Impact Damage Growth in Fiberglass/Epoxy Laminates Subjected to Moisture and Low Temperature Thermal Cycling

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ABSTRACT

A study of delamination damage growth in a fiberglass/epoxy laminate composite subjected to low velocity impacts, moisture and low temperature thermal cycling was undertaken. The research addresses two different ply configurations $[0/90/0/90/0_2]_s$ & $[0_2/90_2/0_2]_s$, three impact energies 5J, 10J, & 15J and two impact masses 7.25 kg & 12.25 kg, at both dry and wet service conditions. Test specimens were subjected to 500 thermal cycles between 25°C and -40°C to determine the extent of delamination growth due to the effects of moisture and differing coefficients of thermal expansion. Visual digital photography techniques were utilized to determine the level of initial damage caused by impact and subsequent damage growth from thermal cycling.

KEY WORDS: Composite; impact; low temperature; thermal cycling; stacking sequence; damage growth.

INTRODUCTION

Composite materials have been a staple of the engineering community for many decades. In recent years these materials have gained interest from other disciplines and they have been introduced to many new applications. These include infrastructure applications such as composite bridge decks and wrapping of concrete columns, where exposure to extreme environments is likely. Harsh environmental conditions such as moisture, low temperature, and thermal cycling can quickly degrade the physical properties and reliability of composite materials. In addition, the two aforementioned applications can expose the composite material system to impact events which can serve to exasperate the situation.

Moisture can adversely affect composites' integrity, durability and performance. Polymer composites are extremely susceptible to moisture degradation (Dutta and Hui, 1997; Kellogg, Kallmeyer, and Dutta, 2000; Kellogg, Kallmeyer, and Dutta, 2003; Kellogg, Patil, Kallmeyer, and Dutta, 2005; Peterson, 2004; Tsotsis, 1989; Wolff, 1993). Moisture is typically present in the materials as either absorbed in the matrix or present in voids or delaminations. Absorbed moisture affects several aspects of polymer composites, including swelling of the matrix material causing residual stress relaxation, altering the coefficient of thermal expansion, and degrading the fiber-matrix bond. These effects of moisture can be greatly increased when subjected to subfreezing temperatures and can cause severe damage to the material.

Thermal cycling is another process which can adversely affect a composite material and is very common in the natural service life of certain structural applications. They can occur daily, monthly, seasonally, or yearly depending on the initial temperature and the ΔT (change in temperature) required. A temperature change, ΔT, will cause a material's volume to change. In typical homogenous and isotropic materials, such as metals, thermal expansion or contraction usually creates little change in structural performance or integrity. Conversely, materials such as polymer composites, which are typically heterogeneous and anisotropic in nature, can be adversely affected when subjected to temperature changes caused by the constituent materials having different coefficients of thermal expansion. The coefficient of thermal expansion represents a material's need to expand or contract during a given change in temperature. Since the reinforcement and matrix do not expand or contract at the same rate, thermal residual stresses of significant magnitudes can develop (Dutta, 1988; Dutta and Hui, 1996). These residual stresses cause a compressive force in one constituent while applying a tensile force in the other. This situation often results in the formation of microcracks in the matrix and/or resin-fiber interface. These microcracks will continue to grow and coalesce with continued cycling. Once microcracking has occurred, moisture can easily access the material which can lead to further deterioration.

Impact events can cause the cross sectional properties to be reduced thus affecting the strength and stiffness of the composite. Internal cracking and delaminations may also occur resulting in decreased material integrity and load transfer performance. Impacts which break the composite surface and penetrate the material also increase the susceptibility of moisture penetration which can lead to concerns previously mentioned. Thus, understanding the effect of such environmental and service factors on a composite material system is a necessity if polymer composites are to further expand into these and other applications.

This paper looks into the effects of moisture, impact damage, low temperature thermal cycling, and stacking sequence on the delamination damage growth characteristics of a commercially available fiber reinforced composite system.

PREVIOUS RESEARCH

Moisture Effects

It is known that moisture has detrimental effects on polymer composite materials. These effects frequently include alterations in coefficients of thermal expansion, stress relaxation and crack and delamination propagation. Alterations in coefficients of thermal expansion and stress relaxation were discussed previously, while the presence of moisture on crack and delamination propagation will be addressed here. These characteristic effects of moisture and environment on the integrity, durability, and performance of polymer composite materials have been studied since the onset of their existence. Much research has been performed and numerous works have been published concerning this issue. Thus, an extensive review of moisture effects would not be warranted here, but if so desired, refer to the work of Wolff (1993) where an excellent compilation of moisture and its effects can be found. The following review will highlight some pertinent information specific to this study.

