Tensile Deformation Studies in Glass/Epoxy Composite Specimen Using Infrared Thermography

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Abstract
The effect of tensile loading on the thermodynamics of Glass fiber reinforced polymeric composites laminates using an Infrared Camera by monitoring the surface temperature changes is reported here. Thermal response of specimens with various lay-up sequences was studied.

Experimental results show distinct thermal characteristics for each type of specimen layup. Temperature was found to be decreasing linearly with increased tensile stress in the elastic region. However, in the plastic region, depending upon the amount of plastic deformation, the composite specimens were observed to be following unique behavior that is characteristic of ply-orientations of the composite.

1. INTRODUCTION
When a material is subjected to tensile loading, from zero to its elastic and then to plastic regime under adiabatic conditions, heat transfer occurs. Both elastic and plastic deformation changes the temperature of the material. During tensile elastic deformation the material gets cooled due to volume expansion and the plastic deformation, causes rise in temperature of the specimen. Due to the coupling effect of thermal and mechanical behavior, measurement of temperature response can provide better understanding of the deformation. Temperature change in an elastic material due to an applied stress ('Thermoelastic effect') was first explained by Lord Kelvin. Under adiabatic conditions, for a linearly elastic material, change in temperature is related to the change in state of stress as,

$$\Delta T = (-\alpha T/\rho C_p)\,\Delta\sigma \tag{1}$$

And the corresponding relation for describing reversible change in temperature in an orthotropic material under plane stress condition is given by, [1,2]

$$\rho c\,(\Delta T/T) = \alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2 \tag{2}$$

Where, ρ is density (g/cc), C_p is heat capacity at constant pressure (J/g-°C), α is coefficient of thermal expansion (μm/m-°C), $\Delta\sigma$ is the change in stress (N/m^2), and T (°C) is the ambient temperature and the subscripts 1 and 2 denote the longitudinal and transverse to fiber directions.

Unlike in metals, the deformation process in fiber reinforced composite materials are complicated which include matrix cracking, fiber-matrix interface debonding, fiber failure, delamination etc and it is often difficult to detect all these damages. Since thermomechanical studies provides more information about the deformation processes and hence better idea about the integrity of the composite structures Infrared Thermography technique (IRT) has been used as a non-destructive non-contact and real time method, which captures the thermal energy being radiated from the surface (The radiated energy is a function of its surface temperature). IRT experimental apparatus includes a camera, equipped with changeable optics, and a PC interface through a high speed frame grabber card. The infrared detector absorbs the IR photons, emitted by the object (whose surface temperature is to be measured) and integrates over time to provide a

proportional electrical voltage or current at every pixel of the detector. These pixels of electrical signal are then represented in the form of thermographic images.

Lee and Chen [3] studied the effect of thermomechanical coupling in a mild steel specimen and presented a theoretical model to account for the cooling phenomena at the elastic region of the material. They showed that the thermoelastic limit coincides with yield point of the specimen. Measurement of temperature changes using a thermometer during uniaxial tensile test in polymer composites was reported by Lindhagen and Berglund [4]. Temperature response of glass/epoxy was found to be linearly decreasing till the elastic limit; whereas carbon/epoxy specimen showed slight increase in temperature due to negative thermal expansion coefficient of carbon fibers. Non-linearity was not observed both in mechanical and thermal responses. Analytical model was developed by Dunn [1] for predicting thermoelastic heat generated during cyclic loading of carbon/epoxy specimens of various lay-up sequences. Effect of surface coating on thermographic analysis was studied by Zhang et. al [5,6] and it was found that above a certain thickness of surface resin layer, heat transfer gets attenuated. Pravin et. al [7] employed infrared thermography for characterizing tensile deformation in SS304 and observed from the experiments that, in the elastic region, drop in temperature increases as the damage accumulated increases within the material. It was also shown that the thermoelastic limit can be used for determining yield point of the material accurately. Bakis and Reifsnider [8] investigated the influence of material inhomogeneity and anisotropy using carbon fibre reinforced plastics. It was found that the thermoelastic response was affected by a number of factors, like the volume fraction, the thermoelastic properties of the micro-constituent materials, the orientations of the laminae within the laminate, and the orientation of the surface ply. For composite materials it was suggested that the non-adiabatic behaviour in CFRP laminates could be due to heat transfer between the fibre and matrix or caused by viscoelastic effects. Wong [9] discussed the effects of nonadiabatic conditions on the thermoelastic signal recorded from the specimen surface due to heat transfer characteristics at large stress gradients, such as those experienced between plies orientated at different angles in a laminate. Cunningham et al. [10] have shown that in glass reinforced epoxy composites the adiabatic assumption is valid and the stress in the surface ply and the resin-rich layer is dependent on the stacking sequence of the laminae that form the laminate. Emery et. al [11] studied thermoelastic response of glass/epoxy composite specimens with various stacking sequences and developed a calibration procedure for Thermoelastic Stress Analysis (TSA) for laminated orthotropic composites. The procedure was based on the laminate strain rather than stresses on the top layer of the specimen which helps to account for the mechanical response of the laminate as well as the surface thermoelastic response.

