Quantitative Assessment of Impact damage in Composites by IR Thermography

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ABSTRACT

Thermography is an advanced NDE technique which is successfully applied for not only defect detection in composite but also for defect characterization. It is becoming popular due to its fast inspection rate and non-contact nature which also provides full field images of the defects. This paper reports the application of flash thermography technique for quantitative estimation of damage area in two composite laminates namely E-glass/epoxy and E-glass/phenolic of 5mm thickness. These laminates were subjected to low velocity impact tests using instrumented drop weight impact tester at three different impact energies viz. 50, 125 and 175J. Results showed that E-glass/phenolic composite absorbed more energy as compared to E-glass/epoxy composite. Absorbed energy was found increasing with impact energy up to threshold energy of perforation (125J), after that no significant increase in absorbed energy was observed with increase in impact energy. These impact tested laminates were subsequently inspected by flash thermography and the extent of delamination due to impact was assessed. Delamination area was estimated by sketching the polygon around the defective area and was found increasing with the impact energy. The three main inferences drawn from thermography inspection are: (1). E-glass/phenolic samples suffered higher extent of damage as compared to E-glass/epoxy samples, which corroborates well with the findings from drop weight impact test (2). Delaminated area was found increasing with the impact energy for both materials (3). Shallow plies in composites suffered less damage as compared to deeper plies.

This study has demonstrated the applicability of thermography for quantitative assessment of impact damages in composites, where most of the other NDT techniques like UT and radiography have limited scope of application.

Keywords: *Composites, Delamination, Flash Thermography, Impact damage, Low velocity impact*

1. Introduction

Infrared thermography (IRT) has been successfully used as a nondestructive testing and evaluation (NDT&E) technique in many engineering applications. Thermal imaging technique has been widely used for many years to inspect the joints, integrity of materials, electrical connections in a wide range of industrial as well as research fields [1]. There are several NDT techniques like radiography, ultrasonic testing, shearography, infrared thermography etc., available for detecting defects in composite. Although traditional techniques such as ultrasonics can easily reveal the presence of flawed areas but they need a coupling agent between the probes and the surface of the investigated component. Moreover they are time consuming, whereas, IRT is a faster and non-contact technique which does not require any coupling agent. IRT is a thermal stimulation technique that deals with measuring the variation of thermal signal on the surface of structures.

IRT technique can be mainly classified into two types: Passive thermography & Active thermography depending on the introduction of thermal stimulation. In passive thermography the object is usually at higher temperature than the ambient so no external thermal stimulation is required. In active thermography external thermal stimulation is needed ideally in a uniform way. The presence of underlying damage or defect disturbs the heat flow during cooling or heating phase and are manifested with local temperature extrema on a two dimensional representation which is captured by the infrared camera. In current studies, the raw data captured by the IR camera after Active heating of the test samples was polynomial fitted at logarithmic scale and then reconstructed back. This procedure eliminates the high frequency noise from temporal data and facilitates the measurement of first and second derivative.

1.1 Principle of Thermal Signal Reconstruction (TSR) technique

This technique is based on the phenomenon of heat conduction in a thick solid sample (semi-infinite), which is described by 1D heat diffusion equation:

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \qquad (1)$$

Where, α: Thermal diffusivity

For the case of pulse heating, a short and high energy pulse impinges on the test surface. The front surface absorbs the energy and the temperature increases instantaneously. Since a temperature

gradient is generated across the thickness of the test article, thermal waves generated on the front surface diffuse to the rear surface causing decrease in temperature on front surface. The solution for temperature response on front surface of a semi-infinite medium after absorption of a Dirac pulse is given by [2]

$$T(x,t)=\frac{1}{\sqrt{\pi\rho ckt}}\exp\left(-\frac{x^2}{4\alpha t}\right) \quad (2)$$

Where, *T*- Surface temperature

I- Incident heat flux

ρ- Material density

c- Specific heat

α- Thermal diffusivity

x- Depth

t- Time

The temperature variation at the surface i.e. x= 0 is given by

$$T(0,t)=\frac{1}{\sqrt{\pi\rho ckt}} \quad (3)$$

By considering equation (3) in the logarithmic domain. This gives:

$$\ln(T)=\ln\left(\frac{I}{e}\right)-\frac{1}{2}\ln(\pi t) \quad (4)$$

This implies that, for an ideal defect-free sample, the relationship of its surface temperature to cooling time is a linear function with a slope of -1/2(Fig.1).

