An investigation into the impact of cryogenic environment on mechanical stresses in FRP composites

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Abstract: Fibre reinforced polymer (FRP) composites are fast becoming a highly utilised engineering material for high performance applications due to their light weight and high strength. Carbon fibre and other high strength fibres are commonly used in design of aerospace structures, wind turbine blades, etc. and potentially for propellant tanks of launch vehicles. For the aforementioned fields of application, stability of the material is essential over a wide range of temperature particularly for structures in hostile environments. Many studies have been conducted, experimentally, over the last decade to investigate the mechanical behaviour of FRP materials at varying subzero temperature. Likewise, tests on aging and cycling effect (room to low temperature) on the mechanical response of FRP have been reported. However, a relatively lesser focused area has been the mechanical behaviour of FRP composites under cryogenic environment. This article reports a finite element method of investigating the changes in the mechanical characteristics of an FRP material when temperature based analysis falls below zero. The simulated tests are carried out using a finite element package with close material properties used in the cited literatures. Tensile test was conducted and the results indicate that the mechanical responses agree with those reported in the literature cited.

1. Introduction

It is widely accepted that fibre reinforced polymer (FRP) composites are the materials for the present and future in many engineering applications, especially for the high performance structures. FRPs are now the primary structural components in aerospace structures, found in the fuselage and wings (Boeing 787 Dreamliner); wind turbine blades; and are increasingly being considered for the propellant tanks of launch vehicles. Also, FRPs are being considered for thermal functionalities as part of an insulating system for superconducting magnet coils [1]. In the aforementioned fields, FRPs are exposed to varying degree of temperature, from room temperature to low and cryogenic temperatures. Therefore, the understanding of their mechanical response at those temperature is becoming important particularly in the event of a fracture or damage to the composite part at low temperature [2]. The behaviour of these materials at elevated temperature has been well documented over the years. However, not so much has been published on the characteristics of the FRPs at low temperatures.

In the last two decades quite a lot has been published on how the microstructure of an FRP composite changes when exposed to low temperature environment. Normally, the formation of micro-cracks on FRP composites warns of an impending failure. However, as the temperature drops so does the level of micro-crack formation in the matrix and the composite becomes more brittle due to loss of toughness in the matrix [3]. In the examination of the fracture toughness of FRPs at low temperature, Shindo et al. [4-5] have conducted tests to evaluate the fracture toughness of woven glass fibre epoxy composite at low temperatures. These involved the introduction of mixed-mode delamination to the laminate. Their results show that there is higher resistance at cryogenic temperature than at room temperature. Likewise, the behaviour of an adhesively bonded joint of an FRP material has been studied under the mode I delamination mode [6]. Research has also indicated that the interlaminar
shear strength decreases with wall thickness of a carbon epoxy torus. Effect of the low temperature on the mechanical properties makes the matrix more brittle as the strain reduces with temperature [7]. Similar tests have been carried out for FRP composites use in tanks of reusable rockets as well as the numerical predictions of delamination and matrix cracks [8].

A large number of the available literature in this area of study has mainly reported experimental tests for both property characterisation and investigative fracture mechanics. Although a number of literature has been published on the thermal behaviour of FRP, some have examined the buckling analysis of FRP materials under thermal conditions [9-10]. Some models assumed temperature dependent-elastic properties in modelling the determination of critical buckling temperature for an FRP laminated composite plates. Some have investigated the influence of fibre orientation, modulus ratio, uniform and non-uniform temperature distribution [9]. Aside the investigation on thermal buckling of FRP, thermal effect on FRP material under tensile loading has also been investigated through finite element method (FEM). FEM has been used in analysing thermal residual stresses and the induced matrix failure has been conducted on a transversely tensile loaded carbon fibre reinforced polymer material[11]. The main temperature range considered for the reported FEM of analysing thermal behaviour of FRP materials has been within the room temperature and above.

Research conducted on cryogenic behaviour of FRP materials and validated using a finite element approach has been to some extent limited. This article reports the examination of FRP material at subzero and cryogenic temperatures. A simple model is developed in a commercial finite element package, ANSYS, and it is subjected to tensile loading at different subzero temperature. The results are also presented for each ply in the model.

2. Damage in Composite
At standard and elevated temperature, FRP composites have been reported to fail in various ways: under loading the matrix fails progressively in cracking; the fibre fractures; there is debonding between the fibres and the matrix; and interlamina failure between the layers. The latter is caused by out-of-plane stresses on the composite [12]. At lower temperature, the failure modes are largely similar. However, the matrix behaves differently. For a thermosetting polymer matrix with high molecular weight upon curing, forms high crosslink density, which amplifies the stiffness as the temperature drops [13]. The matrix shows high concentration of micro-cracks, which is the progressive failure of the matrix at room temperature, but at lower or cryogenic temperatures, the appearance of micro-cracks are scanty as a result of the matrix increasing in stiffness as the temperature reduces[3]. Hence, failure at low temperature is further sudden and abrupt.