This paper investigates the potential of Infrared Thermography (IRT) as a tool for providing in situ characterization technique of damage in glass/epoxy composite specimens with various lay-up sequences and hence to distinguish between them by monitoring temperature response during monotonic and interrupted tensile loading.

2. EXPERIMENTAL WORK MATERIALS AND PREPARATION OF TEST SPECIMENS

Unidirectional E-glass fibers manufactured by Saint Gobain were used for reinforcement of composite laminates. It was supplied in the form of fabric with 10% of the fibers in weft direction. Epoxy based LY556 resin with HY951 hardener (10:1) was employed as the matrix. Laminates of size 260 × 260 mm composed of 12 plies giving thickness of 2.8 mm with lay-up sequences of $[0]_{12}$ and $[0_3,+/-45,90]$s were fabricated by hand lay-up process. The cure took place in vacuum bag and followed the manufacturer's recommendations of 8 hrs at room temperature under a vacuum of 680 mm of Hg. The laminates were further cut into specimens using diamond tipped cutting wheel. Glass/Epoxy tabs of thickness of 2.5 mm thick and 50 mm long with tapered ends were bonded to the specimens using Araldite AV138M and hardener HV998 in the weight ratio 10:4. These tabs ensure gripping of the specimens on the hydraulic grip of the testing machine and hence it allows smooth transfer of load from the grip to the specimen. In order to avoid emissivity problems, the specimens were black coated for the measurements of surface temperature with IR camera. The fiber volume fraction of the composites was 60%. Fig.1. shows schematic of test sample for the tensile tests, conforming ASTM D 3079.

3. EQUIPMENT AND EXPERIMENTAL PROCEDURE

A 100 kN MTS servo-hydraulic testing machine with synchronous data acquisition system shown in Fig.2 was employed for loading the test coupons. Specimens were subjected to monotonic tensile loading at a stroke rate of 2 mm/min.

