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Thermomechanical Studies in Glass/Epoxy Composite Specimen during Tensile Loading

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Abstract**—**This paper presents the results of thermo-mechanical characterization of Glass/Epoxy composite specimens using Infrared Thermography technique. The specimens used for the study were fabricated in-house with three different lay-up sequences and tested on a servo hydraulic machine under uni-axial loading. Infrared Camera was used for on-line monitoring surface temperature changes of composite specimens during tensile deformation.

Experimental results showed that thermomechanical characteristics of each type of specimens were distinct. Temperature was found to be decreasing linearly with increasing tensile stress in the elastic region due to thermo-elastic effect. Yield point could be observed by monitoring the change in temperature profile during tensile testing and this value could be correlated with the results obtained from stress-strain response. The extent of prior plastic deformation in the post-yield region influenced the slopes of temperature response during tensile loading. Partial unloading and reloading of specimens post-yield results in change in slope in elastic and plastic regions of composite specimens.

Keywords**—**Glass/Epoxy composites, Thermomechanical behavior, Infrared Thermography, Thermoelastic slope, Thermoplastic slope.

I. Introduction

ANY object above absolute temperature emits electromagnetic radiation which falls into the infrared region of the electromagnetic spectrum. The radiated energy is a function of its surface temperature. Infrared Thermography Technique (IRT) has been used as a non-destructive non-contact and real time method for capturing the thermal energy being radiated from the surface. IRT basically includes a camera, equipped with a series of changeable optics, and a computer interface. The core of the camera is a high sensitive infrared focal plane array detector, which absorbs the IR energy emitted by the object (whose surface temperature is to be measured) and converts it into electrical voltage or current. This electrical signal is then represented in the form of thermographic images.

It is a well known fact that 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,

$$\Delta T = \left(\frac{-\alpha T}{\rho C_p} \right) \Delta \sigma \tag{1}$$

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

$$-\rho C_p \frac{\Delta T}{T} = \alpha_1 \Delta \sigma_1 + \alpha_2 \Delta \sigma_2 \tag{2}$$

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), Δσ 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.

[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 [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 [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 [5, 6] and it was found that above a certain thickness of surface resin layer, heat transfer gets attenuated. [7] employed infrared thermography for characterizing tensile deformation in SS304 and observed from the experiments that, in the

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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. [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. [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. [10] have shown that in glass reinforced epoxy composites the adiabatic assumption is valid. Eq. (2) states that the thermoelastic response from a laminated composite is dependent on the stress in the surface lamina and neglects the resin-rich layer. 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 deformation in three glass/epoxy composite specimens made of different lay-ups and having same outer layers and hence to distinguish between them by monitoring temperature response during monotonic and interrupted tensile loading.

II. Experimental Work

A. Materials and Preparation 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 LY 556 resin with HY951 hardener (10:1) was employed as the matrix. Laminates of size 260 x 260mm composed of 12 plies giving thickness of 2.8mm 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.

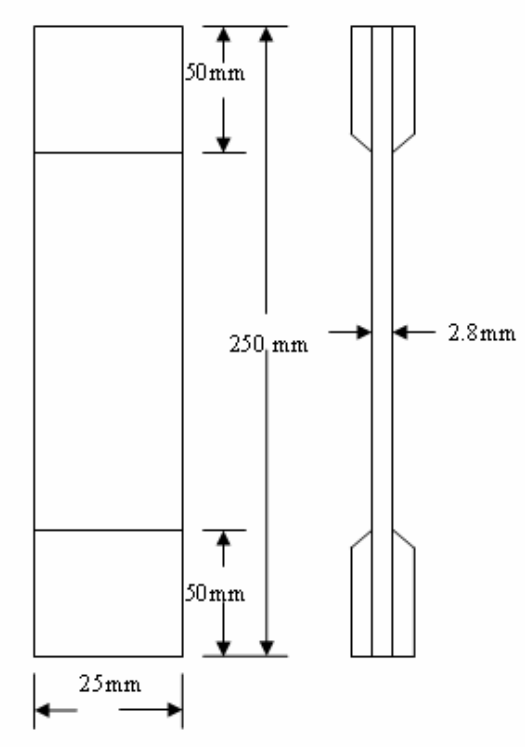


Fig. 1 Dimensions of the specimen used in tensile testing

B. Equipment and Experimental Procedure

Tests were carried out in a 100 kN MTS servo-hydraulic testing machine with synchronous data acquisition system. Specimens were subjected to monotonic tensile loading at a stroke rate of 2mm/min.