Much attention has been given to the effects of freezing upon absorbed water. Tsotsis (1989) performed a comprehensive study on this subject. He reasoned that water absorbed into the matrix could not crystallize at sub-freezing temperatures because the polymer lattice of the matrix is too small for crystal formation since ice crystals are composed of several unit cells. This moisture absorbed into the matrix could, however, cause damage by altering the residual stresses, or causing stress relaxation. Wolff (1993) also supports this concept, arguing that absorbed moisture changes the coefficient of thermal expansion of the matrix material. Stress relaxation and changes in the coefficient of thermal expansion could be either beneficial or detrimental during thermal cycling depending upon the temperature and temperature range. These studies focused on the mechanics of diffusion and the microscopic effects of moisture present in composite materials, however the research presented here focuses on the macroscopic effects of moisture on damage growth.

Dutta and Hui (1997) explain that moisture absorbed into the matrix causes swelling. This swelling at room temperature reduces residual compressive stresses which are caused from curing shrinkage. However, they also suggest that at low temperatures these effects may actually be reversed.

When water is present in voids or delaminations, which are significantly larger then spacing between polymer chains or resin microcracks, Tsotsis (1989) suggests that crystallization would occur and cause damage upon freezing. This damage is caused by water's basic phase transformation principles. As water expands upon transformation from liquid to solid it applies forces against the composite. In the case of delaminations these forces create a prying action to propagate the delamination. Wolff (1993) states that "moisture may . . . have a significant effect on delamination extension at low temperatures." Dutta and Hui (1997) also suggest that moisture present in voids or delaminations can create damage under sub-freezing conditions.

Impact Damage

Damage caused by impacts can be extremely detrimental to polymer composite material behavior. This damage can cause both strength and stiffness losses. Impact damage is dependent upon projectile mass and velocity. It has been shown that the magnitude of damage resulting from an impact event can vary depending upon the impact velocity even though equivalent impact energy was maintained. Several studies have been performed to determine the behavior and difference between low-velocity/high-mass and high-velocity/low-mass impacts.

A study by Hosur, Murthy, Ramamurthy, and Shet (1998) made comparisons between ten different configurations of carbon fiber laminates impacted by high velocity gas gun projectiles and a low velocity drop tower. Their study was intended to determine the effects of impact velocity and ply stacking sequence on the impact damage created. They concluded that high-velocity/low-mass impacts created more damage than low-velocity/high-mass impacts for an equivalent impact energy. The authors tend to argue that the amount of damage created is dependent upon the time duration of the impact event. Low velocity impact events have considerably larger time durations when compared to the high velocity projectile impact. They suggest that during a low velocity impact event, energy is absorbed through the creation of damage and by the stiffness of the specimen since considerable deflection occurs, whereas during a high velocity impact event deflections are minimal, thus nearly all energy must be absorbed by damage propagation.

They also determined that differences occurred between damage areas created by equivalent impact energies in laminates with different stacking sequences. The study used several different lay-ups including; Lay-up A $[0_2/\pm45/0_2/\pm45/0/90]_S$, Lay-up B $[0_2/\pm45/90/\pm45/0_2/\pm45]_S$ and Lay-up C $[0/\pm45/90]_{3S}$. These different stacking sequences provided some interesting results. Under a low velocity impact of 6 joules, lay-up A and B sustained 382 and 335 mm^2 of damage, respectively, while lay-up C sustained only 13 mm^2. Then at 9 joules, all three lay-ups, A, B, and C, had nearly the same damage areas. These results suggest that ply stacking sequence is of considerable importance for the threshold of damage propagation.

They also determined that the largest delamination occurred at an interface between layers of maximum fiber orientations, i.e. 0°/90° and -45°/+45°. Although no discussion of this trend was provided by the authors, one could suspect that this behavior is due to the differences in relative strength and stiffness in each principle direction between adjacent plies. This anomaly was also observed during this study since a unidirectional woven fiber fabric was utilized.

A study by Zhou (1996) attempted to correlate the differences between strain rate and inertia effects of glass fiber laminates subjected to low velocity impact throughout a range of varying masses and velocities. Although the research proved to be inconclusive and suggested further work must be done, it did show that differences between mass and velocity can affect the resulting damage, even at the low velocity levels. This possibility is why it was chosen to use differing impact masses at equal impact energies for this study.

Thermal Cycling

Thermal cycling is utilized as a fatigue loading mechanism to study the effects of environment. Several previous studies have utilized thermal loading as a method to induce damage and thus study the effects. Thermal loading can lead to mixed results depending on the moisture level, change in temperature, and either elevated or reduced temperature cycling. The following studies have utilized thermal fatigue under variations of conditions and discovered similar findings.