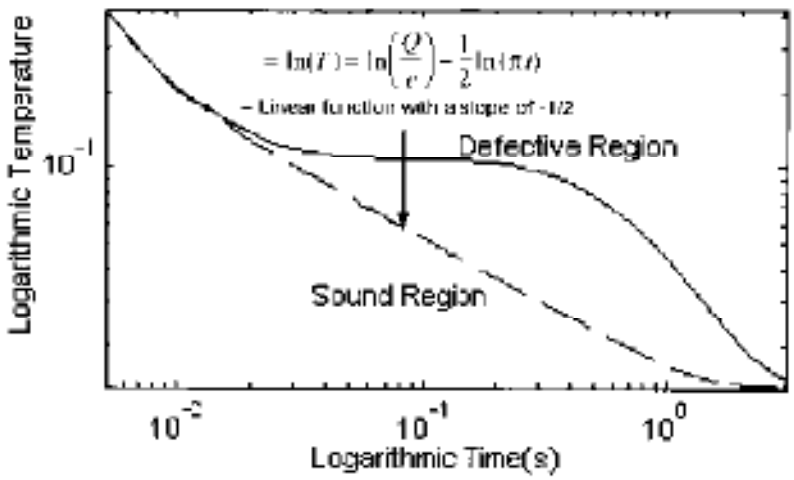

Fig-1: Logarithmic time-Tempevolution of the defect & sound zones

The temperature on the surface over the defect first increases as the defect blocks the heat propagation and the heat buildups over it.Hence, any deviation upward from linear response indicates the presence of the defect. In practice pulse thermography is associated with noise due to non-uniform heating & detector such as non-linear camera response, background radiation. To overcome these problems Thermal signal reconstruction (TSR) proposed by Shepard [3] has been applied. In the TSR temperature response of each pixel is fitted polynomially and subsequently first and second derivatives are calculated.

2. Experimental details

2.1 Materials& fabrication of laminates

Diglycidyl ether of bisphenol-A (DGEBA) epoxy resin (LY556) with hardener Diethyle toluene diamine (DETDA) (HY5200) supplied by M/s. Huntsman Chemicals were used in present studies. Phenolic resin (Novalac grade) was provided by M/s. Permali Wallace Pvt Ltd, Bhopal. Commercially available E-glass woven roving having 0.25mm thickness and 360 GSM with warp and weft of 55x50 per 10 cm width was used as reinforcement. E-glass/epoxy and E-glass/phenolic composite laminates of sizes 350 mm x 350 mm were made through hand layup technique followed by hot pressing under hydraulic pressure details of the laminate curing is given in elsewhere [4].Thickness of fabricated composite laminates was controlled at 5±0.2mm. Specimens were cut in to the dimensions of 150 x100 mm for impact tests.

2.2 Low velocity impact test

Low velocity impact tests were carried by using instrumented drop weight impact tester of Ceast-Instron make (CEAST- 9350) as shown in Fig.2. This instrument has thecircular shape specimen fixture with an internal diameter of 76.2mm. It has also got pneumatic clamping facility to prevent the specimen slippage during impact and anti rebound mechanism to avoid the multiple impacts. Hemi spherical shape steel impactor with 16mm diameter (Fig.2) was used to carry out low velocity impacts. The striker has got force transducer of 45kN capacity to measure force exerted by the specimen on the impactor during the impact. Data acquisition system with the sampling rate of 500 kHz was used to record the force –time history. Required impact energy was obtained by dropping the impactor along with the required mass from a pre-calculated height.Energy absorption of laminate is calculated usingthe software provided by the instrument supplier as per ASTM D7136 [5].