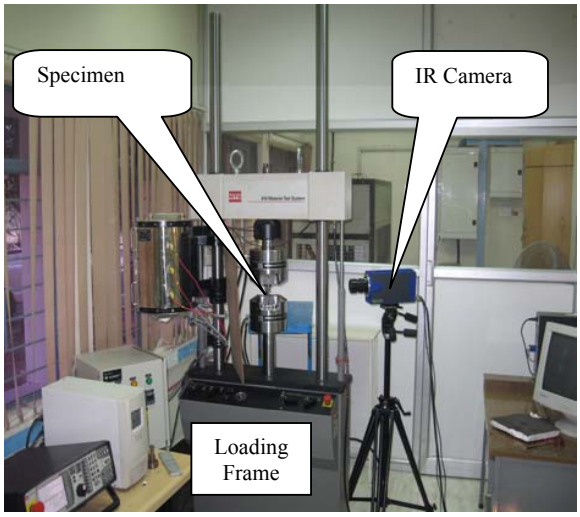


Fig. 2 Experimental setup

The infrared thermal imaging system used for the measurement is a CDIP jade LWIR camera. This 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 320x240 to 320x1pixels, variation of the frame rate from 5 to 1500 Hz, adjustable integration time from 60 to 500µs and real-time lock-in detection. The camera is equipped with a 25mm-objective lens giving a field view of 22°x 16°. The window size used in the experiments is 213x132 pixels and an integration time of 220 µs. The camera was positioned on a tripod approximately about) 0.5m from the specimen surface. A two-point Non Uniformity Correction (NUC) has been 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 calibration function, assuming that the specimen was a perfect black body with an emissivity value of 1. 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 is used as a reference for acquiring fluctuations in ambient temperature.

III. Results and Discussion

Three different lay-ups (i.e., zero:-$[0]_{12,}$ Quasi-isotropic:-$[0_3,+/-45,90]s$, and Cross-ply $[(0,90)_2,0,90]s$ of Glass/Epoxy composite specimens 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 displacement rate. This test was intended to study the residual plastic deformation in composite laminates.

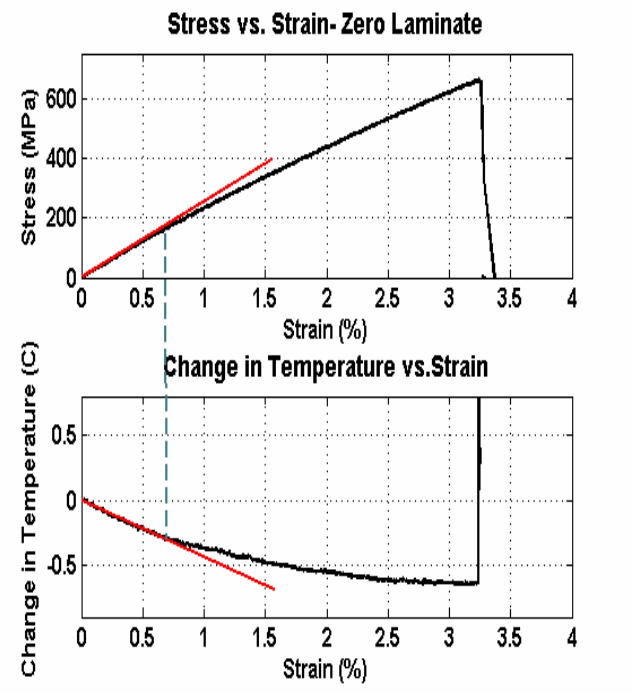
A. Monotonic Loading

Stress vs. Strain and Change in temperature vs. Strain for Zero, Quasi and Cross ply laminates are plotted in Fig.3.Just like in metals, it can be seen that all the three glass/epoxy specimens show a linear decrease in temperature with increased stress state until it reaches the elastic limit .The plots show that, in each case (Zero, Quasi and Cross plies), yield strain from thermal response is exactly matching with the corresponding point obtained from mechanical response. The slopes at the elastic region, referred as Thermoelastic Slope, Zero, Quasi and Cross ply laminates are measured as -0.44,-0.4 and -0.34 with percentage yield strains of 0.6,0.53 and 0.45 respectively.

