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Impact Behaviour of PMC Reinforced with Fibers under Sub Zero Temperature: A Review

P. A. Prasob*, M. Sasikumar and P. Tamil Selvan

School of Mechanical and Building Science (SMBS), VIT University, Chennai Campus,Tamil Nadu, India; pprasob@gmail.com, sasikumar.m@vit.ac.in, tamilselvan.p@vit.ac.in

Abstract

Background/Objective: The objective of this review paper is to know and verify the mechanical properties especially impact behavior of PMC under subzero temperature. Methods/Statistical Analysis: The focus of this paper is on the use of liquid nitrogen as cryogenic liquid, subzero temperature conditions and the mechanical durability of PMC including tensile strength, compressive strength, shear strength, fatigue. The low velocity impact of PMC is reviewed under the Charpy impact and the Drop weight impact. Also the progressive failure and damage of PMC under impact is given due importance in this paper. **Applications/Improvements:** Hybridization of PMC with synthetic, natural fibers and micro fillers can enhance the mechanical properties of PMC at liquid nitrogen temperature. **Findings:** The tensile load response for a composite is very much dependent on the strength properties of the reinforcement fibers, since they are high compared to the resin system on its own. The compression testing of the composites is very challenging due to various reasons. The application of compressive load on the cross section is done in three ways: directly apply the compressive load on the ends of a specimen, loading the edges in shear and mixed shear and direct loading. The compression test results show that the mechanical properties at subzero temperature is comparatively better than properties of the PMC at room temperature. The impact testing of PMC in subzero temperature has better impact strength than PMC tested at room temperature. The reason being the brittleness of the matrix once exposed to liquid nitrogen the layers get contracted on cooling and load transfer does not take place as in the case of composite at room temperature resulting in failure.

Keywords: Cryogenics, Damage, Impact, Polymer Matrix Composite (PMC), Liquid Nitrogen, Subzero

1. Introduction

Aerospace application demand materials with high strength and lower weight. Conventional materials like metal is getting replaced by fiber polymer composite as they satisfy the conditions like good strength, stiffness and lower density. There is a very pronounced demand of fiber polymer composites because of its mechanical properties. Also PMC are stable over a wide temperature range from subzero conditions to more than 100 ^{0}C. Also PMC is stable in environmental conditions like moisture absorption and resists fatigue failure and damage. Mechanical or structural components made of polymer matrix composite may suffer large damage extension when subject to impact loads, with the corresponding decrease of their residual strength and the subsequent risk of structural failure under service loads. Increased thermal stresses are the causes of micro cracks in a composite under sub zero temperature.

1.1 Cryogenics- sub zero temperature

The cryogenic temperature starts around of 123 K. Liquid nitrogen (Liquified nitrogen gas) which is available in abundance is the most widely used cryogen. Special containers called Dewar flask are used for storing liquid nitrogen. Typical laboratory Dewar flasks are spherical, made of glass and protected in a metal outer container. The field of cryogenics advanced developed when scientists found that metals frozen to low temperatures showed more resistance to wear. When experimented cryogenic showed the possibility of increasing the life of metal tools to anywhere between 200%-400% of the original life

* Author for correspondence

expectancy using cryogenic tempering instead of heat treating. Liquid helium is also used as cryogen and is used for freezing and chilling.

1.2 Mechanical Durability of PMC under Sub Zero Temperature

Subzero temperature mechanical properties of polymer matrix composites are dependent upon laminate ply layup and test procedures, material selection, specimen preparation, aging or preconditioning, composite fabrication and handling. Transverse tension and shear, the matrix dominated properties are largely dependent on the effect of temperature on static strength. As temperature is decreased the fatigue life is reduced and development of cracks due to thermal stresses influences the matrix dominated strength. Polymer matrix composite properties is a function of the matrix dominated properties.

Mechanical properties of jute-epoxy composites increases with the increase in fiber loading and also the void content decreases with the increase in fiber loading. The properties like flexural strength and inter-laminar shear strength is greatly influenced by the void content of the composites and the properties reduced from 0 wt.% to 12 wt.% fiber loading and with the reduction in the void content from 12 wt.% to 48 wt.% the properties are improved[1]. Formation of microcracks within the matrix of the carbon-fiber/epoxy resin systems which is a measure of the toughness is prevented at lower temperature. Matrix stiffness and matrix strength increases as the temperature decreases[2]. Cryogenic conditioning of carbon/epoxy composites leads to high amount of residual stresses at the interface and contributes to matrix crakings and interfacial debondings. The anisotropic nature of carbon fibre plays a vital role in interlaminar shear strength of the laminate at cryogenic temperature. Cryogenic conditioning stimulates the formation of rows of cups due to coalesce of transverse microcracks that originate longitudinal cracks along the fibre[3]. Temperature dependent mechanical properties of the epoxy-based, bismaleimide-based and PEEK-based CFRPs are analysed for the laminate behaviours under cryogenic environment to find the possibility of reliable liner system[4].