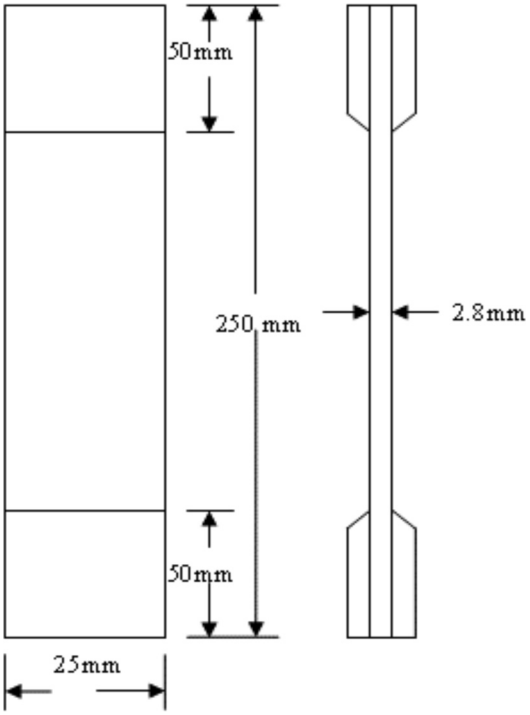

Figure 1. Dimensions of the specimen used in tensile testing

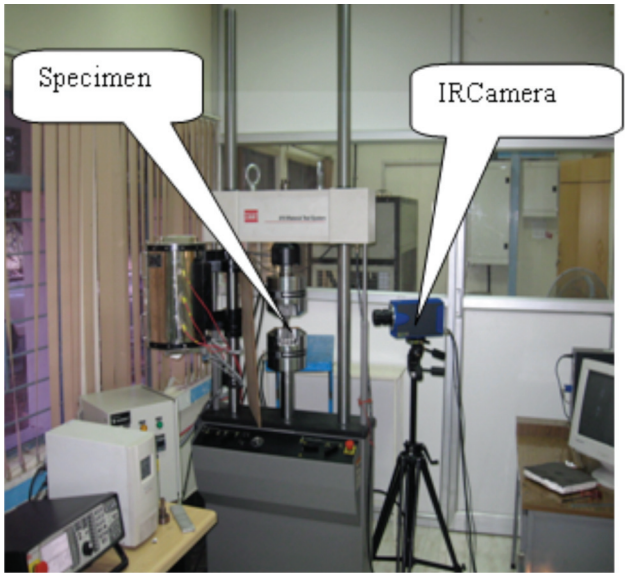

Figure 2. Experimental setup

Infrared thermal imaging system used for the temperature measurement is a CEDIP LWIR Jade camera. This consists of an infrared camera cooled by electronic control of Sterling cooler. The camera contains an Hg-Cd-Te detector which is sensitive to infrared radiation in the wavelength range 8-10µm. The features of the camera are: window size varying from 320 × 240 to 320 × 1 pixels, variation of the frame rate from 5 to 1500 Hz, adjustable integration time from 60 µs to 500 µs and real-time lock-in detection. The camera is equipped with a 25 mm-objective lens with a field of view (FOV) of 22° × 16°. The window size used in the experiments is 213 × 132 pixels and an integration time of 220 µs. The camera was positioned on a tripod approximately about) 0.5 m from the specimen surface. A two-point

Non-Uniformity Correction (NUC) was applied using a blackbody maintained at cold and hot temperature. The digital data given by the IR camera are converted to specific temperature values using a calibration data file that assumes that the specimen was a perfect black body with an emissivity value of 1. In the case of lower emissivity at the sample surface, a correction factor may be used. However, since the surfaces were painted black, the emissivity of 1 was employed in this work. The temperature images were acquired in the Automatic Gain Controlled (AGC) mode at a frame rate of 500 frames sec^{-1} using Altair software and stored in a computer hard disk. The temperature values were averaged over a circular area along the gage length of the specimen.

An unloaded specimen, co-located near the loaded specimen, was used as a reference for acquiring fluctuations in ambient temperature. Figure 3 presents the thermal response from a typical multidirectional laminate during interrupted loading. Temperature variation on the surface of the reference laminate is also shown in the same figure. Since the actual temperature change in the loaded specimen is of the order of ~ 0.5°C, any small change in ambient temperature also becomes significant. The ambient temperature changes by a small amount due to various factors such as time of the day (morning/afternoon/night etc.,) and whether more people or equipment are in operation in the same room. During analysis, the mean value of temperature response from the reference specimen is subtracted from the temperature characteristics of the loaded specimen.