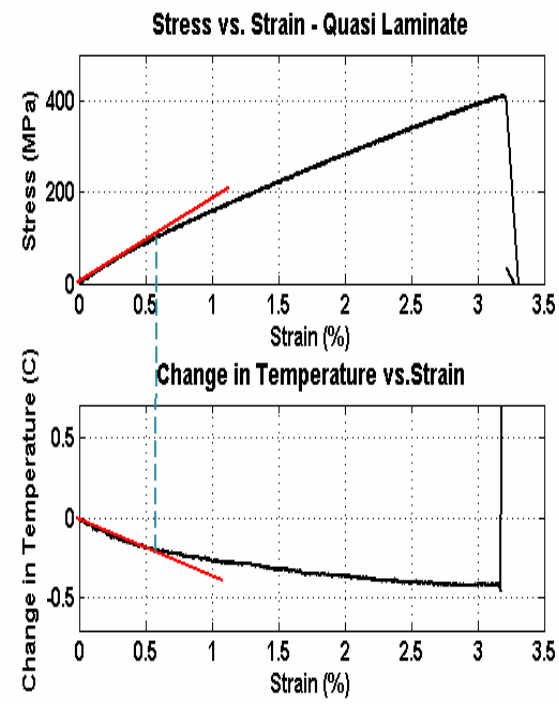
It could be seen that, the thermoelastic response from the laminates is purely depending upon the structure of the laminates (lay-ups) i.e., the temperature response from the surface ply (including isotropic resin layer on the surface of the laminate) is dependent upon the stacking sequence of the laminate [10, 11].

Fig. 3 compares the temperature responses of Zero, Quasi isotropic and Cross-ply laminates. Failure strains of these laminates are 3.3%, 3.25% and 3.2% respectively. It can be seen that Zero, Quasi-isotropic and Cross-ply laminates show different temperature responses even though their outer layers are identical, ie Zero degree. In all the cases, temperature decreases linearly in the elastic region with distinct thermoelastic slopes and then the specimens show non-linear behavior in temperature response. Non-linearity is observed in stress-strain curves also. 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. The presence of 90^0 layers (50% of the laminate) justifies thermomechanical response of the Cross ply laminate which has the minimum global stiffness and hence it is characterized with the lowest thermoelastic slope. The 90^0 layers fail by transverse cracking parallel to the fibers, simultaneously or immediately after, matrix cracking in the 90^0 layers, the 0^0 layers also fail by cracking parallel to the fibers [12]. However, 0^0 layers are still capable of carrying significant load in the axial direction. In all the three cases, it can be observed that the response becomes almost flat before ultimate failure of the laminates. 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.

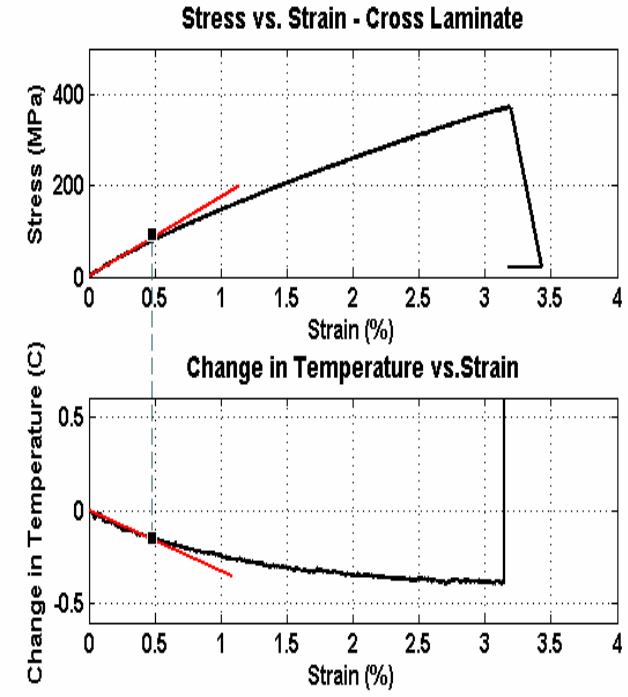
It should be noted that the nonlinear behavior is related to fiber rotations and physical damages (e.g., matrix cracking, interfacial debonding and delaminations), therefore, the nonlinearity differs for various loading directions [13]. Matrix cracks, failure of transverse fibers and friction between 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).