Resin based composites with glass reinforcement at 4K subjected to biaxial tension/shear and uniaxial tension has unpredictable stress raisers due to the presence of glass fibers[5]. Stiffness (transverse and longitudinal) and strength shows a linear relation to temperature for tension loading with variables temperature load and time. Exposure of the laminate to liquid nitrogen for a longer period of time or aging can change the mechanical properties of the composite laminates[6]. The energy dissipation density and laminate strength of glass fiber/epoxy laminates and Carbon fiber/epoxy laminates at 77 K are higher than those at 296 K. The laminate strength is 30–40 % higher for the glass fiber/epoxy laminates and about 15–20 % more for the carbon fiber/epoxy laminates. The damage area is an effect brought by fiber–matrix interface split, micro-rupture events, delaminating and fiber rupture around notch tip, the matrix cracking[7]. Addition of fillers MWNT and BGE increases the fatigue life at 77 K which can be explained with tension-tension fatigue test. Introduction of MWNT and/or BGE have negligible effect on the ultimate tensile strength, Young's modulus, knee point stress. CNTs and soft modifiers when added to the matrix at 77 K improves the matrix dominated properties of composite materials[8].

The cryogenic tensile strength of the blend resins have been drastically improved by up to 77.6% when a small amount (0.05 phr) of siloxane liquid and a bifunctional polymer, SME (20 phr) is added to the matrix epoxy. The siloxane liquid has no detrimental effect on the thermal contraction of the blend resins as can be proved from CTE results. Consequently, the blend epoxy resin is promising matrix to be employed in cryogenic applications[9]. Cryogenic adhesive resins based on modified DGEBA with MPDA–NPHB liquid mixture showed improved impact strength and shear strength at both RT and 77 K compared to the unmodified adhesive[10]. The addition of carboxylic Nitrile- butadiene NR to DGEBF–DETD epoxy system (15 phr NR) increased the cyrogenic tensile strength at 77 K by 40.2% and enhanced the fracture toughness (KIC) at 77 K by 48.3% compared with that of the pure epoxy[11]. Ultimate Tensile Strength (UTS) and tensile strain of a three-dimensional (3D) C/SiC composite at 25◦C, −40◦C, −80◦C, and −100 ◦C revealed that 3D C/SiC composite has a considerable ductility at cryogenic temperatures but the specimen suffers the most violent degradation at −40 ◦C[12].

Through thickness properties of GFRP composites at 77K and 310K is determined by conducting tensile test. The better fiber/matrix interface bonding ensures increased through thickness tensile strength at cryogenic temperature[13]. Carbon nanotube reinforced epoxy nanocomposites with an optimized formulation of diglycidyl ether of bisphenol-F (DGEBF) /diethyl toluene diamine (DETD) system, toughened by a reactive aliphatic diluent has better cryogenic mechanical properties (tensile strength, Young's modulus, failure strain and impact strength) at 77 K than at RT since the CNT–epoxy interfacial bonding becomes stronger at 77 K than at RT due to thermal contraction effect[14]. Inclusion of 1 wt% of organic-MMT in MMT/epoxy nanocomposites improved the mechanical and thermal properties by 3.1% and 13.2% at 27 ^{0}C and 77 K respectively [15].

Tensile behaviour of unidirectional composites at very lower temperatures is analysed using Monte Carlo simulation[16]. Glass fiber reinforced diethyl toluene diamine (DETD) cured diglycidyl ether of bisphenol F (DGEBF) epoxy with modifiers E102, ETBN and IPBE showed improved interlaminar shear strength compared to the pristine samples with a maximum of 14.87 % increment in IPBE modifier[17]. Incorporation of GO 0.3 wt. % into the epoxy matrix of glass fabric/epoxy composites can effectively enhance the ILSS by 32.1% and 32.7% at 77 K and RT respectively[18]. The results of the short beam shear test conducted to measure the ILSS of woven GFRP and polyimide film hybrid laminates at 77 K and 4 K was in accordance with the predictions of progressive damage analysis. The apparent ILSS calculated from the classical beam theory is lower than the failure shear stress results obtained from finite element analysis[19].