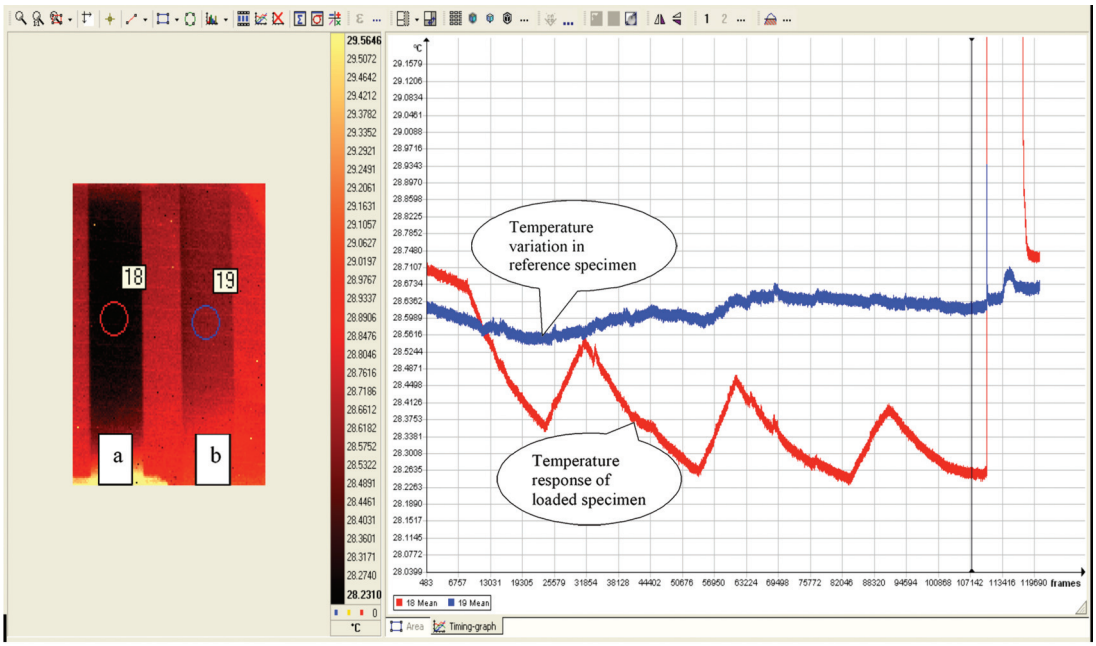

Figure 3. Temperature response of loaded and reference specimens with time. (a) Loaded specimen (b) Reference specimen

4. RESULTS AND DISCUSSION STRESS-CHANGE IN TEMPERATURE-STRAIN CURVES

Glass/Epoxy composite specimens with four different lay-ups (ie, zero:-$[0]_{12}$, 90:-$[90]_{12}$, 45:-$[45]_{12}$ and quasi-isotropic:-$[0_3,+/-45,90]s$) were tested at a displacement rate of 2 mm/min. Two types of experiments, i.e. monotonic and interrupted tensile tests, were conducted on the specimens. All specimens were loaded till fracture. One specimen of each kind was subjected to interrupted loading in which specimen was loaded and unloaded at the same strain rate. This test was intended to study the residual plastic deformation in composite laminates.

5. MONOTONIC LOADING

Stress vs. Strain and change-in-temperature vs. Strain for zero and 45 degree laminates are plotted in Fig.4. Just like in metals, it can be seen that both glass/epoxy specimens show a linear decrease in

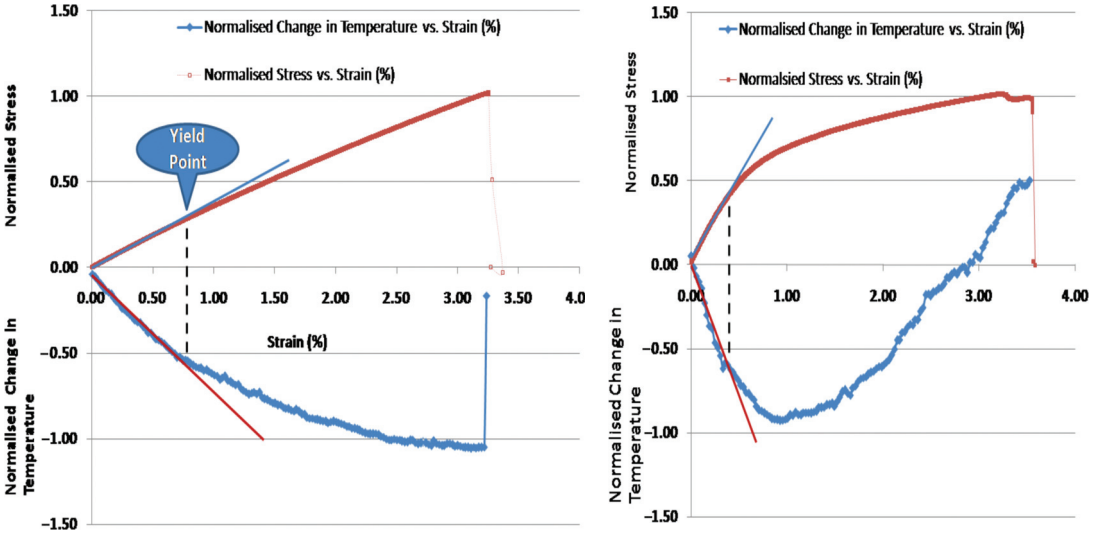

Figure 4. Thermomechanical behavior of zero and 45 degree laminates during continuous tensile loading