3. Model Setup and Material Properties
The model was developed according to the ASTM D 3039 [14]. The material properties chosen for this study corresponds to a high strength carbon reinforced epoxy composite commonly used in structures designed for extreme environments. The IM7/8551-7 carbon-epoxy composite by Hexcel has been used in aerospace industry for decades. The properties are as shown in Table 1. The model was developed using Shell181, which can be used for analysing thin to moderately thick laminate structure. It has four nodes with six degree of freedom at each node.

The model was assumed to be transversely isotropic laminate of 2.5 mm thickness and was represented by a thin rectangular shell for tensile test. It was modelled as an eight-layer material with [45/0/-45/90]s stacking for the layers. The model was subjected to 1000N tensile load at 25, 0, -50, -100, and -150 degree Celsius.
## Table 1. IM7/8551-7

|       | 158.58        | GPa | 8.34 | GPa | 8.34 | GPa | 5.86 | GPa | 3.5  | GPa | 5.86 | GPa | 0.28 |  | 0.28 |  | 0.35 |  | -4e⁻⁷ | C | -5e⁻⁷ | C | -5e⁻⁷ | C |
|-------|----------------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------| | | | | | | | |
| E₁₁   | G              | E₂₂ | G    | E₃₃ | G    | G₁₂ | G    | G₁₃ | G₂₃  | G₁₂ | ν₁₂  | ν₁₃ | ν₂₃  | | | | | | | |

### Coefficient of Thermal Expansion @20 °C

- CTEX: -4e⁻⁷ C⁻¹
- CTEy: 3e⁻⁷ C⁻¹
- CTEz: 3e⁻⁷ C⁻¹

## 4. Results and Discussion

The room temperature model is included for comparison of the changes in the material as its temperature drops. Among the main response that were evaluated are the deformation in the primary loading direction, the stress and the strain in each ply, all in the loading direction. Given the type of material and its high stiffness, it was expected that under normal conditions the deformation experienced from 1000 N would be minuscule. Under this tensile load, the extension at room temperature was 3.02 mm, Figure 1. The extension is minimal at the fixed left end and maximal at the right end where the load is applied. However, as the temperature reduces so does the tensile elongation of the material, microscopically. It appears that the material retains its behaviour even at low temperatures except for small reduction in elongation of the material in comparison to the behaviour at room temperature. The deformation was reduced by 8 µm, 24 µm, 40 µm, and 56 µm, for 0°C, -50°C, -100°C, and -150°C respectively in comparison with the room temperature (25°C) deformation.

![Figure 1. Deformation along the loading direction](image.jpg)

Similarly, the stress and elastic strain developed in the material under the tensile axial loading were examined in individual layer of the composite. Since the graphic representation of the results for each temperature level bares close similarities, only the figures from the 25 °C model are presented. Also,
due to the symmetric stacking sequence of the laminate, only the results for three unique layers are presented. The results for the test at room temperature are presented in the Table 2 and it is used as the standard to compare the changes in the material behaviour for the lower temperature tests.

Table 2. Stress ($\sigma_x$) and strain ($\varepsilon_x$) developed in the material at room temperature (25 °C), where ($n_1$, $n_2$) is the ply position

| Orientation of ply ($n_1$, $n_2$) (degrees) | Stress in the loading direction, $\sigma_x$, (GPa) | Strain in the loading direction, $\varepsilon_x$ |
|---------------------------------------------|-----------------------------------------------|------------------------------------------|
| 0 (2,7)                                     | 2.84                                         | 17.88                                    |
| 45 (1,8)                                    | 0.733                                        | 17.812                                   |
| -45 (3, 6)                                  | 0.733                                        | 17.812                                   |
| 90 (4,5)                                    | 0.136                                        | 17.736                                   |