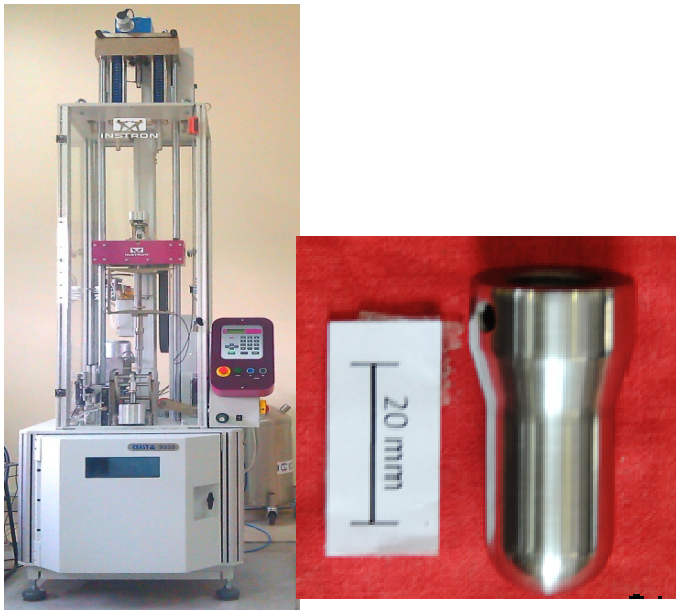

Fig.2: Instrumented drop weight impact tester (Model-9350) and impactor

Based on distinct behaviour of laminate, three different incident energies namely 50, 125 & 175 J were selected. The corresponding impactor velocities were 4.53, 6.88, & 8.14 m/s respectively. The response of laminates in terms of energy-time is compared at above independent energies. Minimum of three samples for each type were tested at each energy level.

2.3 NDE analysis

Damage analysis was carried out using IR camera (Model: ThermaCAM SC 3000) supplied by M/s. FLIR system AB, (Sweden). The equipment utilizes sterling cooled Quantum Well Infrared

PhotonicDetector (QWIP) which produces a resolution of 0.03 ^{0}C at 30^{0}C and a spectral response of 8-9µm. Specimens of size 150mmx 100 mm x 5mm were heated for 5ms using two flash lamps mounted horizontally on each side of the IR camera with focal plane array pixel format of 320x240. Fig.3 shows the schematic & experimental setup. The flash lamp impinges 9.6KJ energy on specimen surface. The image acquisition was automatically executed by the system at a frame rate of 25Hz for both the type of samples, immediately after pulse heating the sample. Further the acquired data was processed using Thermal wave imaging software with TSR technique.