Many previous studies have provided an extensive review of low temperature thermal cycling (Dutta and Hui, 1997; Kellogg, Kallmeyer, and Dutta, 2000; Kellogg, Kallmeyer, and Dutta, 2003; Kellogg, Patil, Kallmeyer, and Dutta, 2005; Peterson, 2004; Tsotsis, 1989). Studies have shown that low temperature thermal cycling accentuates residual stress effects as the number of thermal cycles increases. The severity and density of matrix cracks in a laminate also increase with each additional thermal cycle. It has also been documented that a high incidence of cracking occurs during the first few cycles, which then levels out with continued cycling.

Dutta (1988) subjected glass/epoxy laminates to low temperature thermal cycling between -60° and 60° C. It was shown that strength progressively decreased with the number of cycles. In addition, development of microcracks during decreasing temperatures was documented through the use of acoustic emission. Dutta suggests that low temperature thermal cycling accentuates the residual stress effects, which would agree with increased acoustic emissions from microcracking, while reducing the temperature.

Other studies by Dutta and Hui (1996) found that low temperature thermal cycling between -60° and 50° C significantly reduced glass/polyester shear modulus, G, and Young's Modulus, E. Dutta, Kalafut, and Lord (1988) examined the effects of low temperature thermal cycling on the tensile strength of unidirectional Fiberite material. They performed ten thermal cycles between -180° and 24° C. The results showed that strength in the longitudinal (0°) direction increased, while the strength in the transverse direction (90°) decreased.

Kasap, Yannacopoulos, Mirchandani, and Hildebrandt (1992) studied the effects of elevated temperature thermal cycling on the bending strength of three types of E-glass fiber composites. The samples were cycled between 27° and 77° C. They concluded that the flexural strength and stiffness were decreased by thermal cycling and that this reduction was typically caused by fiber-matrix debonding.

Forsyth, Kasap, Wacker, and Yanncopoulos (1994) utilized low temperature thermal cycling to study the damage growth in carbon/epoxy and aramid/epoxy composites. Damage growth caused by cycling between -25° and 75° C was monitored by the use of ultrasonic attenuation and velocity. They determined that microcracks grew rapidly during the early cycles, but slowed quickly during continued cycling. This was in agreement with previous works of Kasap et al (1992). They concluded that stress relaxation caused by fiber end pull-out reduced the effects of the continued thermal cycling.

Tai, Yip, and Tseng (1999) studied the effects of both low temperature thermal cycling and low energy impact on the fatigue behavior of carbon/PEEK laminates. They concluded that thermal cycling between -60° and 60° C insignificantly affected the tensile strength of impacted laminates. Their results also show that low temperature thermal cycling significantly reduces fatigue life. They also reported that x-ray inspections did not reveal any matrix cracks due to cyclic thermal exposure. The absence of matrix cracking may seem to contradict what many previous works have proven, although the PEEK matrix material is much more resistant to thermal expansion and/or contraction.

Previously, Peterson (2004) studied the effects of low temperature thermal cycling on the strength and stiffness in either axial tension or bending loading conditions of unidirectional carbon/epoxy laminates. He found that thermal cycling between -50° and 25° C decreased 90° axial strength, and both fiber and cross-fiber bending strengths. He also found that 0° axial strength increased, which corresponds to the findings of Dutta, Kalafut, and Lord (1988). Peterson also suggests that although microcracks and debonding occurred during thermal cycling, they have little effect on stiffness. This may occur since tensile properties are little affected by thermal cycling, as proven previously, and compression would result in the closing of microcracks. The study confirmed that thermal cycling has almost no effect on the stiffness for either the axial or bending loading conditions.

EXPERIMENTAL PROCEDURES

Material Preparation

Fiberglass/epoxy laminates are often used for infrastructure applications and thus were chosen for this study. Both the reinforcing and the matrix materials were acquired from Fibre Glast Development Corporation. As a basis for comparison studies, which will be discussed later, a unidirectional E-Glass cloth was selected. This cloth has an 80 x 18 plain weave style, which develops 95% of the fiber density in the principle direction and only 5% in the off-axis direction. This E-Glass woven cloth has a thickness of 0.203 mm (0.008 in).

The thermoset epoxy resin chosen was the Fibre Glast System 2000. Since the lay-up sheet size was reasonably small the System 2020 Hardener was used, which provided a 20-minute cure time. Table 1 provides the material properties for the Fibre Glast materials chosen.

Table 1. Constituent Material Properties.

