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Thermomechanical Coupled Analysis of Fiber Reinforced Polymer Composite Square Tube: A Finite Element Study

M. Ali, K. Alam, E. Ohioma

Abstract**—**This paper presents a numerical investigation on the behavior of fiber reinforced polymer composite tubes (FRP) under thermomechanical coupled loading using finite element software ABAQUS and a special add-on subroutine, CZone. Three cases were explored; pure mechanical loading, pure thermal loading, and coupled thermomechanical loading. The failure index (Tsai-Wu) under all three loading cases was assessed for all plies in the tube walls. The simulation results under pure mechanical loading showed that composite tube failed at a tensile load of 3.1 kN. However, with the superposition of thermal load on mechanical load on the composite tube, the failure index of the previously failed plies in tube walls reduced significantly causing the tube to fail at 6 kN. This showed 93% improvement in the load carrying capacity of the composite tube in present study. The increase in load carrying capacity was attributed to the stress effects of the coefficients of thermal expansion (CTE) on the laminate as well as the inter-lamina stresses induced due to the composite stack layup.

Keywords**—**Thermal, mechanical, composites, square tubes.

I. INTRODUCTION

THE need for composites in applications where high strength-weight and high stiffness-weight ratios are needed is high. The automotive is one such industry with increasing demand for composite use in vehicle load bearing components such as front rail members. In some applications, these composite components are usually exposed to thermal loads due to their operational environments such as proximity to hot engine bay. This calls for thorough analysis of their behavior under coupled thermomechanical loading conditions.

Researchers have studied effects of thermal loading on mechanical behavior. The influence of imposed temperature loads on the properties and stresses within the lamina have been studied for a variety of composites [2]-[4]. The variation in mechanical properties in a number of composites is reported by Isaac M. Daniel and O. Ishai for carbon/epoxy (AS4/3501-6), and silicon carbide/aluminum (SCS-2/6061-Al). Since the fibers are usually less sensitive to environmental factors, the most effects are observed in the matrix dominated properties (Transverse Failure strengths, Transverse Moduli) [2], [4]. Carbon/epoxy (AS4/3501-6) shows a steady decrease in the transverse modulus and failure stress, and shows the same behavior in the in-plane shear [4]. Silicon carbide/aluminum exhibits similar behavior with increasing temperature; however, the initial modulus is not affected with similar behavior exhibited in the in-plane shear [3], [4].

Effects of thermal loads have also been reported to induce intra and inter lamina stresses [4], [5]. The intra lamina stresses are as a results of the varying thermal expansion coefficients of the fiber and matrix, while the inter lamina stresses are as a result of different expansion coefficients between the plies. M. Leong and B. V. Sankar studied the micro-thermal stresses that occurred due to the fiber and matrix expansion coefficients by employing the direct micromechanics method. The authors developed an exact failure envelop and compared it to the Tsai-Wu failure envelop. The Tsai-Wu envelop incorrectly estimated the failure since it improperly accounted for the micro-thermal stresses [5].

Thermomechanical loading of unidirectional composite lamina has previously been conducted at both cryogenic temperatures and at elevated temperatures [2]-[4], [9]. In these cases, the temperature of the testing environment is maintained constant. Typically the inclusion of thermal loading on the composites contributes to two things; the mechanical properties [2]-[4], [8], [9], and the thermo-elastic effects (Inter and Intra Lamina stresses due to Material anisotropy) [5], [6], [8].

Previous research has shown that the effect of temperature change on the mechanical properties along the fiber direction (i.e. Longitudinal Modulus, Longitudinal Tensile and Compressive Strength) is minimal. However, the effects on the matrix dominated mechanical properties (i.e. Transverse Modulus, Transverse Tensile Strength, and Transverse Compressive Strength) are substantial. The effect in typical cases is reduction in mechanical properties (Moduli and Strength) and increase in the ultimate strain with increasing temperature of the working environment. The stress-strain Moduli for the transversely loaded lamina are dependent on the plasticity of the matrix. Mechanical property changes with respect to temperature change are less pronounced for composite lamina having a matrix with a higher glass transition temperature [4].

In this paper, the effects of coupling thermal loads with mechanical loads on failure of the composite are analyzed. The aim is to properly identify the effects of thermal loads on

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the composites and how these effects can be considered in design of the composite laminate.

II. Methodology

A. Model

Carbon Fiber reinforce polymer composite square tube was analyzed under coupled mechanical and thermal loading using the commercially available finite element package, ABAQUS. The laminate lay-up for the tube was a $[0/90]_s$ stack with 4 plies (as shown in Fig. 1). The tube dimensions are given in Table I.

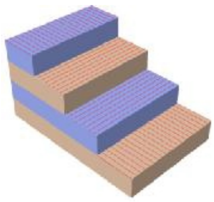


Fig. 1 Ply stack (Ply thickness = 1.25 mm)

TABLE I
TUBE DIMENSIONS

No of Plies	Cross-ply Laminate Lay-Up	Length (mm)	Cross-Sectional Dimension (mm)	Thickness (mm)
4	$[0/90]_s$	304.8	50.8 X 50.8	5

B. Material

For the purpose of this study, the carbon/epoxy composite, IM7/977-3, was used with properties listed in Table II.