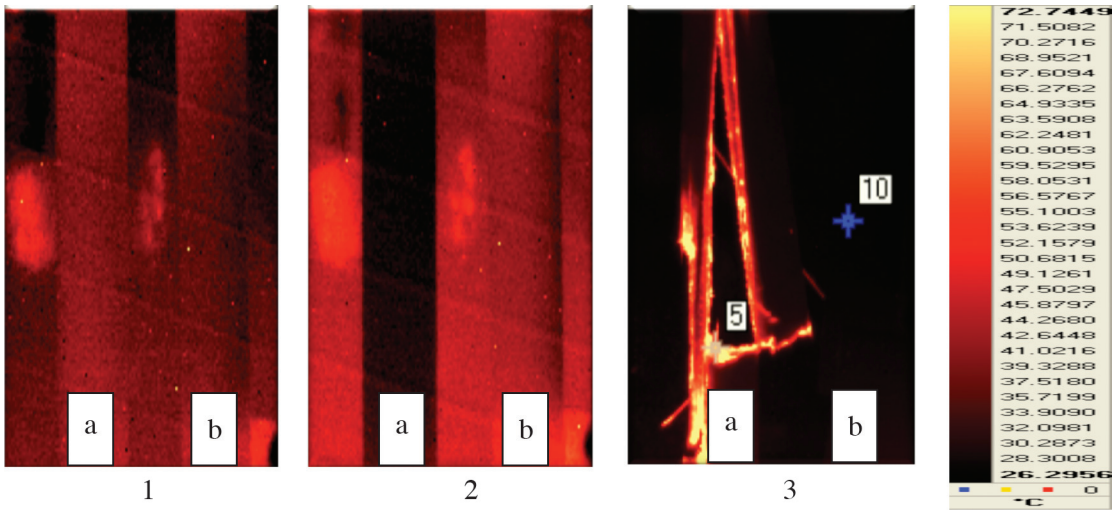

Figure 5. Thermograms showing temperature variation in 45 degree specimen loaded in tension. (1) before (2) during and (3) at fracture. (a) Loaded specimen (b) Reference specimen

temperature with increased stress state until it reaches the elastic limit. Figure 5 shows the thermograms of zero degree laminate at various stages of monotnic loading.

Figure 6 compares the temperature responses of zero and quasi-isotropic laminates. Failure strains of these laminates are 3.3% and 3.2% respectively. It can be seen that zero and quasi-isotropic laminates show different temperature responses even though their outer layers are identical, i.e., zero degree. In both cases, temperature decreases linearly in the elastic region with distinct slopes –0.46 and –0.44 respectively and then the specimens show non-linear behavior in temperature response. Non linearity in temperature response of laminates may be due to the presence of matrix cracks, as the epoxy matrix used was relatively brittle. This may noticed from the thermo-mechanical behavior exhibited by the epoxy resin (Fig. 7) employed in the study. (which cools during elastic deformation and heats up when it reaches its fracture strain). Therefore, cracks appear between the fibres and parallel to them in the longitudinal layers, due to contraction induced by poisson effect. These cracks start to occur at about the same strain as the transverse cracks, and their appearance contributes to the heating of the specimens. Since the fibers continue

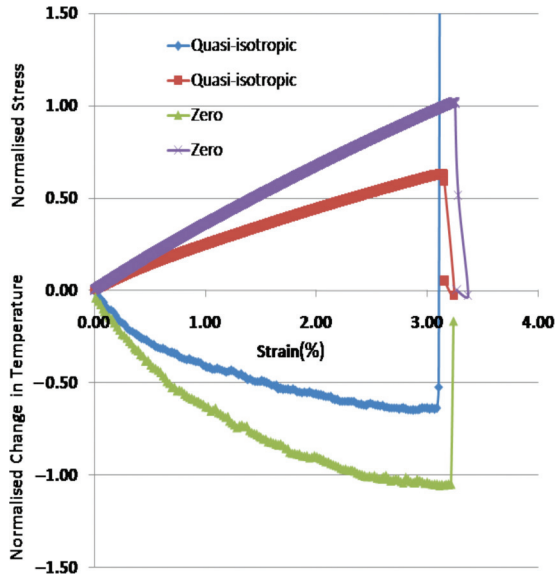

Figure 6. Temperature response of zero and quasi-isotropic laminates during continuous tensile loading