Figure 2 shows the elastic strain in the material. As would be expected under a normal test, the area between the two clamped tab ends illustrates the region of maximum strain for the first and third layers, the ±45° oriented plies. This is true for the other orientations (0°’s and 90°’s) and all the temperature levels considered. This demonstrates that the pattern of strain development is not significantly affected at low or at cryogenic temperatures. However, this is not true for the magnitude of the strain. As shown in Figure 3, the strain linearly increases for the diagonally and transversely oriented layers (the ±45°s and 90°s respectively) and decreases steadily for longitudinal layers, the 0°s layers. The disparity in the strain level in the layers can be attributed to the matrix being stiffer at low temperatures and the apparent high strength of the layers oriented parallel to the loading direction. Since the former, variable of high stiffness, at cryogenic conditions applies to all layers, it can be said the latter, variable of orientation, is the defining factor in influencing the material’s response to axial tensile loading.
Figure 4 shows a graphical presentation of the change in the stress developed in the material benchmarked against those at room temperature. It shows less stress in the longitudinal fibres, which are parallel to the loading direction. This indicates that low temperature stiffens the matrix and delays the transfer of stress from the matrix to the fibres. This is particularly evident in the plies oriented perpendicularly to the loading direction. The results reveal that the 90 degree plies were subjected to more stress than any other in the composite laminate as the temperature reduces. It appears that the stresses shed-off by the longitudinal fibres were transferred to the transverse plies. Although, the stress magnitude in the longitudinal fibres is significantly higher than those in the 90 degree plies, it however shows the vulnerabilities of the fibres oriented at large angles. The stresses in the two principal axes change within close margin of each other. Figure 5 shows that longitudinal stress in the 0˚ oriented ply drops by 20 percent with every degree fall in temperature and similarly, 24 percent rise in stress experienced by the transverse plies. Given that the similarity in the rate at which the longitudinal fibres and transverse fibres are experiencing reduction, and accumulation of stress respectively, it can be envisaged that in the event of increase in load and high fatigue, the transverse layers will be expected to fail first under the current loading condition. It can be said that these vulnerable transverse layers presented the least resistance path and almost no existence of fortification against the axial tensile load.

Figure 4. Change in induced stress as the temperature drops
5. Conclusion

This article investigates the mechanical response of fibre reinforced polymer composite under tensile loading in a cryogenic environment using ANSYS. The results agree with some of the published experimental work in this area, in that, the FRPs do not drastically deviate from their behaviour at room temperature when exposed to cryogenic temperature. This study allows individual ply in such laminate at cryogenic temperature to be examined and analysed. It can be said that plies oriented parallel to loading direction or axis, though they account for majority of the load carrying capacity of the laminate, are the least vulnerable as strain builds up in them at a very slow rate. However, the off
axis plies or the transverse plies appear to accumulate strain rapidly and therefore have the propensity to initiate the failure of the composite.

Reference:

[1] Mitchell N, Bauer P, Bessette D, Devred A, Gallix R, Jong C, Knaster J, Libeyre P, Lim B, Sahu A and Simon F 2009 Status of the ITER magnets Fusion Engineering and Design 84 113-21
[2] Yokozeki T, Ogasawara T, Aoki T and Ishikawa T 2009 Experimental evaluation of gas permeability through damaged composite laminates for cryogenic tank Compos. Sci. Technol. 69 1334-40
[3] Nettles A T and Biss E J 1996 Low temperature mechanical testing of carbon-fiber/epoxy composite materials NASA Technical Paper 3663 George C Marshall Space Flight Center Report
[4] Shindo Y, Miura M, Takeda T, Saito N and Narita F 2011 Cryogenic delamination growth in woven glass/epoxy composite laminates under mixed-mode I/II fatigue loading Compos. Sci. Technol. 71 647-52
[5] Shindo Y, Takeda T, Narita F, Saito N, Watanabe S and Sanada KY 2009 Delamination growth mechanisms in woven glass fiber reinforced polymer composites under Mode II fatigue loading at cryogenic temperatures Compos. Sci. Technol. 69 1904-11
[6] Melcher R J and Johnson W S 2007 Mode I fracture toughness of an adhesively bonded composite–composite joint in a cryogenic environment Compos. Sci. Technol. 67 501-6
[7] Ahlborn K and Knaak S 1988 Cryogenic mechanical behaviour of a thick-walled carbon fibre reinforced plastic structure Cryogenics 28 273-7
[8] Aoki T I T, Kumazawa H and Morino Y 2001 Cryogenic mechanical properties of CF/polymer composites for tanks of reusable rockets Adv. Compos. Mater. 10
[9] Chen L W and Chen L Y 1991 Thermal postbuckling behaviors of laminated composite plates with temperature-dependent properties Compos. Struct. 19 267-83
[10] Kabir H R H, Askar H and Chaudhuri R A 2003 Thermal buckling response of shear flexible laminated anisotropic plates using a three-node isoparametric element Compos. Struct. 59 173-87
[11] Fiedler B, Hojo M, Ochiai S, Schulte K and Ochi M 2001 Finite-element modeling of initial matrix failure in CFRP under static transverse tensile load Compos. Sci. Technol. 61 95-105
[12] Fifo O, Ryan K and Basu B 2013 Investigations on the effectiveness of cyanoacrylate adhesive for repair of fibre-reinforced polymer laminates under different environmental conditions J. Compos. Mater. 24
[13] Callaghan M T 1991 Use of resin composites for cryogenic tankage Cryogenics, 31 282-7
[14] ASTM 2014 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials in ASTM D3039/D3039M-14, (ed. West Conshohocken, PA: ASTM International)