Inter laminar shear stress values of laminates is 5-20% lower due to irradiation at 60 ^{0}C compared to laminates irradiated at subzero temperatures of 5K. The reduction in inter laminar shear stress is more for E glass fiber epoxy laminates and is about 35%[20]. Flexural static loading on CF/RC sandwich beams resulted in core shear failure only while the influence of subzero temperature on failure was not appreciable. Compared to ambient temperatures and high load level the fatigue life of sandwich beams were increased by 20-40 cycle times at -22 ^{0}C while the increment was 100 cycle times at 60 ^{0}C[21]. Cross link formation is affected by the addition of 0.3 wt. % MWCNT to glass fiber/epoxy composite which lowers the glass transition temperature to 120 ^{0}C. At subzero temperatures of -80 ^{0}C the reinforcement efficiency is 30% higher for GE composite due to the addition of CNT[22].

Flexural fatigue and electrical resistance responses of MWNT/polycarbonate composites at cryogenic temperatures is assessed with three-point bending method and electrical resistance-based sensing method is used for monitoring the cyclic deformation and failure process in the nanocomposites. Cooling from room temperature to 77 K increases the fatigue resistance of the nano composites[23]. Finite element results shows a strengthening and weakening influence of thermal stresses at the mid-section when specimen fails due to thermal load from cooling and the failure often occur at the interface when the specimen are tested on different test fixtures (θ = 150, 450, and 700) based tri-axial failure criteria[24].

Effect of temperature on mechanical behaviour of carbon fibre-reinforced polymer truss core sandwich panels showed that there is an increase in stiffness and strength of sandwich panels while tests were conducted on-600C, 200C, 700C, 1000C, 1400C, 160 0C, respectively [25]. Tailored carbon nanotubes CCNTs and NSCNTs can enhance the strength of polymer-based composites due to their tailored geometrical patterns when exposed to cryogenic environment. Compared with straight-type of CNTs, CCNT and NSCNT can compensate many problems arising from poor interfacial bonding properties, brittleness of polymers and agglomeration of CNTs[26].

Adhesive thickness and lap shear strength of adhesive joints share a inversely proportional relationship for aluminum and stainless steel adhesive joints at -150 ^{0}C. Thermal stress in the adhesive layer and lower fracture toughness of adhesive are factors affecting lower lap shear strength[27]. Stycast 2850 FT epoxy is developed to resist thermal shock in cryogenic applications (77K) as an alternative to LNG application. The fatigue life of the metal/epoxy combination at 77K increased by a factor of 20 without any damage and withstands repeated cool down at liquid nitrogen temperature[28]. For composites with different core heights the failure mechanism are almost the same, but the brittle failure feature becomes more obvious at 77K for three-point bending testing of 3D integrated woven spacer composites with different core heights[29]. The mechanical response (tension, compression and flexure) of non-woven polyester fabric/epoxy composites at 77 K showed an increase in stiffness and strength. Also interface debonding between the fiber and the matrix is seen on the tensile fracture surfaces[30]. Reinforcing PUF with chopped fiber (10%) increases the compressive, tensile strengths, fracture toughness, especially more at the cryogenic temperature compared to room temperature[31]. An integrated heuristic knowledge base and experimental data is used to create a knowledge based system to provide solutions for design problems in composites. The experimental data are results from composite testing especially polymer composite and data from expert's databases[32].

2. Impact of PMC under Sub Zero Temperature

2.1 Charpy Impact

The impact performance of the composites is reduced at lower temperatures (from 23°C to -30°C) and energy levels equal to 10, 15 and 30 J for low velocity impact. Matrix cracking which is the prominent failure mechanism at 23 ^{0}C is replaced by delamination and fiber breakage at -30 °C[33]. Ductile-phase-reinforced BMGMCs and their BMG matrix has similar impact toughness below 200 K and also values are nearly identical at 100 K. Also a series of heating curves were developed to determine the impacting temperature for metallic glass matrix composites during Charpy impact testing at 77K[34]. Stress propagation is limited when the matrix solidifies due to the better interfacial adhesion between the matrix and fiber which improves the impact characteristics of 3D MWK composites at liquid nitrogen temperature. As the fiber ply angle increases the impact properties decreases at 27 ^{0}C and 77K[35]. Impact strength of GFRP composite depends is controlled by fiber volume fraction and exposure to temperature and are directly connected to the parameter controlling the mode of failure, i.e. matrix or fiber. The 0 ^{0} unidirectional laminated composite presented higher impact strength than the cross-ply laminate within the whole temperature range and for all fiber volume fractions[36].