TABLE II
MATERIAL PROPERTIES OF CARBON/EPOXY (IM7/977-3) [4]

Property	Carbon/Epoxy (IM7/977-3)
Density (g/cm^3)	1.61
Longitudinal Modulus (GPa)	190
Transverse Modulus (GPa)	9.9
In-Plane Shear Modulus (GPa)	7.8
Major Poisson's Ratio	0.35
Longitudinal Tensile Strength (MPa)	3250
Transverse Tensile Strength (MPa)	62
In-Plane Shear Strength (MPa)	75
Longitudinal Compressive Strength (MPa)	1590
Transverse Compressive Strength (MPa)	200
Longitudinal Thermal Expansion Coefficient (10^6/°C)	-0.9
Transverse Thermal Expansion Coefficient (10^6/°C)	22
Thermal Conductivity	0.75

The tube was discretized using coupled temperature-displacement quadrilateral elements of a quadratic order. The interactive tensor polynomial (Tsai-Wu) failure theory and first ply failure criteria were used to determine lamina failure.

Multiple loading cases were analyzed, which are presented below:

1) Case A

In this case, the composite tube was fixed on one end, and a tensile load of 3.1kN was applied to the free end as shown in Fig. 2.

Fig. 2 Case A loading setup

2) Case B

In the second analysis, one end of the composite tube was fixed and was set at ambient temperature (21°C, 294K). The tensile load was removed and replaced with a thermal load of 80°C (353K). All other sides of the tube were kept insulated. The analysis was conducted for steady state response.

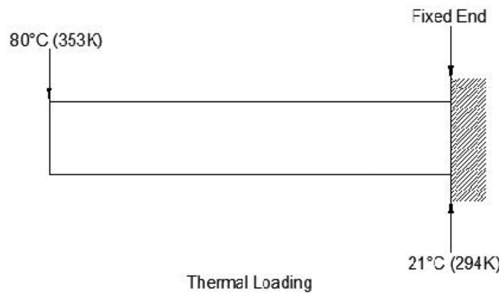


Fig. 3 Case B loading setup

3) Case C

The final analysis was conducted for simultaneous loading of the composite tube with a mechanical load (3.1kN tensile load) and a thermal load (80°C on free end, and 21°C on the fixed end).

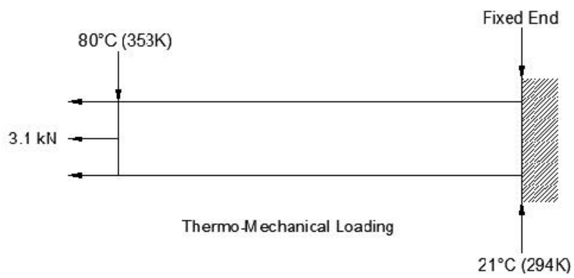


Fig. 4 Case C loading setup

III. Results

A. Case A

Fig. 5 shows the results of mechanical loading on the composite tube. A value of less than unity for a given ply indicates that the state of stress is inside the failure envelope (no failure), while values equal or higher than unity indicate failure.