Fibre Glast Material Properties*

Unidirectional E-Glass - #1093	**System 2000 Epoxy Laminating System w/ Hardner****
Style 7715	Color → Light Amber
80 x 18 Plain Weave	Viscosity → 9.5 - 9.75 g/cm-s (950 - 975 cps)
0.2032 mm Thick (0.008 in)	Specific Gravity → 1.12 - 1.13
237.4 g/m^2 (7 Oz/Yd^2)	Cured Hardness, Shore D → 86 - 88 D
95% Fiber Density in Wrap Direction	Density → 1.135 g/cc (0.041 lb/in^3)
Breaking Strength → 328 x 25	Specific Volume → 881.5 cc/kg (24.4 in^3/lb)
Specific Gravity → 2.5	Elongation → 1.93%
Color → Greenish - White	Tensile Strength → 312.5 MPa (45,326 psi)
	Tensile Modulus → 17.44 GPa (2.53 x 10^6 psi)
System 2000 Epoxy	Flexural Strength → 450.3 MPa (65,308 psi)
Color → Light Amber	Flexural Modulus → 19.51 GPa (2.83 x 10^6 psi)
Viscosity → 16.5 g/cm-s (1,650 cps)	Glass Transition Temperature, T_g → 82.2°C (180°F)
Specific Gravity → 1.15	Coefficient of Thermal Expansion Range: 37.8°C - 65.6°C (100°F - 150°F) → 67.14 µm/m-°C (3.73 x 10^{-5} in/in/°F)
System 2020 Hardener	
Color → Amber	* Information taken from Fibre Glast Development Corporation Literature
Pot Life → 18 - 20 minutes	** Properties derived with 10 Ply laminate, hand lay-up, style 181 glass fabric, 55% glass content
Specific Gravity → 1.065	
Viscosity → 2-2.5 g/cm-s (200-250 cps)	

All laminate sheets were hand laid up utilizing a vacuum bag system. The sheets were cast upon glass to provide a smooth surface. The laminates were created by alternating placement of fiber and matrix until all twelve plies had been placed. Plastic vacuum bagging was then affixed over the laminate sheet to the glass, which created a sealed environment. This system proved to be more than adequate since an extremely smooth surface was created while maintaining a consistent sheet thickness.

To fulfill the chosen test matrix, 120 fiberglass/epoxy specimens were required. To efficiently utilize the materials, yet create uniform samples, it was necessary to produce eight sheets. Each sheet was approximately 48.25 cm square and was cut into16 individual 10.16 cm square specimens. The sheets were cut by use of a diamond blade band saw. The band saw was chosen because it can create an extremely straight cut, which was necessary for the constructed testing apparatus. The band saw does produce a jagged cut edge, which can induce the onset of edge delaminations. The possible damage caused by such cutting techniques was outside of the intended impact test area and thus was not of concern.

The specimens consisted of twelve plies placed either in the 0° or 90° directions. For clarity and conformity, in this study the 0° axis will be referred to as the x-axis and the 90° axis as the y-axis. Since the chosen E-Glass fiber was of a unidirectional nature, the intent was to study the effects of a laminate that had different principle strengths. Thus, of the twelve plies per sheet, eight were placed along the x-axis and four along the y-axis. It was seen from preliminary tests that this specially orthotropic laminate created different impact damage patterns, thus the laminates could possibly have different delamination growth rates in either principle direction.

In addition to being a specially orthotropic laminate, the specimens consisted of two different stacking sequences. Two different ply stacking sequences were created to determine the effects of proximity of the y-axis layers when placed closer or further away from each other. Hosur, Murthy, Ramamurthy, and Shet (1998) argued that the maximum delamination will occur at the interface between plies of maximum fiber orientation. The first stacking sequence, to be referred to as Type “A”, was $[0/90/0/90/0_2]_S$ which separated the y-axis layers by one ply in the x-axis direction and created eight maximum fiber interfaces. The other stacking sequence, to be referred to as Type “B”, was $[0_2/90_2/0_2]_S$ which layered the y-axis plies together and only created four maximum fiber interfaces. These stacking sequences were chosen to study the effects of ply configuration and anisotropic characteristics on the initial impact damage and the subsequent damage created.

