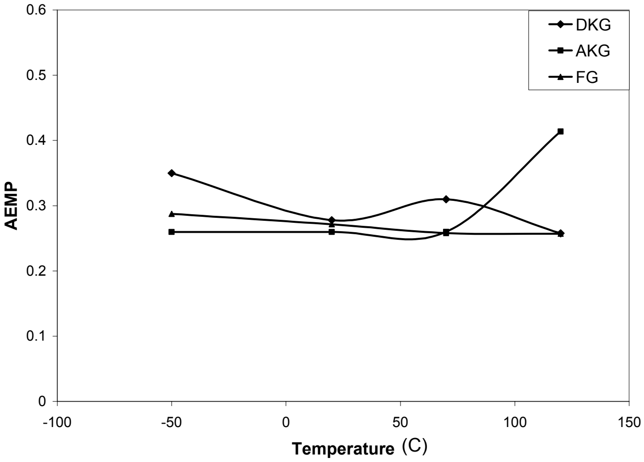

Figure 4: AEMP results for 45 Joule impact

Similar behavior variations occur when investigating the non-dimensional parameter PI. As the energy increases, the fluctuation in the values of PI versus temperature tends to decrease. At the lowest energy state (Figure 5), FG and DKG showed similar PI behavior with a maximum value at 120C and a minimum value at 70C. The trend of AKG increased from -50C to room temperature and decreased with higher temperatures. At the intermediate energy level (Figure 6), fiberglass PI increased from -50C to 20C and decreased with elevated temperatures. AKG decreases steadily along the entire temperature range. At standard temperature conditions, all PI values are identical, but as the temperature approaches both extremes the DKG outperforms the FG and AKG. Lastly, when evaluating the highest energy level (Figure 7), the fluctuation in PI is very small for each of the sandwich composites. Overall results show that DKG outperformed AKG and FG, especially at the temperature extremes. In addition, AKG showed the poorest performance in high temperature tests in each of the energy levels. At the low extreme temperature, AKG showed the poorest performance at the lowest energy and FG showed the poorest performance in the middle and high energy. Once again these temperature variation tests show that when designing for cases where impact deflection to the inner structure is critical, tests of the parameter PI over the predicted operating temperatures would be beneficial. Also we see that the addition of an outside layer of Kevlar (AKG) is not beneficial, however the addition of an inside layer (DKG) gives improvement to the impact performance.