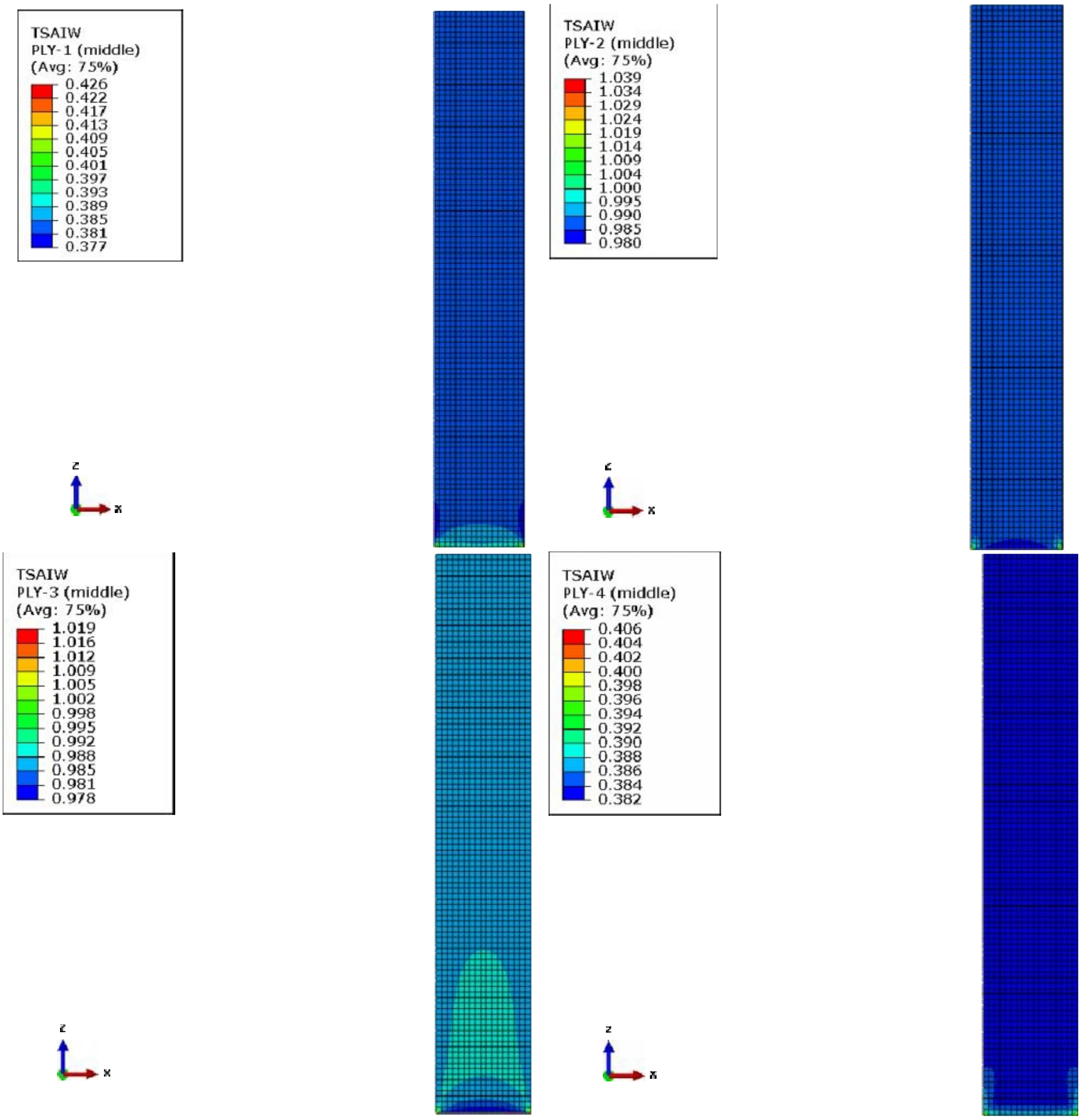


Fig. 5 Case A failure index (4 Plies)

The maximum values for plies 1, 2, 3, and 4 were 0.426, 1.039, 1.019, and 0.406, respectively. It is evident from the results that the 2nd and 3rd plies have failed under the applied mechanical load.

B. Case B

Fig. 6 shows the results for the analysis conducted for Case B. The failure index increased monotonically in the axial direction towards the free end of the tube.

In all cases, the failure index and their distribution along the tube axis remained invariant for all 4 plies. None of the plies failed under this loading condition as compared to the pure mechanical loading.

C. Case C

The results of the final analysis are shown in Fig. 7. The maximum failure index values observed for all 4 plies were 0.525, 0.072, 0.072, and 0.525.

In contrast to purely mechanical loading in Case A, here the laminate does not fail. It is evident from the coupling of the mechanical and thermal loads, that the superposition of thermal gradients on mechanical loading reduced the stress levels along the composite tube.