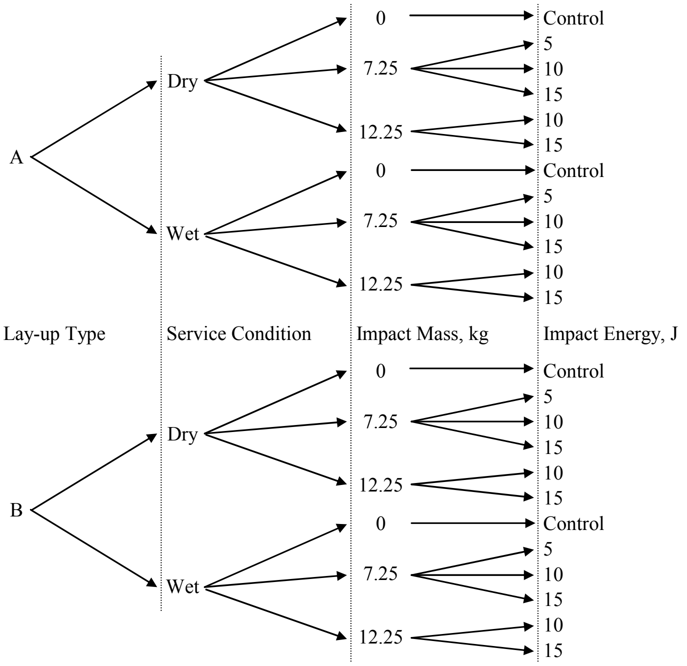
Test Matrix

As previously mentioned, a test matrix involving 120 specimens was chosen. To have statistically accurate results, it was chosen to use five samples per group. This created 24-five sample groups. The intent of this matrix was to study the effects of stacking sequence, service condition, impact velocity, impact energy and the anisotropic nature of the laminate. Figure 1 shows a pictorial representation of the chosen test matrix.

Notice that the 12.25 kg mass does not have an impact energy of 5 joules. This impact group was not studied due to the drop weight impact tower used. The Instron impact tower was equipped with an environmental chamber. This chamber had rubber “wipers” covering the opening where the impact tup came through. Based upon the combination of impact energy and mass, the necessary drop height was approximately 4 cm. This located the tup amidst the wipers. Thus it was decided that this drop height was too low and that unnecessary interference from the environmental chamber should be avoided.

Impact Damage

To induce damage, specimens were subjected to a low velocity impact in accordance with Figure 1. An Instron Dynatup 9500 series impact tower was used. This system included a complete data acquisition system and pneumatic rebound breaks. A 12.7 mm spherical tup was used to impact specimens in a 76.2 mm diameter fully clamped impact zone. Prior to impacting, all samples were allowed two weeks to fully cure and were impacted at ambient room temperature.



* Five samples per division

Figure 1. Specimen test matrix.

Moisture and Thermal Cycling

The intent of the study was to visually compare, through digital photography, the initial damage in the specimens to the damage present after 500 low temperature thermal cycles. A thermal cycle would start at 25°C followed by a five minute ramp down to -40°C, hold -40°C for fifteen minutes, then a five minute ramp back up to 25°C and hold 25°C for fifteen minutes before ramping down again. Both the wet and dry specimens were thermally cycled.

To ensure that saturation of the wet samples was reached prior to thermal cycling the specimens were placed in a water bath and periodically removed and weighed. Figure 2 shows the results of the initial saturation procedure for lay-up “A”, lay-up “B” was similar. Based on these results a six day water bath was utilized.

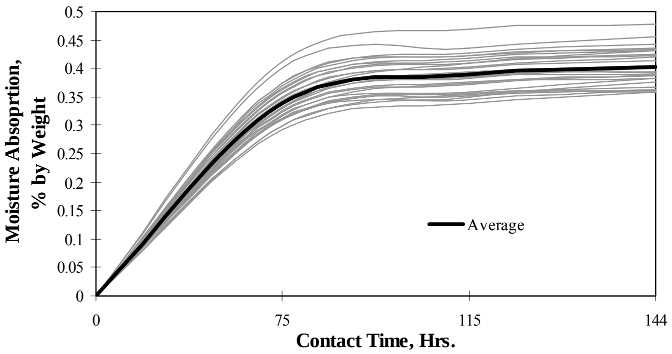


Figure 2. Lay-up “A” initial moisture absorption.

Realizing that damage growth from thermal cycling could occur in the early cycles the 500 thermal cycles were broken into five stages with each stage followed by a six day re-soak of the specimens. This would reproduce more closely what can occur in the real world. The initial stage was set at 50 cycles, with stages 2 through 4 being 100 cycles each, and the final stage consisting of 150 cycles.

Digital Photography

Digital photographs of all specimens were taken prior to thermal cycling and then again when all cycling was completed. All photos were taken using a black background and from the same distance. Since the damage areas of the laminate were white in color, the black background aided in visualization of the delamination zone. Figure 3 provides a schematic view of the fixtures utilized to acquire the most reliable photographs as possible. Each photograph was taken with the same camera and identical settings and procedures were utilized.

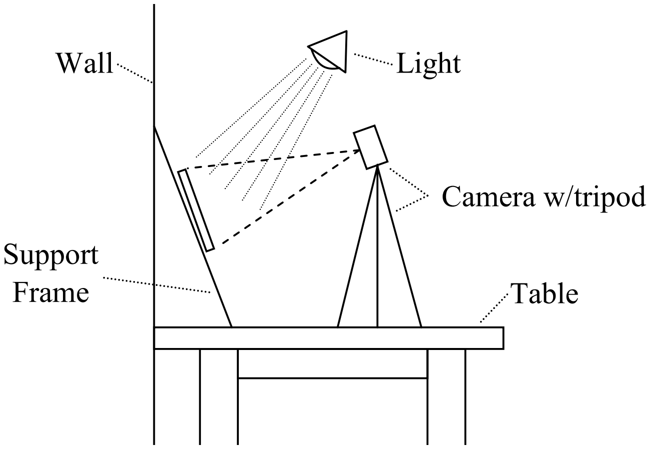


Figure 3. Photograph fixture schematic.