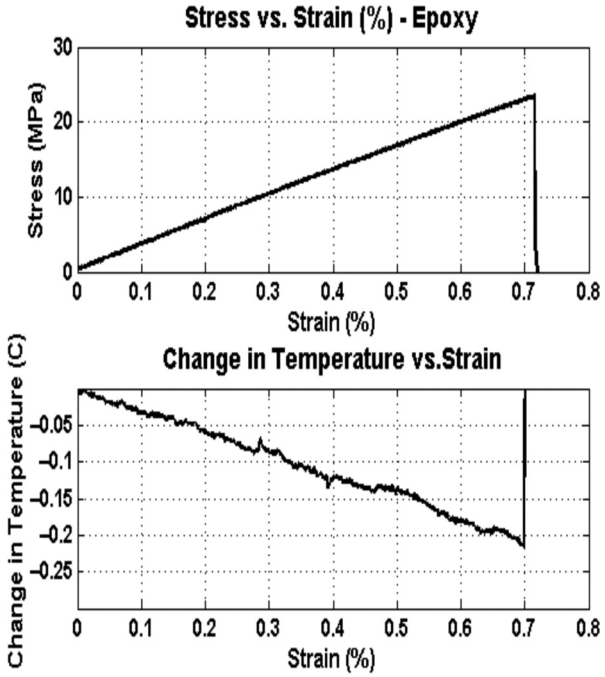

Figure 7. Thermomechanical behavior of the epoxy specimen loaded in tension

to cool till the onset of fracture, the overall temperature response of the laminate keeps decreasing even though matrix cracks acts as small heat sources. This ultimately leads to variation in the slope of thermal response curve.

Unidirectional laminate shows maximum drop in temperature. It is found that the rate of change of temperature decreases with increased stress state which is due to accumulation of damage in the specimen. Final failure was catastrophic in all the laminates where zero degree fibers were dominating and it was characterized with an instantaneous increase in temperature in the material by releasing the strain energy.

It should be noted that the nonlinear behavior in composite laminates is related to fiber rotations and physical damages (e.g., matrix cracking, interfacial debonding and delaminations), therefore, the nonlinearity differs for various loading directions. Also, the amount of the matrix involvement in the

deformation mode also would affect the nonlinearity [8]. Matrix cracks, failure of transverse fibers and friction between fibers at the cross over points changes the slope of the temperature response after the elastic limit (the longitudinal glass fibers do not get plasticized until the final fracture but it continuous to cool due to elastic deformation).

Figure 8 (a) shows stress and change in temperature against strain of a 45 degree laminate. This is the only exceptional behavior from the other cases discussed earlier. Positive slope in temperature response after the elastic-limit indicates plastic deformation due to the shear-extension coupling and also more significant fiber rotation during deformation [12].

6. INTERRUPTED LOADING

Unloading (interrupted) tests of simple tension were also carried out on the composite specimens. The unloading result of tension for zero degree laminate (Fig.8 (b)) show that the specimen retains the stiffness till the third unloading segment and no significant residual plastic strain was observed. Therefore not much variation can be noticed in the thermal response of zero degree laminate until final failure. The stress-strain curve of 45 degree laminate, Fig.8 (a), during interrupted loading indicates the amount of plastic residual strain in the laminate.