(a)

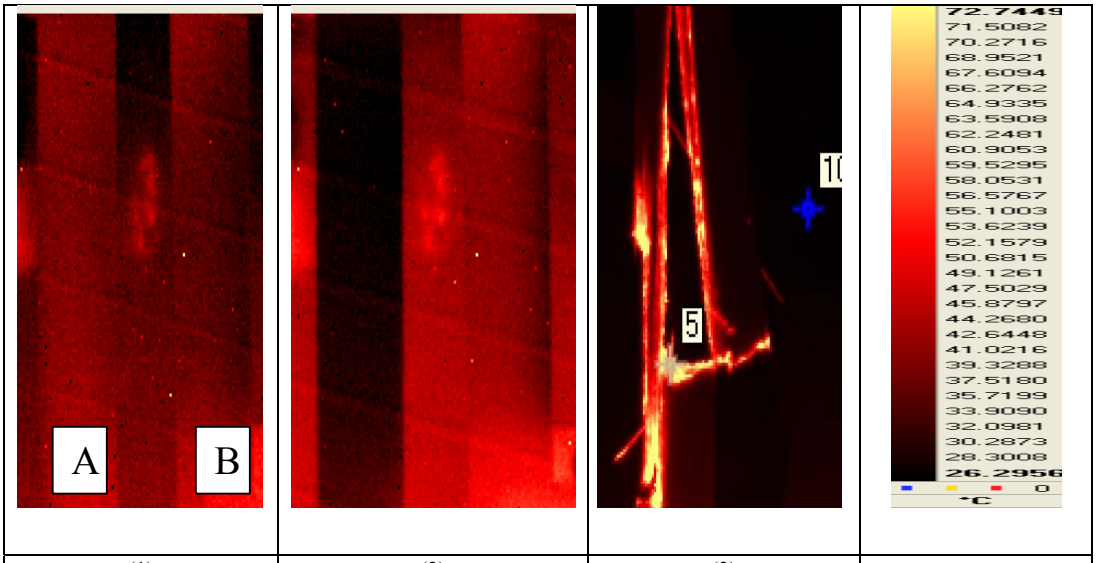


(b)



(c)

Fig. 3 Stress and Change in Temperature vs. Strain for (a) Zero (b) Quasi-isotropic and (c) Cross-ply laminates



(1) (2) (3)

Fig. 4 Thermograms showing temperature variation in Zero degree specimen loaded in tension.(A) Loaded specimen (B) Reference specimen