Once the photographs were taken the images needed to be analyzed. AutoCAD was utilized to perform the damage characterizing measurements. AutoCAD was well suited for this application since the program has the ability to import and scale photographs. The next step was to determine the spatial dimensions of all the samples using a digital caliper. A Starrett brand caliper was used with a resolution of ± 0.01 mm and an accuracy of ± 0.03 mm. Once the measurements were complete, the photographs were uploaded into AutoCAD and scaled to 1:1.

RESULTS AND DISCUSSION

Impact Energies and Stacking Sequence

Intuitively one would anticipate that the damage area should increase due to increasing impact energy. As expected, all three measurements (area, length, and width) had a nearly linear increase in damage with increasing impact energy. Figures 4 and 5 are photographs of the typical initial damage zones associated with each impact group for lay-up "A" and lay-up "B", respectively.

A significant difference between the two laminate lay-ups was observed. On average the damage width was 12 percent greater and the damage length was 25 percent greater for lay-up "B" compared to lay-up "A". The damage area, which is a function of length and width, was 40 percent greater for lay-up "B" compared to lay-up "A", see Figure 6. Hosur, Murthy, Ramamurthy, and Shet (1998) had shown even greater increases in damage area between laminates of different stacking sequences.

Hosur et. al. (1998) observed that the area of maximum damage typically occurs between plies of maximum fiber orientation. Maximum fiber orientation would be 0/90 or +45/-45, etc. This observation may be of particular importance to this study. It has been shown that lay-up "B" has significantly more damage than lay-up "A". Analyzing the two lay-ups used, lay-up "A" has eight ply interfaces of maximum orientation, yet lay-up "B" only has four. Making a gross assumption that delamination will only occur between plies of maximum orientation, then lay-up "A" will have eight delaminations to absorb the impact energy, while lay-up "B" only has four. Thus, the delamination area of lay-up "B" would be twice that of lay-up "A" for an equivalent impact energy. It was observed that lay-up "B" had 40 percent more damage on average; this finding would tend to conclude that this assumption is somewhat correct. Obviously many factors are contributing to the degree of damage caused by impact loading, yet this hypothesis could account for the majority of the difference between the two lay-ups. These findings illustrate the importance of stacking sequence.

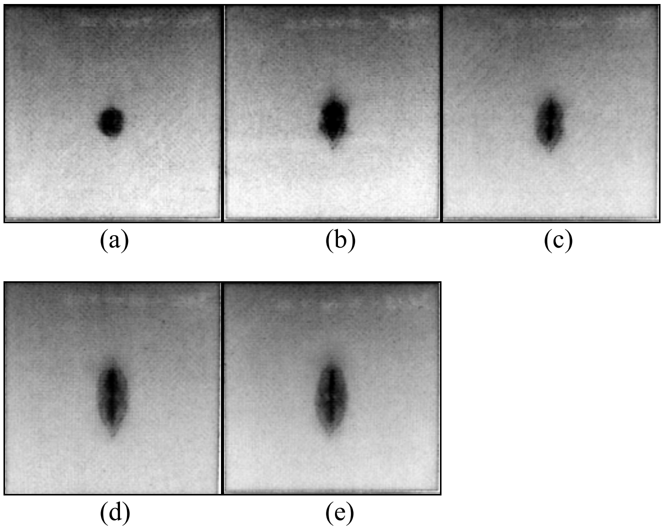

(a) (b) (c)
(d) (e)

Figure 4. Typical photographs of initial impact damage zones for lay-up "A": (a) 5J – 7.25kg; (b) 10J – 7.25kg; (c) 10J – 12.25kg; (d) 15J – 7.25kg; (e) 15J – 12.25kg.

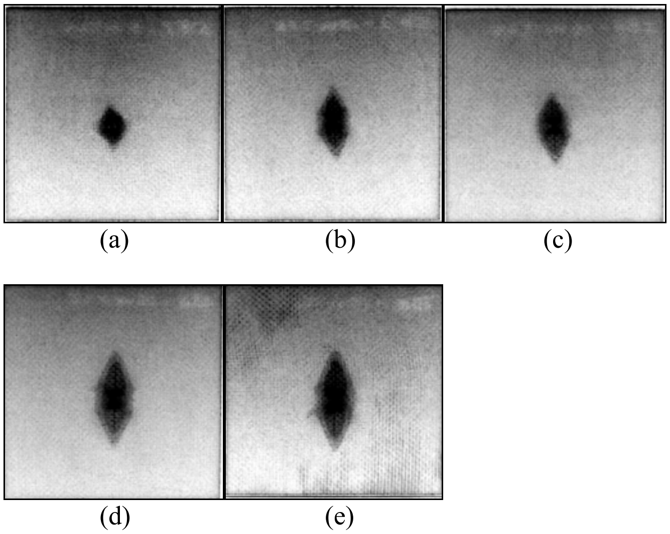

(a) (b) (c)
(d) (e)