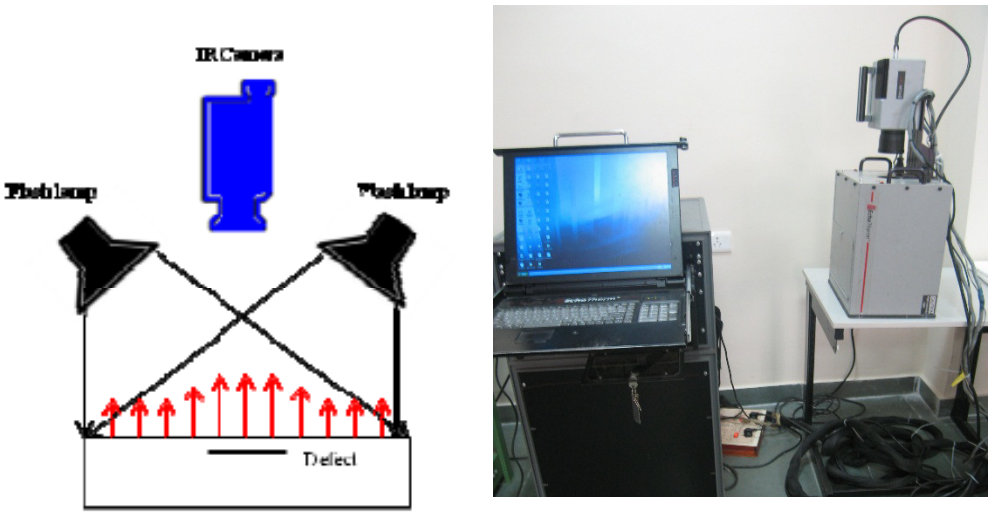

Fig.3 Schematic view & experimental setup

3. Results & discussions:

3.1 Energy absorption of the laminates:

Energy-time curve presents how the given energy is absorbed during impact event. Energy absorbed by the specimen can be calculated as follows. In case of non perforated samples, the total absorbed energy (E_a) is sum of dissipated energy (E_d) due to damage in the specimen and rebound energy (E_r) [6, 7]. Whereas in case of perforated samples part of impact energy is absorbed for complete perforation of the target and rest is absorbed asfrictional energy (E_f) between lateral surface of the impactor and target. In some instances we observed minute difference in measured impact energy and incident energy due to friction between impactor and guiding rods of the drop tower.

$E_a = E_d + E_r$ ..... for non-perforation

$E_a = E_d + E_f$ ..... for perforation

Fig.4 show energy-time curve for the laminates impacted at different impact energies. It is observed that at 50J (Fig.4a) laminates shows rebound of impactor and phenolic laminate shows more energy absorption than epoxy laminate. At 125J impact energy (Fig.4b) no rebound of impactor is observed and the energy curve became a flat after reaching its maximum energy absorption. This may be a threshold value for laminates. At 175J impact energy both the laminates show two stages in energy- time curve (Fig.4c) due to complete penetration. The first stage (125-130J) is related to the energy absorbed by the laminate and the second stage corresponds to the frictional energy between the impactor and the perforated laminate. At 125 & 175J impact energy both the laminates have shown similar performance in terms of energy absorption which indicates that below the threshold energy (i.e. <125J in the present case) the effect of matrix on energy absorption is observed whereas above the threshold energy the effect of matrix is not significant on laminate energy absorption. Laminates mostly undergo localized deformation or elastic deformation being a thermoset nature which limits for its energy absorption. The slope of the energy-time curve indicates rate of energy absorption and it is found to be similar for both the laminates since fibers are the main load bearing materials.