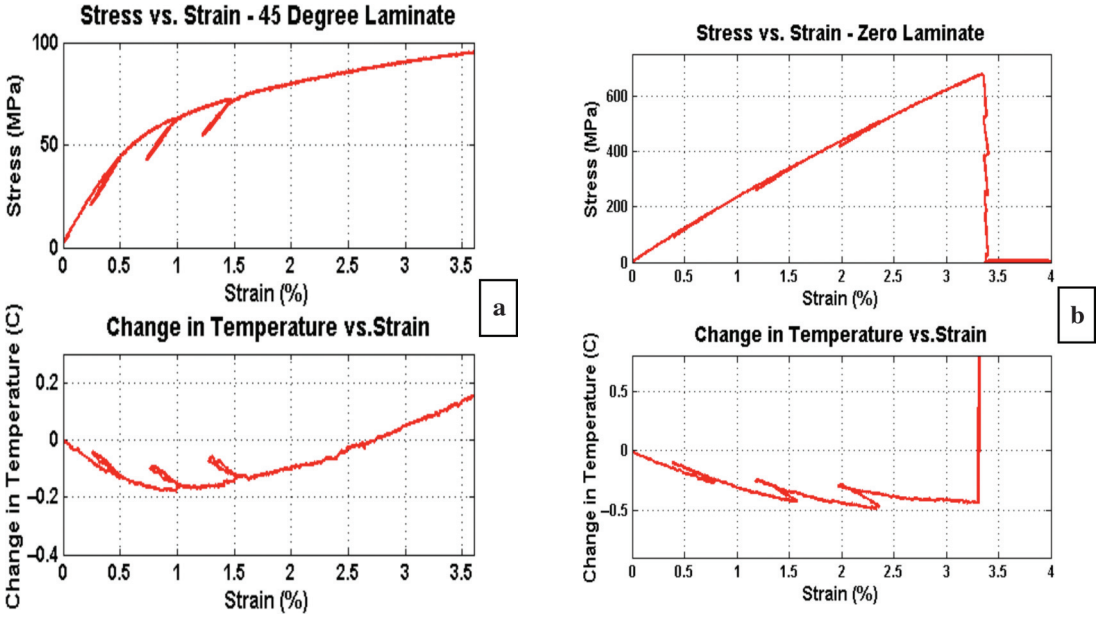

Figure 8. Comparison of thermal responses of (a) 45 degree laminate (b) zero degree laminate during interrupted tensile loading

Linear increase in temperature response of each specimen during unloading might be due to the friction between fibers at the cross over points, and at the fiber matrix interface apart from the volume change.

As reported by Neubart et.al [13], a significant rise in temperature of the specimen due to crack formation, was not observed. This may be due to many reasons, firstly outer plies were made up of zero degree lamina, the one which fails at last and second factor might be the effect of surface resin layer [5, 6], both of these attenuates the heat transfer, also comparatively smaller amount of (or intensity of heat source) heat generated during the formation of cracks being produced locally may not be enough to heat the whole specimen [4].

Thermal response of Zero, Quasi, 45 and 90 laminates are compared and shown in Fig.9. Slopes of the respective curves are measured as –0.46, –0.44, –0.39 and –0.37. It was observed that the thermoelastic behavior of Quasi specimen can be predicted from the responses of individual plies employing the rule of mixtures.

7. CONCLUSION

Infrared Thermography technique was employed for characterizing tensile deformation of glass/epoxy composite specimens. Zero, Quasi, 45 and 90 degree laminates were used for studying their

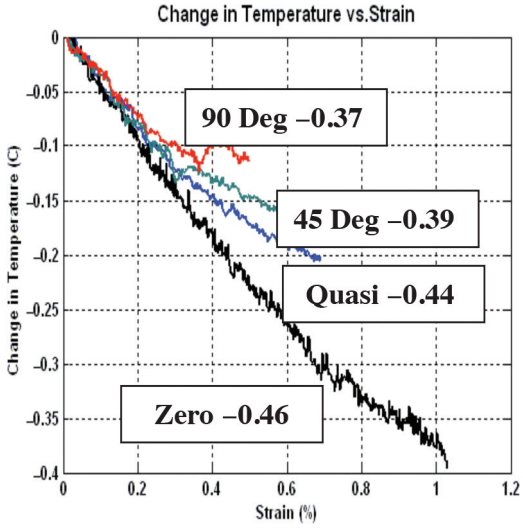

Figure 9. Comparison of thermoelastic slopes (°Cmm/mm) of Zero, Quasi, 45 and 90 degree laminates

thermomechanical behavior. Observed thermal responses of each one of them were distinct, corresponding to their mechanical deformation during tensile loading. Like other materials glass/epoxy composite specimen exhibited linear response during thermoelastic cooling and the extent of plastic deformation in each of the specimen appeared to be reflecting in their respective temperature responses. Thermoelastic behavior of a mixed lay-up sequence was found to follow the simple rule of mixtures.

8. ACKNOWLEDGEMENT

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