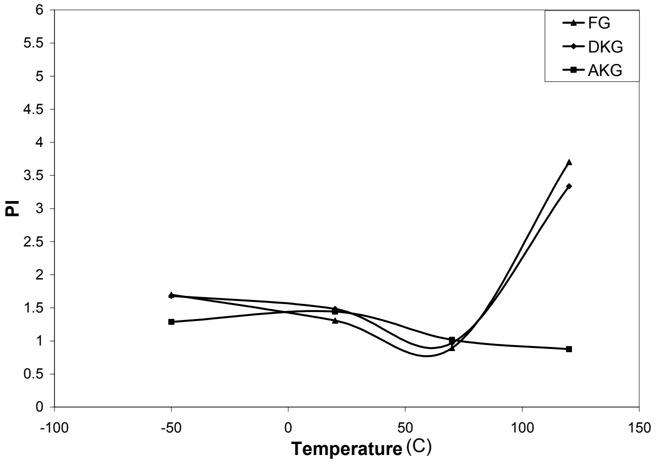

Figure 5: PI results for 15 Joule impact

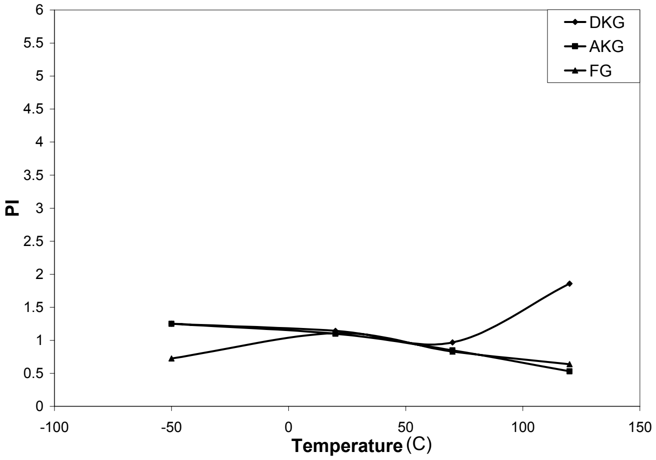

Figure 6: PI results for 25 Joule impact

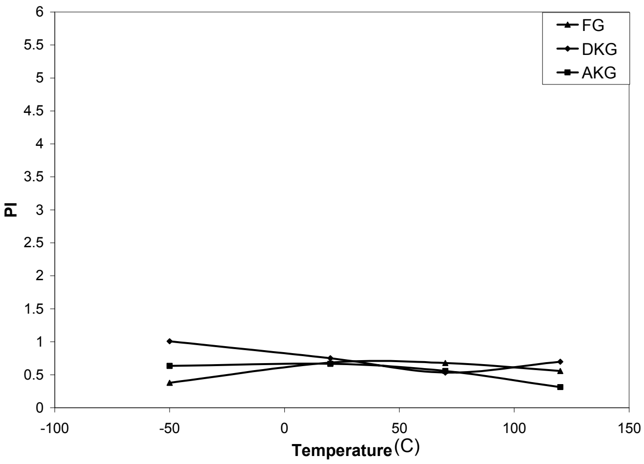

Figure 7: PI results for 45 Joule impact

Impact Stress Performance

The applied impact force produces bending force (Moment) and consequently internal reaction forces in the composite that counteract such bending. The best way to visualize the structure of a sandwich core panel is to use the analogy of a simple I-beam. Like the I-beam, a sandwich core panel consists of strong skins (flanges) bonded to a core (web). The skins are subject to tension/compression and are largely responsible for the strength of the sandwich. The function of the core is to support the thin skins so that they don't buckle (deform) and stay fixed relative to each other. The core experiences mostly shear stresses (sliding) as well as some degree of vertical tension and compression. Its material properties and thickness determine the stiffness of the sandwich composite.

Maximum moment (M_{rmax}) and in plane normal and shear stress (σ_r, σ_θ, τ_{max}) equations are used in evaluation of mechanical properties of composite materials. Clamped edge (cantilevered) circular plate model closely represents the loading and constraints experienced during testing. These equations derived for a clamped edge circular plate are as follows:

$$\left.\sigma_r\right)_{\max} = \frac{P_{\max} Z}{4\pi \cdot I} \qquad \left.\sigma_\theta\right)_{\max} = \frac{P_{\max} Z \upsilon}{4\pi \cdot I}$$

$$\tau_{\max} = \frac{1.5 P_{\max}}{Z \cdot \pi \cdot D_{striker}} \qquad M_{r\max} = -\frac{P_{\max}}{4R}\left[1 + (1+\upsilon)\right]\ln\frac{r}{a}$$

Where:

P_{max} = Applied Maximum Force of Impact

R = Radius of Clamped Circular Plate

I = second area moment of inertia

Z = distance from neutral line to top of face sheet

$D_{striker}$ = Diameter of Striker Head

υ = Face Sheet Poisson's Ratio

As the temperature varied, the maximum stresses seen by the composite fluctuated considerably. This would lead to the conclusion that temperature does have an effect on the composite stress of a sandwich composite. Figures 8 & 9 demonstrate that each of the composites could withstand the most stress at room temperature, but in general as the temperature went to either extreme, the stress the composite could withstand diminished. Damage Kevlar, however, showed an exception to this trend and increased performance at high temperatures. Once again Damage Kevlar seems to have unique impact characteristics at the 120 C temperature range. Lastly, from Figures 8 & 9 it is observed that the AKG has good impact performance at standard and low temperatures.

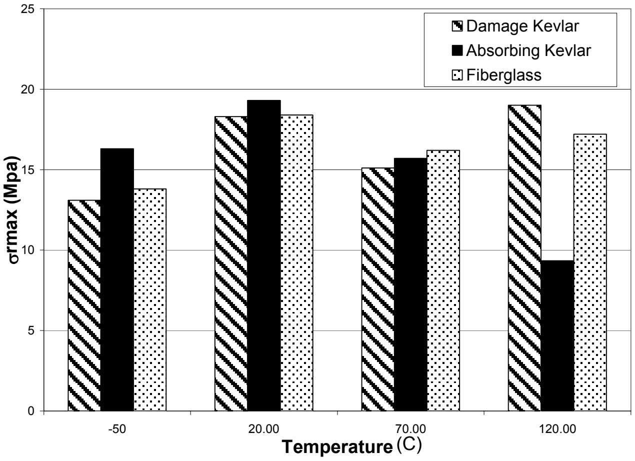

Figure 8: σ_{rmax} at 45 Joule energy level

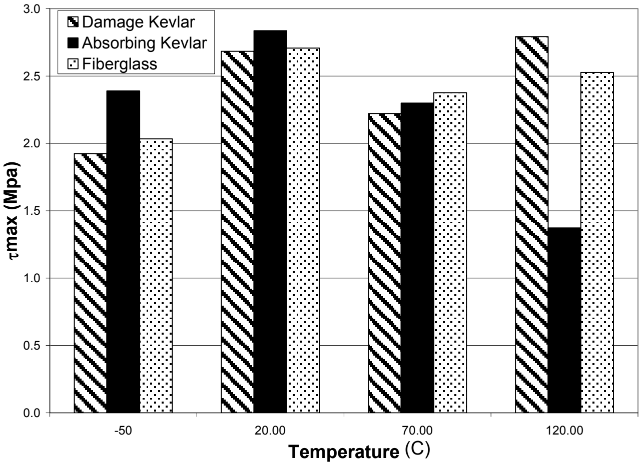

Figure 9: $\tau_{\max}$ at 45 Joule energy level

Conclusion

Every result taken from this study indicates the importance of temperature effects. For a given design application and operating environment, tests should be conducted and/or quantitative results from this study should be used to adjust for the impact behavior change due to temperature. Results also indicated, depending on temperature, improved performance with the addition of a Kevlar layer to the Fiberglass composite. Overall the information obtained from these studies is useful in identifying trends and making comparisons in the design of sandwich composites subjected to a range of temperature.

Acknowledgments

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