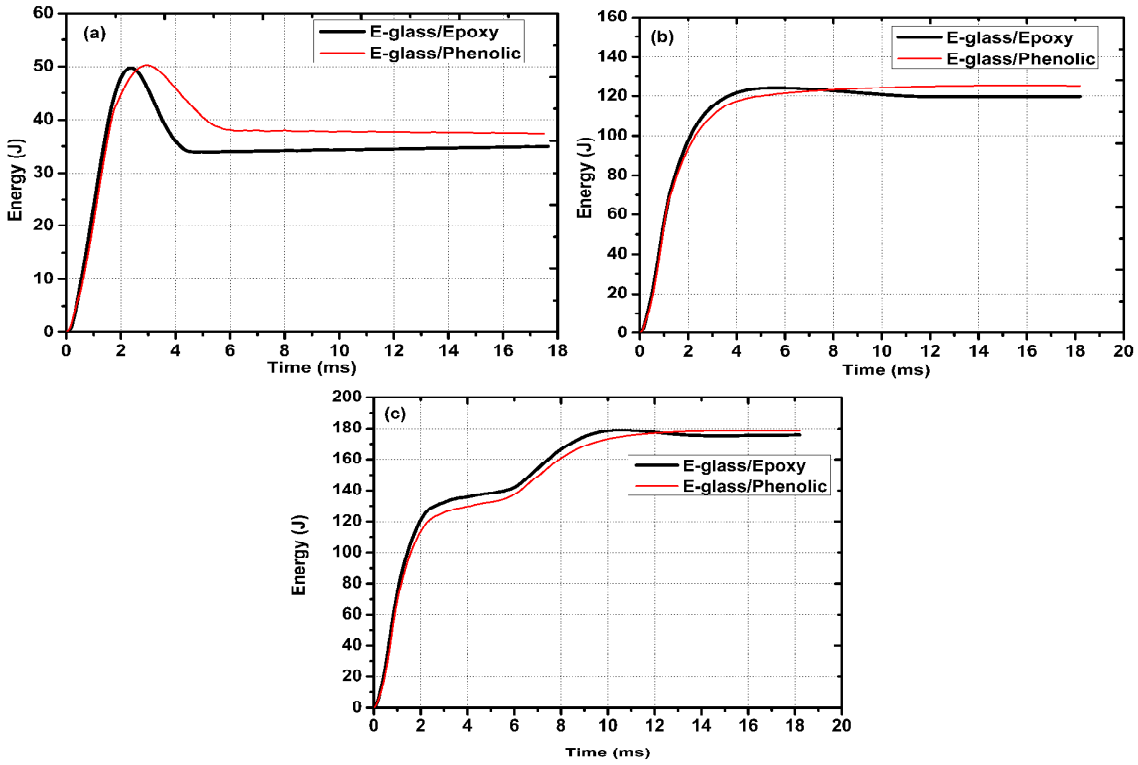

Fig.4 Energy – time response of E-glass laminates (a) 50J (b) 125J & (c) 175J

4. Post impact analysis

4.1 Visual observations

Visual inspection of impacted laminate revealed various damage modes like matrix cracking, fiber damage, indentation, radial delamination It can be assumed that energy is dissipated by the sample through these localized plastic deformation modes in addition to elastic deformation.