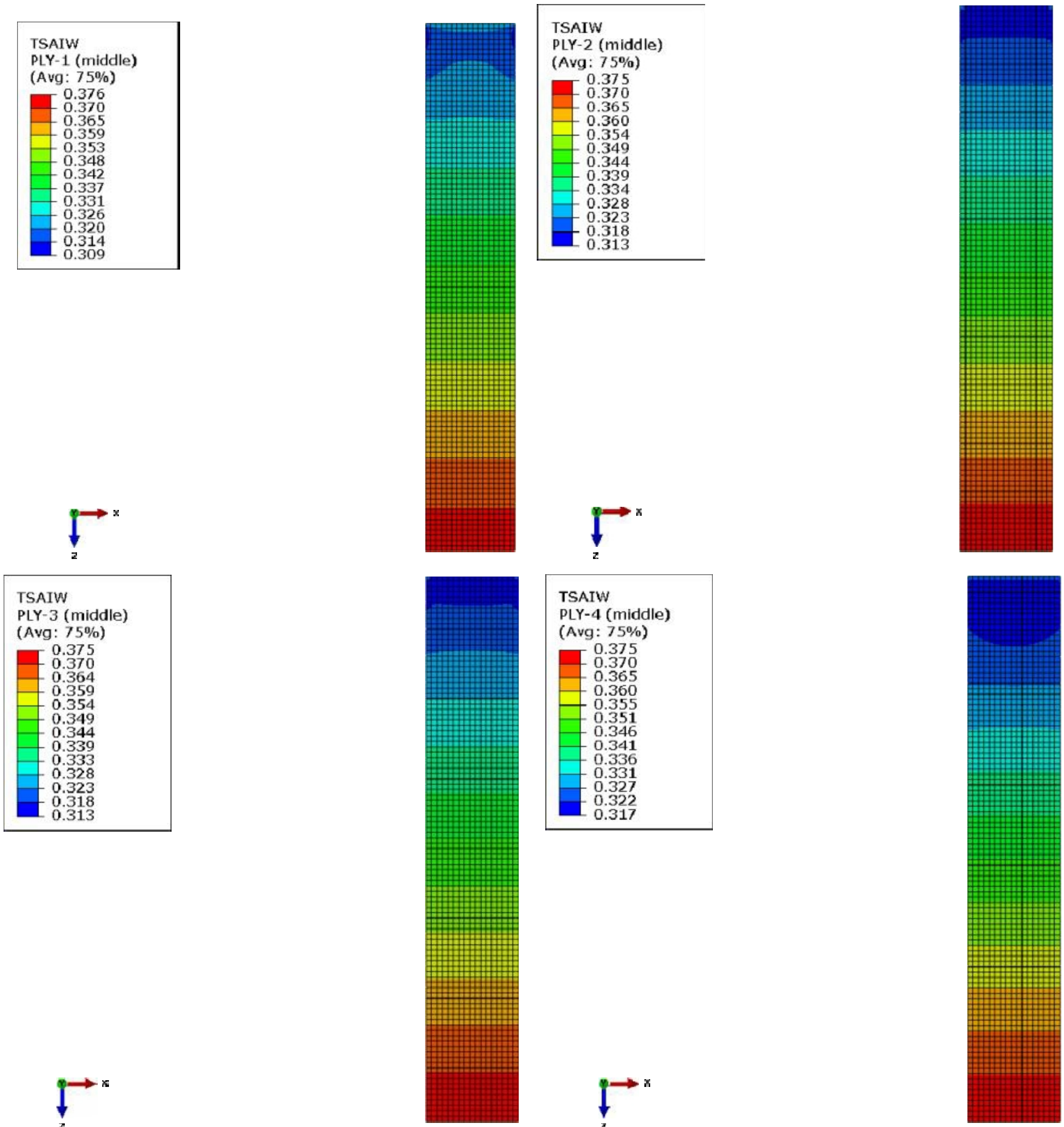


Fig. 6 Case B failure index (4 Plies)

IV. Discussion

The FEA analysis presented here does not include the variation in mechanical properties with respect to changes in temperature. The observed changes are strictly restricted to thermo-elastic effects in the composite, specifically Inter-lamina stresses. To analyze in detail, the effects of thermal loads on the composite plies must be understood. Fig. 9 shows the contour plots for the stresses developed in the 2nd principal direction for the transversely loaded ply (Ply 2).

As can be observed from the plot in the pure mechanical loading case, we have a typical uniform tensile stress distribution in the lamina. In this case a stress concentration exists at the constrained distal end where the lamina fails due to the matrix (assuming first ply failure criterion). The stress induced in the lamina is close to the transverse failure strength of the composite. On the other hand, the stresses experienced in the lamina due to thermal loading only are compressive (this is also the case for ply 3). This is attributed to the inter-lamina stresses developed due to the negative CTE's (coefficient of thermal expansion) in the longitudinal direction of the adjacent ply (in this case ply 1 and 4). The heating of the laminate causes expansion in the transverse direction, and contraction in the longitudinal direction for each lamina. Due to the ply stack lay-up, the contraction of plies 1 and 4 in their longitudinal direction would induce a compressive stress on ply 2 and 3 in their transverse direction. While the expansion in their transverse direction (Plies 2 and 3) will result in tensile stresses developed in the longitudinal direction of the adjacent plies (Plies 1 and 4).

As can be observed in this case, the counteracting of the negative and positive CTE's would reduce the tensile stresses developed in the lamina substantially and ultimately eliminate failure due to the tensile load [1], [7], [10]. Thus, the coupled thermomechanical stress at each point along the lamina is the resultant of the tensile stress experienced at that point and the thermal compressive stress at the same point. The resultants for this case are compressive stresses that are not close to the transverse failure strength of the lamina.