2.2 Drop Weight Impact

The increase in volume fraction aramid/epoxy, steel, glass epoxy specimen resulted in impact energy decreases for the tested temperatures. The energy absorbed at 40^{0}C was 268 KJ/m2, 1190 and 388 respectively[37]. Impact velocity and temperature affects energy absorption, residual flexural strength. Impact and post impact damage characteristics show that the predominant failure mode of jute/UP composites was delamination, irrespective of the impact temperature and velocity [38]. The energy absorption decreases and the deformation increases in both the zero and cross ply specimens as the temperature of the impact increases for CFRP composite laminates[39]. From parameters residual tensile strength, impact pressure, permanent deformation obtained as a result of tension test after impact ,impact test the impact resistance of chopped E-glass fiber reinforced PUF composites are measured at liquid nitrogen temperature of -196^{0}C[40].

Damage tolerance and the impact response of quasi - isotropic glass/epoxy laminates upto Ei = 20 J is the same for all tested temperatures. For impact energy beyond 20 J with decrease of temperature the perforation threshold increases[41]. Kevlar/fiberglass composite laminate impact properties dependence on damage is investigated[42]. Properties like elastic modulus and residual compressive buckling strength have inverse relation for impact damage and temperature. The lower temperature increases the residual strength while residual strength is reduced when composite are prone to damage due to impact[43]. VAIRM process is employed to manufacture the graphite/epoxy samples which became plasticized and exhibited more ductility to withstand higher peak loads when they are subjected to cold-moist conditionings at energy levels of 15, 30 and 45J[44].

Low temperature impact resistance which is highly dependent on glass transition temperature is absent in PP composites resulting in high energy absorption due to impact below Tg when impact test are carried out at temperatures between -50^{0}C and 120^{0}C[45]. Impact strength, failure strain, tensile strength of the methyltetrahydrophthalic anhydride (MeTHPA) cured DGEBA is improved by the addition of H30(10 wt%) at liquid nitrogen temperature. The elongation at break at liquid nitrogen temperature is also improved by adding H30[46]. For the woven glass- fabric laminates, the parameters which are highly dependent on temperature for a range of -65^{0}C and 100^{0}C are the threshold parameters, U_0 and c_0, the incipient damage load, Pi[47].

Low temperature affects the impact behaviour of the tape laminate negatively due to the high inplane thermal stresses. As velocity increases above the ballistic limit damage saturation takes place and in this velocity range, temperature has no influence on damage extension[48]. Effect of temperature on the impact damages; matrix cracking and interfacial delamination in CFRP composite plate laminate is discussed[49]. For sandwich composites the performance improved with the addition of a Kevlar layer to the fiber glass composite at different temperature[50]. Interlaminar thermal stresses and interlaminar residual thermal stresses are induced in CFRP laminate composite at lower temperatures when subjected to low velocity impact loading resulting in acceleration of matrix cracks and deamination. There is 50% decrease in the threshold energy as temperature is lowered from 20 to -150 ^{0}C[51].

Impact resistance and Cryogenic tensile strength, ductility of the DGEBA/ MeTHPA system has been enhanced by the introduction of polyethylene glycol (PEG-4000)[52]. The parameters cryogenic strength, ductility and impact resistance is improved by adding BGE for DETD-cured DGEBF epoxy system modified by n-butyl glycidyl ether 53. Addition of 1.5 wt. % of thermoplastic PEI at 77K improved the impact strength of epoxy matrix by 45% and the lowered the thermal expansion coefficient by 23%[54]. Low temperature stresses affects the impact parameters of unidirectional glass/epoxy composite for temperatures of 20, 90 and -50 °C[55].