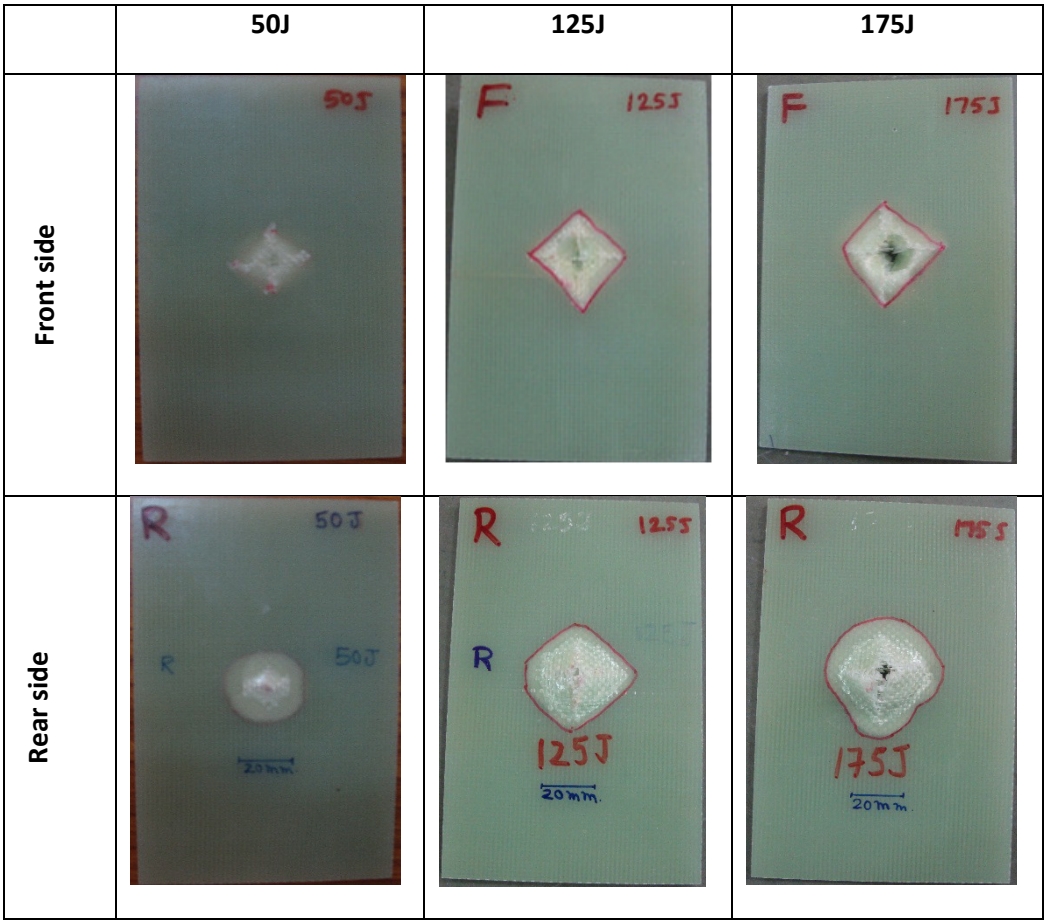

Fig. 5: Damage progression in E-glass/epoxy laminates with increased incident energy

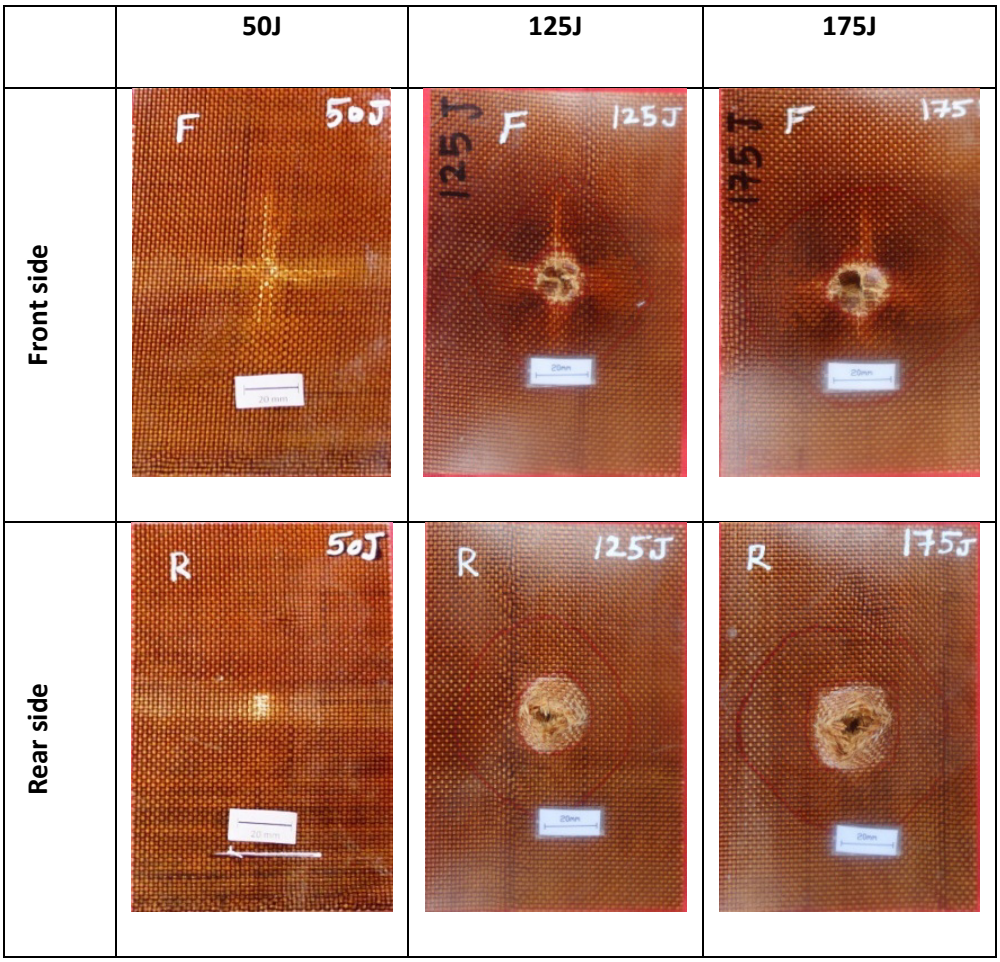

Fig. 6: Damage progression in E-glass/phenolic laminates with increased incident energy

4.2 NDE Analysis:

Flash Thermography was carried out on E-glass/epoxy and E-glass/phenolic of 5mm thickness laminates. From thermograms it was observed that area of matrix cracking & delaminations are increasing as the impact energy is increasing from 50J to 175J. Delamination area was calculated by sketching the polygon around the defective area as visible second derivative thermograms and was found increasing with the impact energy as given in Tables 1 & 2.