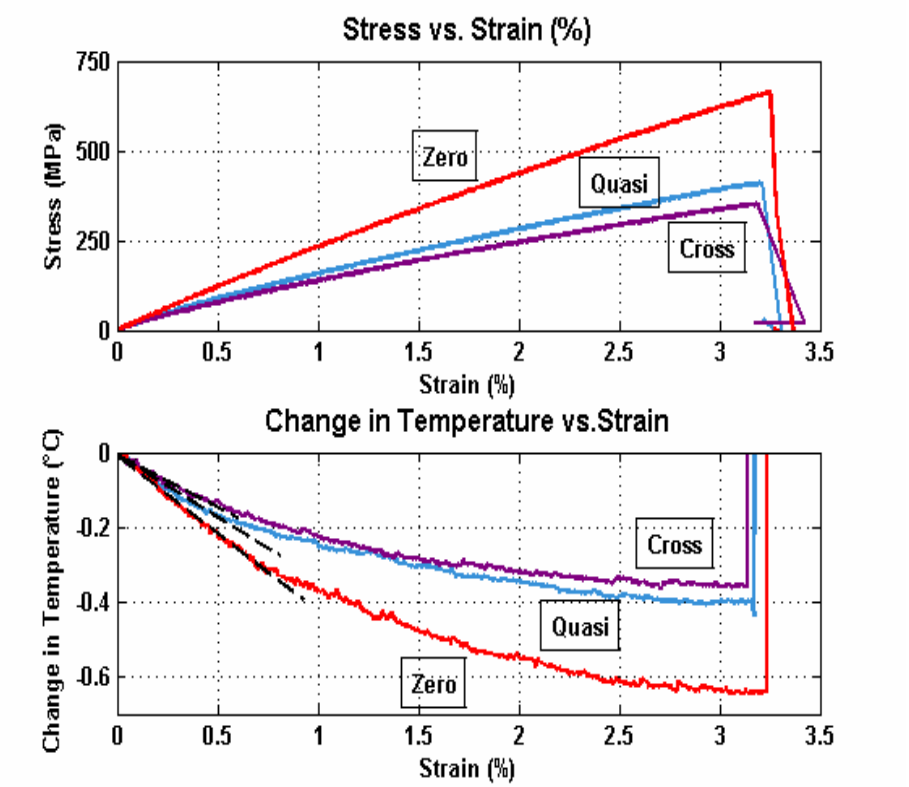


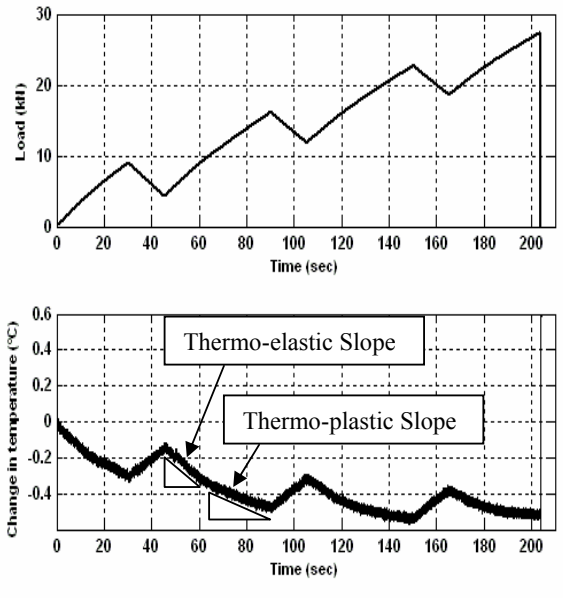
Fig. 5 Comparison of Stress and Change in Temperature vs. Strain for Zero, Quasi-isotropic and Cross-ply laminates

B. Interrupted Loading

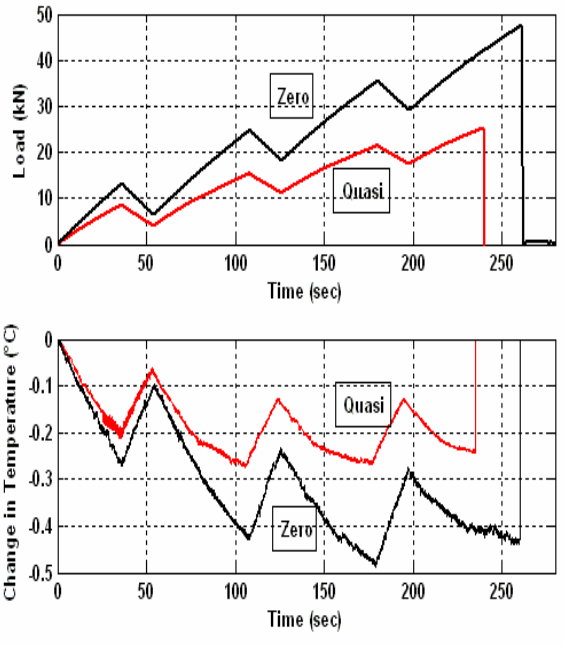
Unloading (interrupted) tests of simple tension were also carried out on the composite specimens. A typical interrupted loading response for Cross-ply laminate is shown in Fig. 6 (a). Each loading segments consists of two distinct linear regions with different slopes, named Thermoelastic and Thermoplastic regions. It can also be observed that slope of both thermoelastic and thermoplastic segments changes with increase in strain. Thermal response of Zero, and Quasi-isotropic laminates during interrupted loading are compared and shown in Fig. 6 (b). It may be observed that, both Quasi-isotropic and Cross-ply laminates show very distinct thermoelastic and thermoplastic segments whereas in the case of zero degree laminate thermoplastic region is not so prominent in first two partial unloading segments.