Figure 5. Typical photographs of initial impact damage zones for lay-up "B": (a) 5J – 7.25kg; (b) 10J – 7.25kg; (c) 10J – 12.25kg; (d) 15J – 7.25kg; (e) 15J – 12.25kg.

The trend between impact velocities was less prominent. The results suggest that the 12.25 kg impact mass creates more damage than the

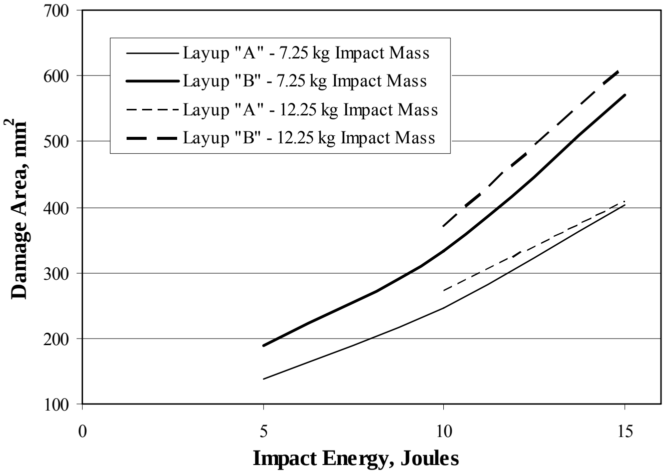


Figure 6. Comparison of initial damage area based on impact energy, impact mass and lay-up.

7.25 kg impact mass. So, a lower impact velocity causes more damage. This trend is typically noticed for the damage measurements taken here. However, other studies suggest that high-velocity/low-mass impacts typically create more damage. Although the other studies typically focused on the differences between low velocity drop weights and high velocity projectile impacts, the reversal of their hypothesis seems to be very interesting. Their conclusions suggest that strain rate and inertia effects both contribute to damage growth. They suggest that time duration of a drop weight impact event is considerably longer and thus more energy is absorbed by deformation rather than damage growth. This theory would seem to be understandable, yet the results found don't necessarily support this concept.

Zhou (1996) also suggests that a velocity difference of less than 30 percent is typically not sufficient to establish trends between subsequent damage. This may be of particular importance when comparing the results found here against this and others studies. The impact velocity for the 7.25 kg impact mass is exactly 30 percent greater than the 12.25 kg mass. Based on Zhou's assumption, the difference between impact velocities may be significant enough to notice differences in damage.

Further comparison against Zhou's findings suggests striking similarities to the study presented here. Zhou utilized drop weight velocities ranging from 2.0 to 8.0 meters per second, where this study's velocity ranged from 1.17 to 2.03 meters per second. Notice that the difference in damage between the 12.25 kg and the 7.25 kg impacts is decreasing with increasing impact energy. This shows that the damage caused by the higher velocity impact is increasing faster than the lower velocity, when compared against increasing impact energy. This trend may suggest that at impact energies higher than utilized here, the 7.25 kg impact mass could possibly have greater damage than the 12.25 kg mass. Zhou's results show similar findings. As the impact energy increases, the difference in damage between the higher velocity impact and the lower velocity is increasing as well.

Thermal Cycling

As previously mentioned both the dry and wet samples underwent thermal cycling after impact in order to monitor the growth of damage due to the effects of moisture and thermal cycling. Damage growth did occur in both sub groups but the magnitude of damage growth in the dry samples was minimal, an overall average of roughly 6.2 percent. Table 2 provides the results. Since moisture was absent from these samples, the damage growth seen is likely due to the mismatches in coefficients of thermal expansion and resulting residual stresses.

Table 2. Damage Area Growth for Dry Service Condition

Impact Group	Layup "A"			Layup "B"		
	Initial Damage, mm^2	Final Damage, mm^2	Damage Growth, %	Initial Damage, mm^2	Final Damage, mm^2	Damage Growth, %
5 J - 7.25 kg	137	146	6.7	184	196	6.5
10 J - 7.25 kg	224	242	8.1	320	344	7.5
15 J - 7.25 kg	376	394	5.0	555	581	4.5
10 J - 12.25 kg	257	277	7.7	345	371	7.6
15 J - 12.25 kg	392	410	4.7	598	622	4.0

The results from the thermal cycling of the wet specimens reveal that moisture does have a pronounced effect on delamination growth in this material system. Table 3 and Figure 7 reveal that the percent growth in damage area ranged from 48.3 for the 15J – 12.25 kg impact group of lay-up "B" to 118.5 for the 5J -7.25kg impact group of lay-up "A".