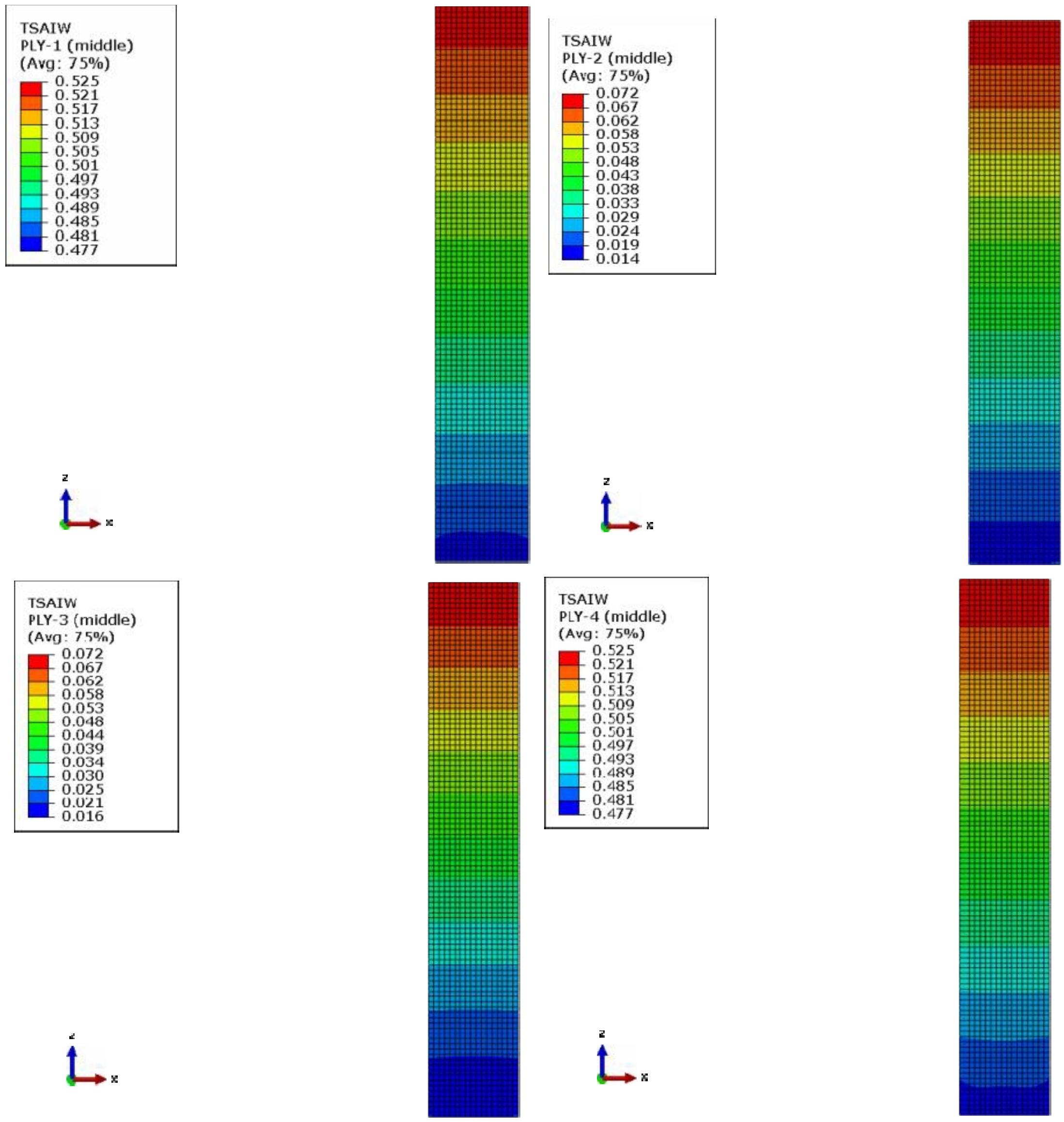


Fig. 7 Case C failure index (4 Plies)

The stresses in the lamina in the longitudinal direction due to thermal loading are tensile stresses that arise from the expansion of the adjacent ply (plies 2 and 3) in the transverse direction. The stresses developed in the coupled loading case are the resultant of the stress experienced at any point due to thermal and tensile loads combined as can be observed in Fig. 11.

Further analysis through simulation on the failure point of the lamina under the coupled loading case (Case C), showed that failure would occur at approximately 6kN. This reflects improvements of approximately 93% in the mechanical load carrying capacity of the laminate.

As previously stated, our analysis does not factor in the behavior of the mechanical properties across the temperature gradient. This would affect the failure strengths (Compressive and Tensile) in both longitudinal and transverse direction and ultimately could lead to failure of the lamina since there is increased tensile stress in the longitudinal direction. This topic will be investigated in a future study.

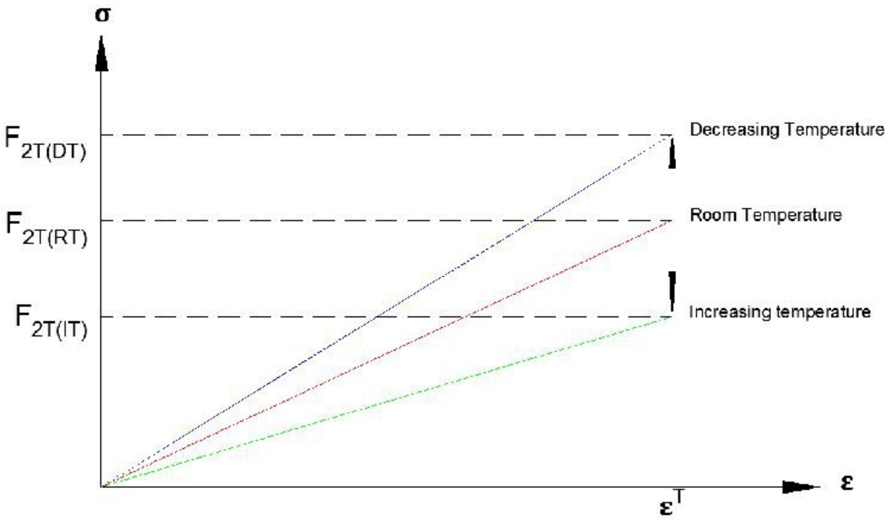
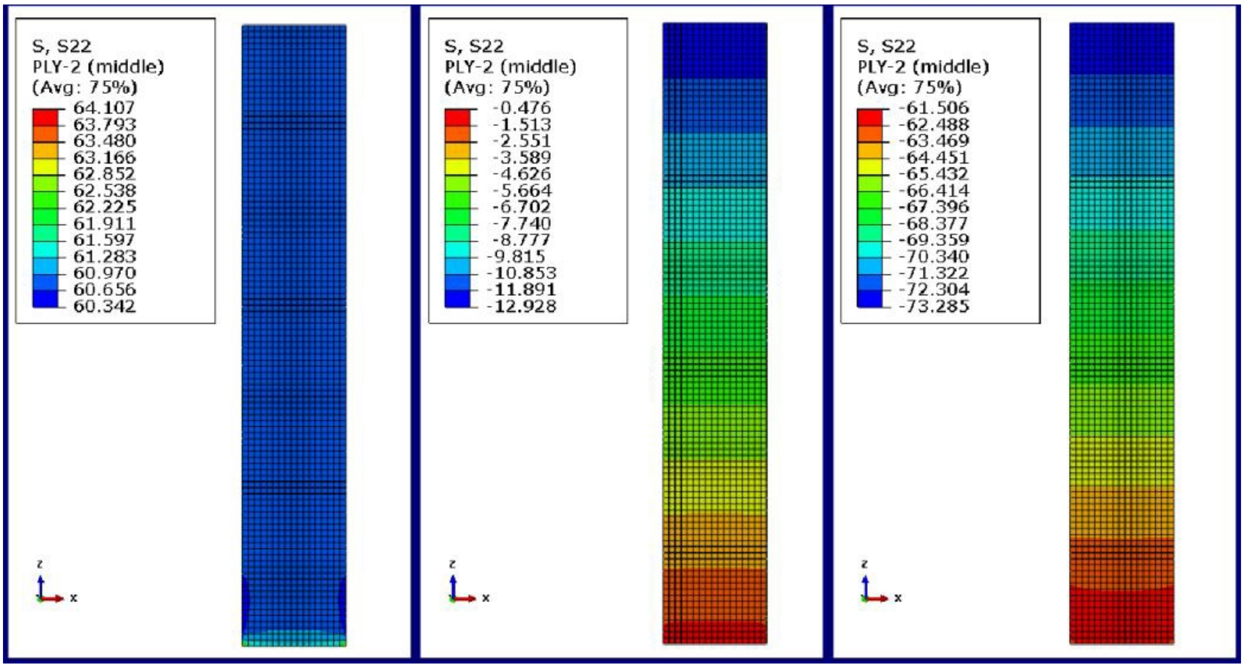