The unloading result of tension for Zero, Quasi-isotropic and Cross-ply laminates (Fig. 7 (a), (b) and (c)) 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 these laminates until final failure. 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 [14], 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].

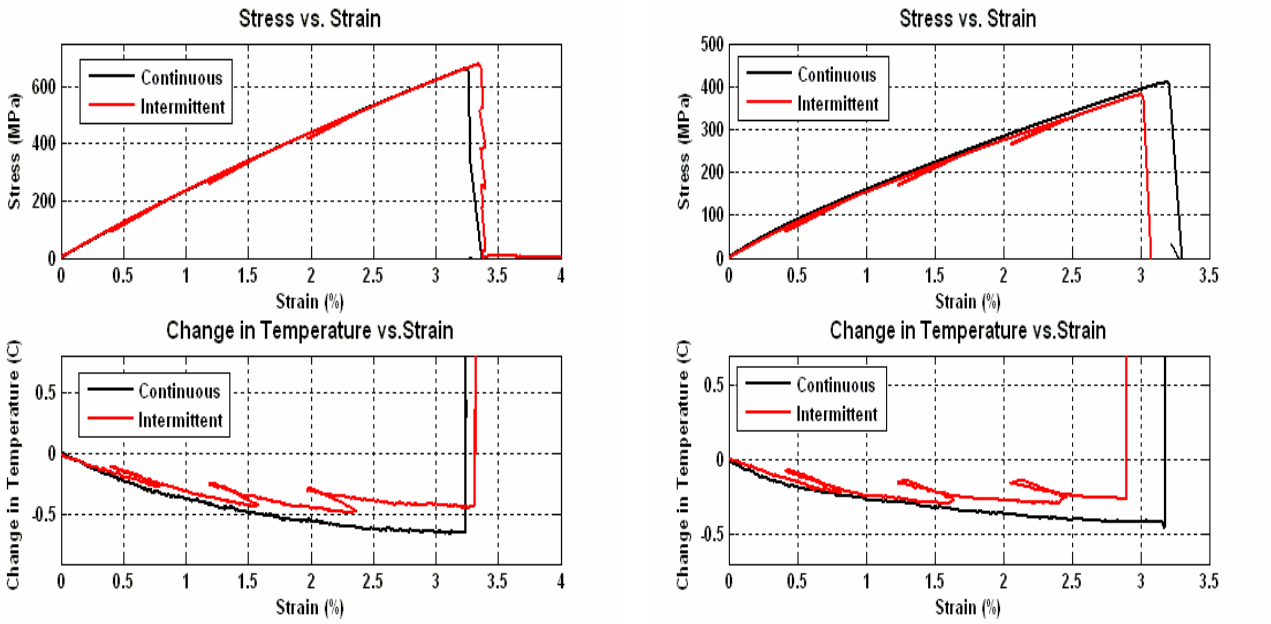


(a)



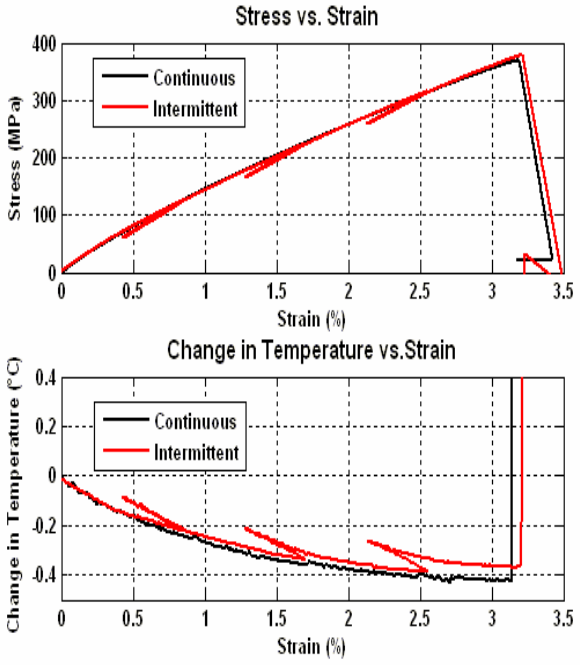
(b)