2.3 Damage of PMC under sub zero temperature

The effect of thickness as a factor for damage formation is measured in terms of crack opening displacement measurements and crack density measurements for carbon fiber/PEEK laminates. Large residual stresses and severe thermal gradients were observed for thicker laminate[56]. Fracture toughness of GFRP composites increases as the Mode III loading increases and delamination fracture toughness under mixed II/III loading increases at 77K compared to 310K[57]. The relation between Young's modulus and temperature is inversely proportional for cracked satin woven T800H/3633 5HS composite laminates under tension at 77 K as proven from 3D finite element analysis. When the tensile load direction is transverse to the fiber orientation the Young's modulus decreases at lower temperatures[58]. Cryogenic micro cracking is dependent on the fiber and matrix for CF epoxy composite[59].

Micro-cracking of carbon/bismaleimide composite submerged in liquid nitrogen shows a linear relationship between the number of times submerged and micro crack density[60]. Prediction of composite laminate damage, permeability and optimised cryo-tank design and analysis of linerless composite cryo-tanks with a novel numerical methodology[61]. Piezoelectric ceramics and woven GFRP laminates exhibits temperature dependent material properties with temperature strongly influencing the piezoelectric control. The results of experiments on a double cantilever beam DCB of both materials were also verified using finite element analysis[62].

Residual stresses, maximum service tempertature and damage accumulation are the major factors affecting composites in cryogenic cycling[63]. Threshold energy release rate is inversely proportional and delamination growth rate is directly proportional to temperature under Mode II fatigue loading at 77K[64]. For woven-fabric composites AE and progressive analysis can be efficiently used to determine damage initiation and accumulation under cryogenic temperature[65]. Bending properties of 3D integrated woven spacer composites are affected by the core height and increase significantly with that of core height at 27^{0}C and 77K. At 77K the composite shows brittle fracture feature and zigzag fluctuation process[66].

Delamination growth rate as a function of the energy release rate range of woven GFRP laminates under mixed-mode II/III loading conditions is obtained from fatigue delamination tests conducted at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K) using the 6PBP method[67]. Creep deformation in the resins at low temperatures show that resin strength has a non-linear relationship with size of small defects. Also thermal stress calculation is made from fracture stress measurement of resins with a small flaw in the resins by using thermo-mechanical properties[68]. Stress-strain behaviour of UD laminate under tensile loads in longitudinal direction is linear elastic until breakage and the strength increased about 12% as the temperature decreased to -60 °C. Also, as temperature is decreased, strain to failure decreased slightly about 10%[69]. From FE models of CFRP–steel double-strap joints it is confirmed that "interfacial adhesive debonding" failure was the triggering failure mode for conditioning temperatures in composite[70].

2.4 Cryogenic Properties

Tensile behavior of unidirectional glass epoxy laminates at lower temperatures when exposed to thermo-mechanical loading shows linear elastic behavior in longitudinal direction and nonlinear elastic behavior in the transverse direction. The compressive behavior of the same specimen is nonlinear elastic in both longitudinal and transverse direction until failure[71]. Fiber dominated failure and matrix cracking are the mechanism of failure at 77K for G11 woven glass epoxy composite. Prediction of the G11 woven glass epoxy composite elastic properties can be made with the help of a micromechanics model[72]. The ratio of tensile strength to thermal conductivity below 77 K is a criteria for cryogenic support material and it's good for high carbon-fire content CFRP[73]. The properties of the fiber such as thermal expansion and conductivity, tensile, compressive strength and modulus are critical for support element cryogenic applications [74]. Fiber composites stress concentration and thermal residual stresses can be lowered by replacing brittle epoxy resins with low temperature ductile thermoplastics[75]. For CFRP and GFRP with decreasing temperatures the ILSS increases. The rate of ILSS increase from 80 ^{0}C to room temperature is 98psi per ^{0}C and 17.89 psi per ^{0}C from room temperature to -100 ^{0}C. The shear strength of GFRP is almost half of CFRP at all temperature[76].

The inclusion of nano particle in the form of silica has enhanced the cryogenic temperature tensile strength of bisphenol-F type epoxy resin (DGEBF) and tetraethylorthosilicate (TEOS) while the nano silica had no influence on tensile strength at room temperature. The thermal expansion coefficient was also reduced when the temperature was reduced from 298K to 77 K with the addition of nano particles[77]. Curing behaviour of di-epoxies or multifunctional epoxies when mixed with hardeners such as anhydride, amine or phenol and were blended with polycarbonate, carboxyl-terminated butadiene acrylonitrile copolymer or phenoxy reveals that the two-dimensional network structured linear polymer shows high performance cryogenic temperature[78]. Cryogenic composite supports is discussed[79]. Addition of 10% chopped glass fiber with PUF increased the compressive strength (35% and 54%), tensile strength (220% and 210%), fracture toughness (290% and 360%) at room temperature and cryogenic temperature respectively[80] .