Fig. 8 Transverse tensile strength behavior with temperature change (AS4/3501-6)



(a) (b) (c)

Fig. 9 Principal Stress (σ_2) contour map for ply 2 (a) Mechanical Loading (b) Thermomechanical Loading (c) Thermal Loading

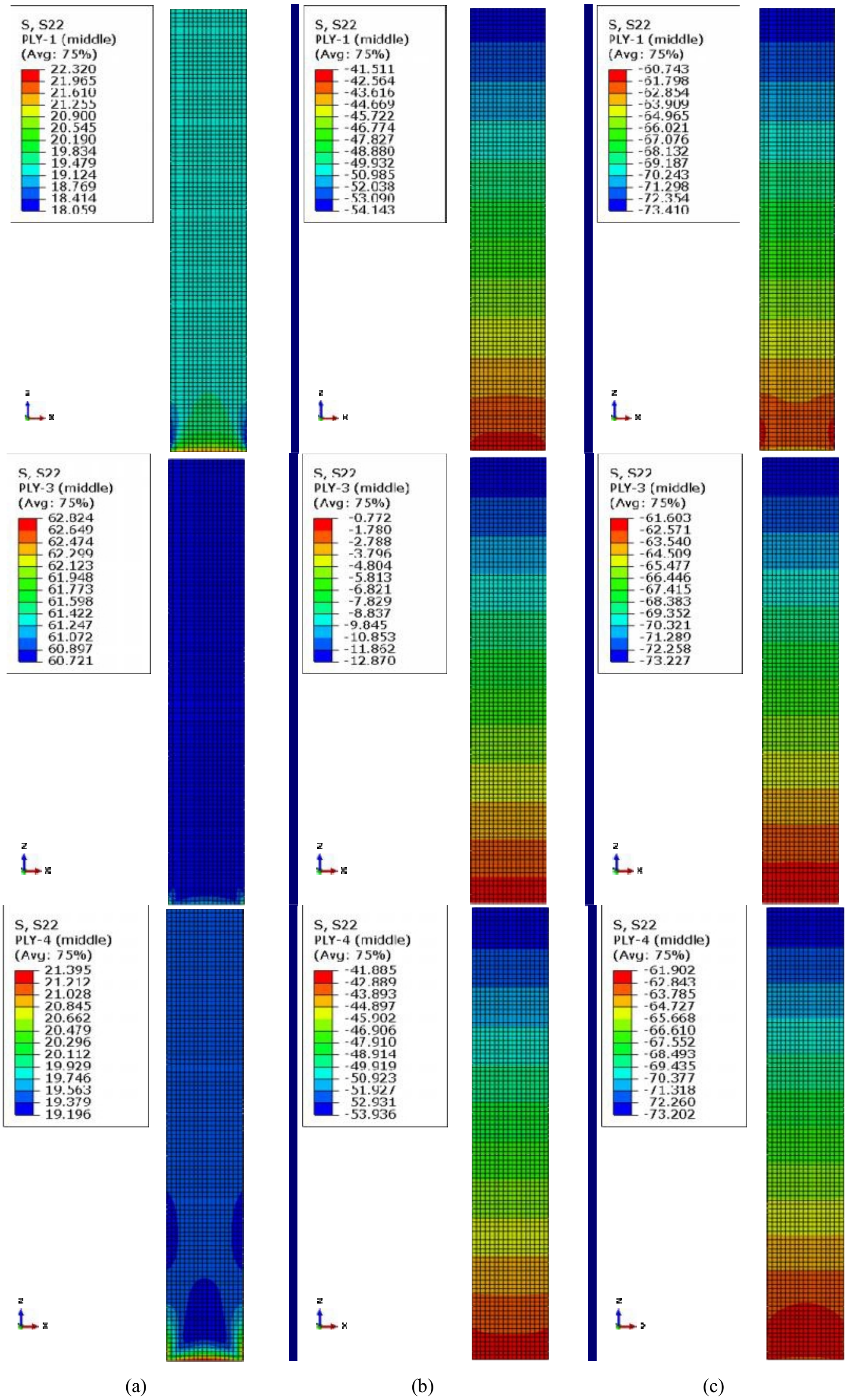
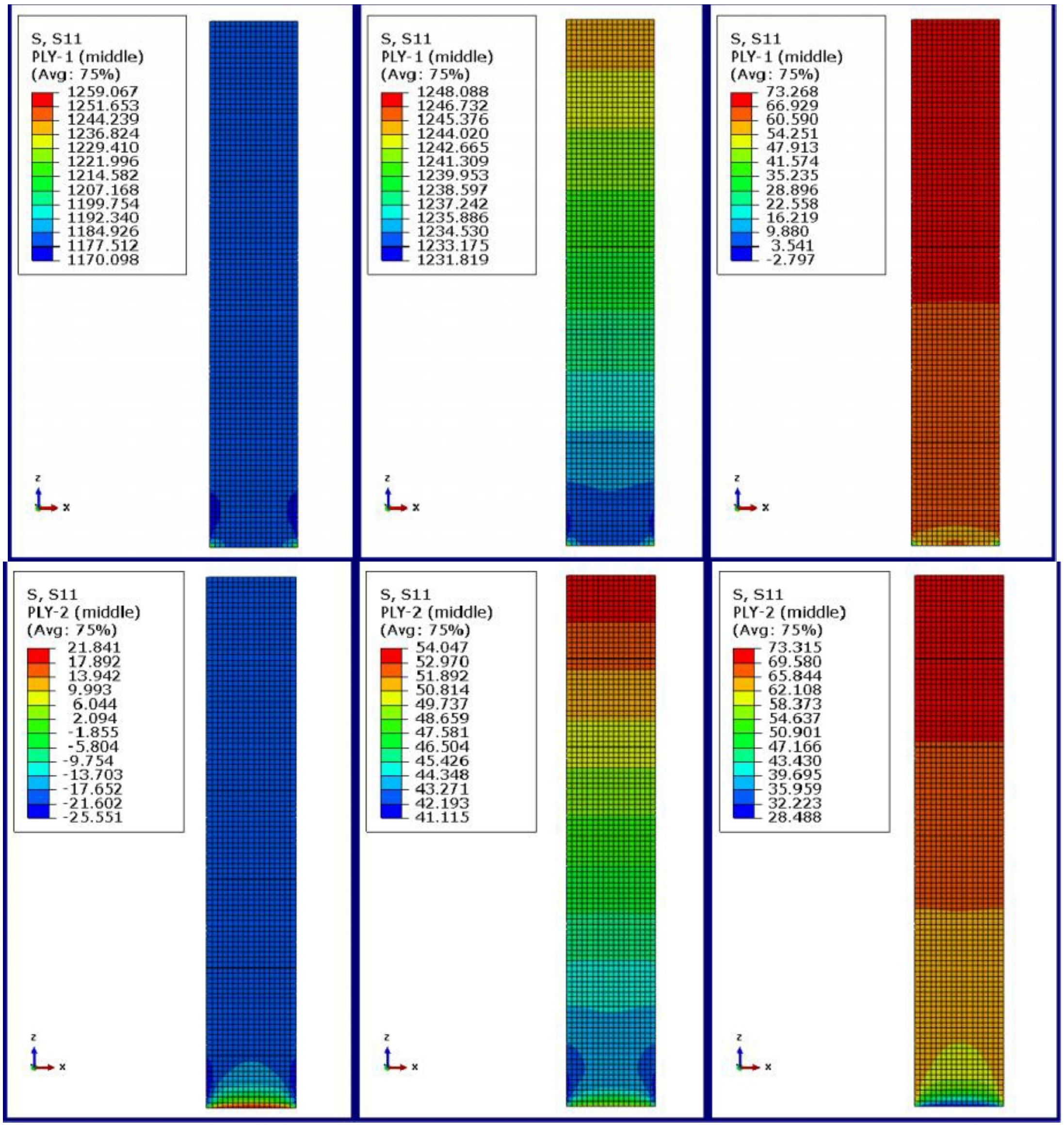
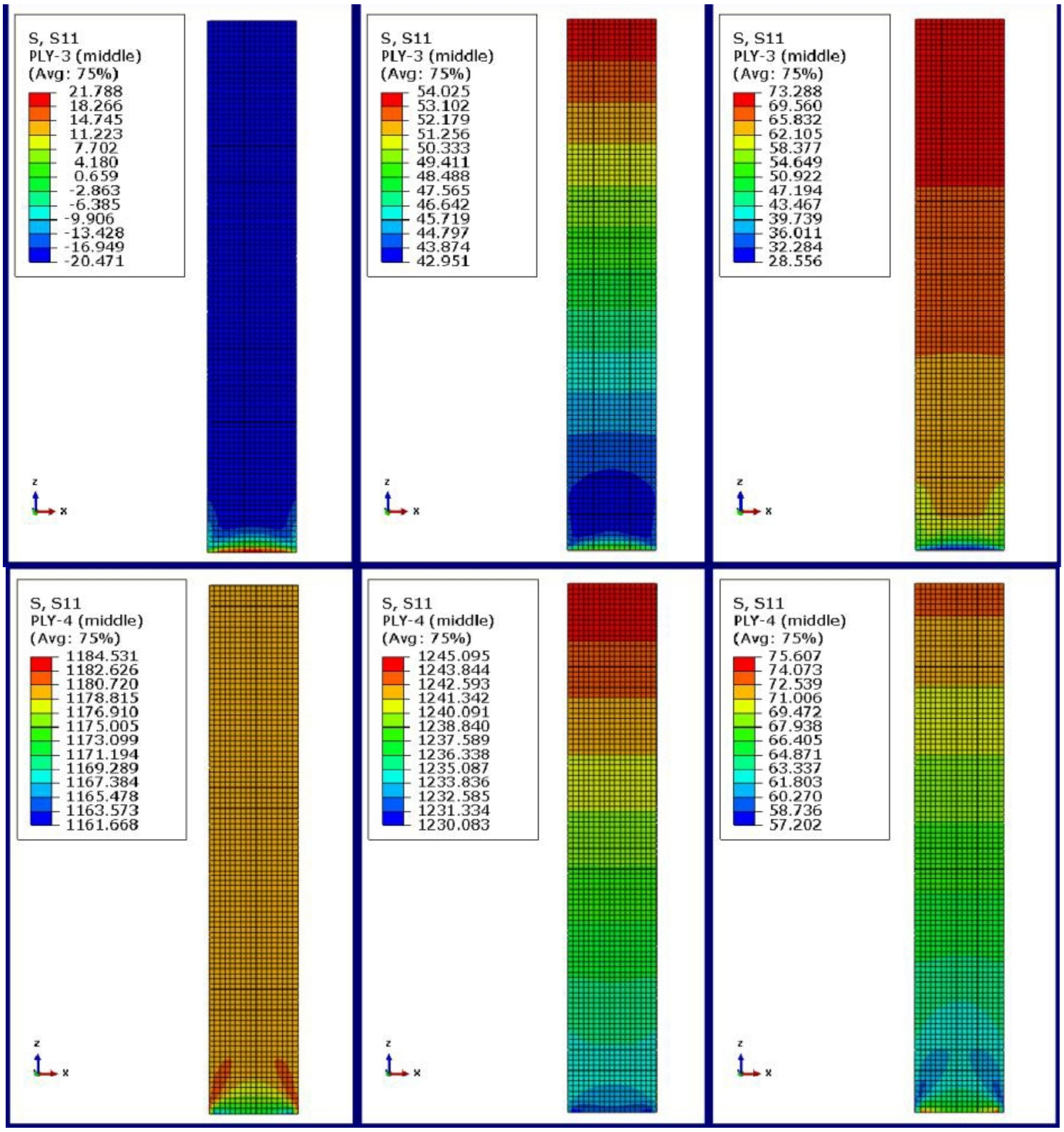