Table 3. Damage Area Growth for Wet Service Condition

Impact Group	Layup "A"			Layup "B"		
	Initial Damage, mm^2	Final Damage, mm^2	Damage Growth, %	Initial Damage, mm^2	Final Damage, mm^2	Damage Growth, %
5 J - 7.25 kg	140	306	118.5	195	337	72.8
10 J - 7.25 kg	269	476	76.7	348	572	64.2
15 J - 7.25 kg	430	688	60.2	588	866	47.4
10 J - 12.25 kg	286	500	75.0	394	598	51.6
15 J - 12.25 kg	423	689	62.8	631	935	48.3

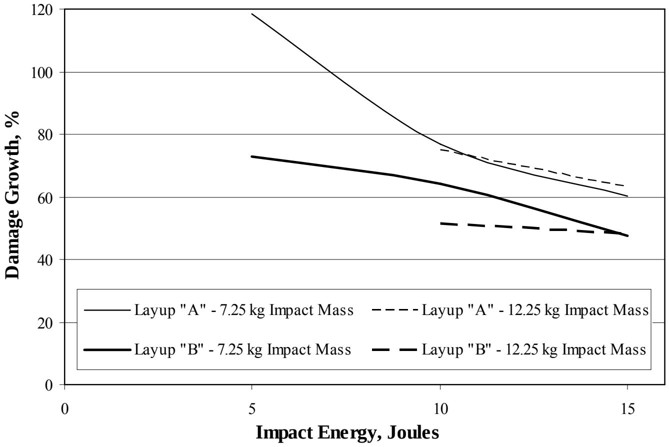


Figure 7. Comparison of damage area growth based on impact energy, impact mass and lay-up under a wet service condition.

The initial damage area for all impact groups of lay-up "B" were larger than the corresponding impact groups for lay-up "A", yet the percent growth in damage area due to thermal cycling for lay-up "A" exceeded that of lay-up "B". It is believed this behavior is due to two distinct conditions. The first is that the initial damage areas of lay-up "B" had longer delamination zones. Consequently in order to develop similar prying wedges between laminates the moisture in lay-up "B" would have to migrate deeper into the delamination.

Secondly, the relative stiffness of plies between delamination layers was double in lay-up "B" due to the stacking sequence. Lay-up "B" had two plies between layers of maximum orientation whereas lay-up

"A" alternated between each lamina. Lay-up "B" would then offer more resistance to prying action when moisture within the delamination underwent a phase change.

One other item to note is that the damage growth comparison is being made relative to areas. The relative differences in damage growth shown in Figure 7 for the 5J impact is about 50% between lay-up "A" and "B". In reality the differences are smaller because the comparisons are made to the original damage areas. The absolute dimensional changes in the damage region are very similar, indicating that the damage growth is independent of initial damage area.

CONCLUSIONS

Fiberglass/epoxy laminates were subjected to low velocity impacts and then underwent low temperature thermal cycling in dry and wet states. The main intent of this study was to determine the effects of moisture on the delamination damage growth caused by thermal cycling. This study also examined the differences between impact energy, impact velocity and laminate stacking sequence for initial impact damage and damage caused by subsequent thermal cycling. The following conclusions are drawn:

- Moisture had a detrimental effect on delamination damage growth. Samples subjected to 500 low temperature thermal cycles under the presence of moisture revealed 43 to 112 percent more damage growth relative to the dry samples.
- A nearly linear increase in damage area with respect to increasing impact energies was observed.
- The differing impact velocities showed that the lower velocity impact event created more damage. This indicates that a low-velocity/high-mass impact is worse than a high-velocity/low-mass impact.
- The stacking sequence was extremely significant to the damage response characteristics. For equivalent impact energies, a $[0_2/90_2/0_2]_S$ lay-up ("B") received 40 percent more damage on average than a $[0/90/0/90/0_2]_S$ lay-up ("A"). This indicates that the number of maximum fiber orientation interfaces is a primary contributor to this additional impact damage.
- Saturation of the specimens was achieved after approximately 90 hours of soaking. At that time the samples had reached an average equilibrium near 0.4% moisture by weight.
- Trends between the damage growth rates for different impact energies and stacking sequences are suspected to be dependent upon delamination length and the distance between delaminated plies. Long delamination zones require moisture to penetrate deeper into the delamination for water crystallization to be effective in developing adequate prying action to propagate the delamination. In addition, the relative stiffness of the material between delamination plies will have an effect on the ease of producing the prying wedge.

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