Fig. 6 Variation of Load and Temperature with Time (a) Cross-ply (b) Zero and Quasi-isotropic Laminates



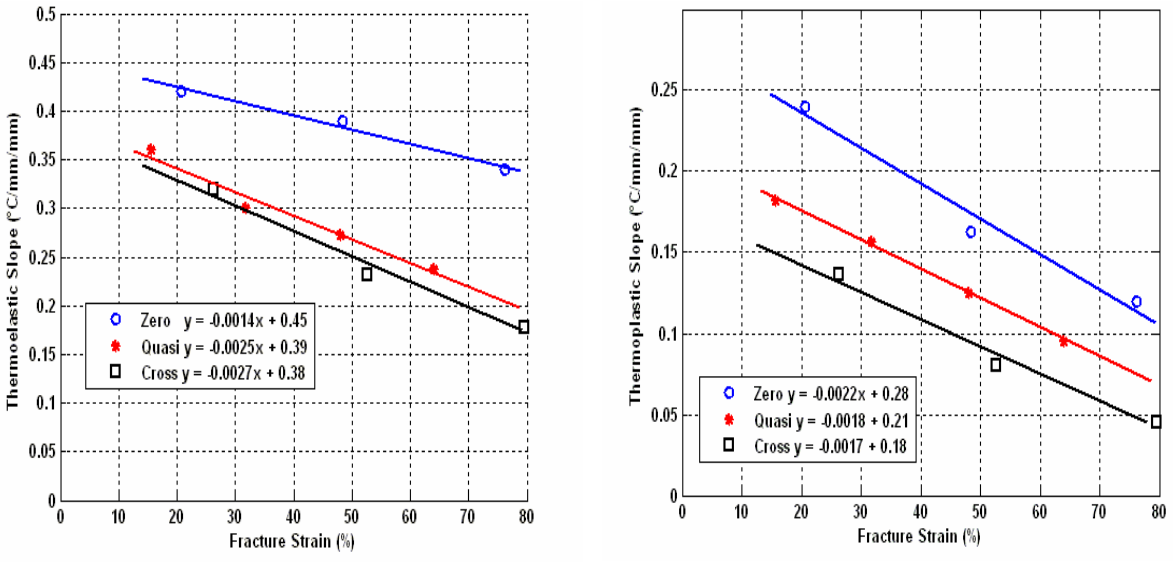
(a) (b)

Fig. 7 (a) Temperature response during continuous and interrupted tensile loading (a) Zero (b) Quasi-isotropic laminate.



(c)

Fig. (7) (c)Temperature response of Cross-ply laminate during continuous and interrupted tensile loading



(a) (b)

Fig. 8 Comparison of change in thermoelastic and thermoplastic slopes with fracture strain

Fig. 8 (a ,b) shows that the thermoelastic slope as well as thermoplastic slopes of all three composite laminates keep decreasing (numerically) with increase in strain. The variation of thermoelastic slope with strain indicates the stiffness reduction and hence it can be considered as a measure of damage accumulation in the laminates [15]. Zero degree laminate showed lowest reduction in stiffness whereas in the other two (Quasi and Cross) laminates change in thermoelastic slope depicts faster degradation in the material, this is due to the presence of off-axis plies which fails much earlier than the longitudinal fibers.

IV. Conclusion

Infrared Thermography technique was employed for characterizing tensile deformation of glass/epoxy composite specimens. Zero, Quasi, and Cross ply laminates were used for studying their 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. Interrupted test results showed that the specimens were getting heated up during unloading and thereby a residual heating in the laminates after each unloading segments. Study on thermoelastic slope as well as thermoplastic slope revealed that both parameters decrease with increase in strain due to the accumulation of damage in the specimen.

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