Flexural and tensile properties of the wool fiber epoxy composite is improved by hybridization with jute fibers. From acoustic emission monitoring its evident that debonding, fiber pullout and matrix micro cracks contributes to damage in the hybridized composite[81]. Addition of MWCNT's to carbon fiber epoxy composite at 0.5wt% enhances the transverse tensile strength by 51.7 % at liquid nitrogen temperature and 29.3% at room temperature respectively for the composite. The MWCNT's improves the adhesion property as well[82]. CFA method is employed to evaluate the thermal expansion co-efficient of polymers within the range of 4-300 K. Coating's thermo- mechanical properties, physical properties of the fiber and geometry of the assembly are the dependent factors for the temperature response of a coated FBG[83]. The single fiber tensile test proves that the electric resistance ratio is directly proportional to the tensile stress for carbon fiber reinforced composite[84].

The relationship between changes in the Electrical Resistance Ratio (ERR) and the tensile stress of CF is obtained from the single fiber tensile test and the tensile stress of CF was found to be directly proportional to the ERR[84]. The properties of 3-D braided basalt/ epoxy composite materials like peak stress, specific energy absorption, Compression modulus, failure strain have different sensitivity to strain rate and temperature. The dominant factor for out of plane damage due to impact at 77k is shear failure while fiber buckling and squeezing are dominant for in plane impact[85]. MKF-GF/PP composites when subjected to temperature of -40^{0}C up to 80^{0}C develop in plane stresses which are temperature dependent and can be related to the characteristic function in terms of the mechanical properties. The mechanical properties of GF/PP composite is largely dependent on the glass transition temperatures as shown by the dynamic mechanical analysis[86]. The relationship between subzero temperature mechanical properties and thermal treatment of phenolic-resin plywood with multiple grain orientations is obtained from bending and tensile test conducted with cryogenic immersion and cyclic thermal shocks [87].

E-glass/epoxy composites manufactured in the form of box type face for advanced sandwich type insulation board system resists mechanical load as well as thermal loads and the shear loads are resisted by the low density polymeric foam. Comparing to conventional insulation board system the thermal conductivity of sandwich type is 30% lower and is only 0.018 W/m K[88]. Tensile strength, Impact strength and Young's modulus of the composites were enhanced when graphene (0.1 wt. %) is added to the epoxy matrix. The impact strength showed betterment of 10.5% and 23.7% while tensile strength improved by 3.5% and 17% at room temperature and 77 K respectively[88].

3. Conclusion

The recent progresses of the response of mechanical characteristics the composite PCMs under sub zero temperature mainly at liquid nitrogen temperature and their performance enhancement were reviewed in the present paper. The main focus is placed on the impact characteristics of natural fiber epoxy composites under subzero temperature. This review paper has given emphasis on areas like mechanical characteristics like tensile strength, compression strength, flexure, fatigue, impact. Also the progressive damage behaviour of the PMC under subzero temperature with micromechanical approach gives due importance. Much effort is also made to concentrate on the cryogenic behaviour of the polymer matrix composite. The following conclusions are drawn from the review.

- At subzero temperatures the void contents of the polymer matrix composite greatly influence the mechanical properties.
- Lower temperature does not affect the load transfer from matrix to the fibers and also with decreasing temperatures the matrix strength increases for PMC.
- The mechanical properties are changed when polymer matrix composites are subjected to cryogenic temperature for a longer duration.
- Addition of micro fillers improves the mechanical properties of PMC at cryogenic temperature.
- The impact performance of composite is reduced by decreasing temperature when composite are subjected to low velocity impact.
- Varying volume fraction alters the impact energy of the composite.
- Elastic modulus and residual compressive buckling strength negative influence on temperature and impact damage.
- Delamination of the composite occurs at low velocity impact due to accelerated matrix cracking from ILSS at low temperatures.
- In plane thermal stresses developed at low temperatures affects the impact behavior of PMC.
- Debonding, micro cracks and pull out of fiber are the factors affecting damage in fiber reinforced composite.
- With decreasing temperatures the threshold energy release rate increases but the delamination growth rate becomes less.
- Damage behavior at cryogenic temperature can be analyzed with progressive failure analysis.

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