Fig. 10 Principal Stress (σ_2) contour map for ply 1, 2, 4 (a) Mechanical Loading (b) Thermomechanical Loading (c) Thermal Loading


S, S11
PLY-1 (middle)
(Avg: 75%)
1259.067
1251.653
1244.239
1236.824
1229.410
1221.996
1214.582
1207.168
1199.754
1192.340
1184.926
1177.512
1170.098
S, S11
PLY-1 (middle)
(Avg: 75%)
1248.088
1246.732
1245.376
1244.020
1242.665
1241.309
1239.953
1238.597
1237.242
1235.886
1234.530
1233.175
1231.819
S, S11
PLY-1 (middle)
(Avg: 75%)
73.268
66.929
60.590
54.251
47.913
41.574
35.235
28.896
22.558
16.219
9.880
3.541
-2.797
S, S11
PLY-2 (middle)
(Avg: 75%)
21.841
17.892
13.942
9.993
6.044
2.094
-1.855
-5.804
-9.754
-13.703
-17.652
-21.602
-25.551
S, S11
PLY-2 (middle)
(Avg: 75%)
54.047
52.970
51.892
50.814
49.737
48.659
47.581
46.504
45.426
44.348
43.271
42.193
41.115
S, S11
PLY-2 (middle)
(Avg: 75%)
73.315
69.580
65.844
62.108
58.373
54.637
50.901
47.166
43.430
39.695
35.959
32.223
28.488
z
x

(a1) (b1) (c1)



(a2) (b2) (c2)

Fig. 11 Principal Stress (σ_1) contour map for plies 1- 4 (a1&a2) Mechanical loading (b1&b2) Thermomechanical loading (c1&c2) Thermal loading

V. Conclusions

This paper presents a finite element study on the thermomechanical coupled loading of fiber reinforced polymer composites. The analysis is separated into three cases which address the component loading conditions i.e. mechanical loading and thermal loading, as well as the coupled loading conditions.

Our findings show that:

1. Improvements can be made to the load carrying capacity of a laminate by the introduction of a thermal load. This however is dependent on two aspects. First, the magnitude and positive or negative values of component coefficients of expansions in both longitudinal and transverse directions of the lamina. Secondly, the stacking sequence of plies in a laminate.
2. The effects of the thermal loads are not restricted to improvements but can also have adverse implications on the load carrying capacity. A thorough understanding of the effects of the CTE's (positive and negative) in inducing stresses in a laminate in both the longitudinal and transverse directions is necessary to estimate the overall stresses due to coupled loading and failure.

3. The effect of the temperature on mechanical properties needs to be characterized adequately in order to have a correct estimate of failure stresses of the laminate.

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