Table 1: Impact damage area in E-Glass/Epoxy

E-glass epoxylaminate	**Energy 50J**	**Energy 125J**	**Energy 175J**
Impact Damage Area (mm^2)	1255	2072	2405

Table 2: Impact damage area in E-Glass/Phenolic laminates

E-glass phenoliclaminate	**Energy 50J**	**Energy 125J**	**Energy 175J**
Impact Damage Area (mm^2)	3593	4073	5681

The thermogramsin Fig.7 show the increasing impact damage areawith increasing impact energy in different samples.

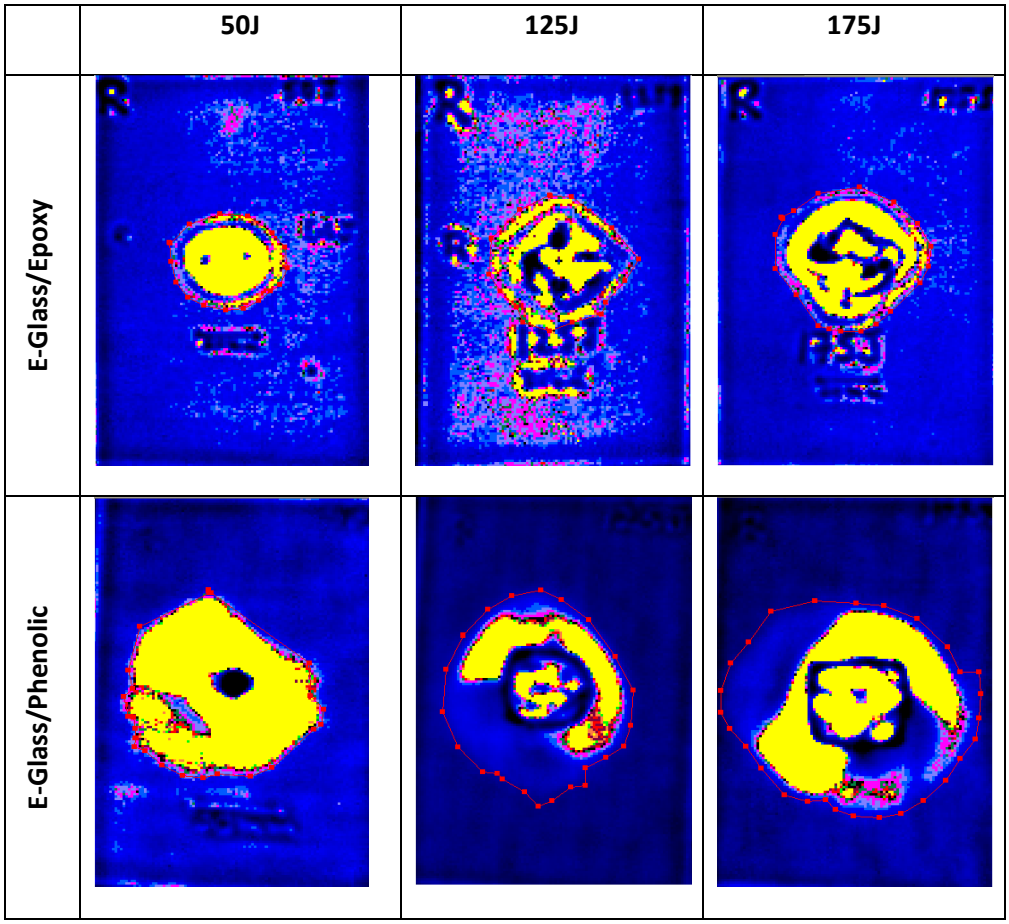

Fig.7: Thermograms in E-Glass/Epoxy & E-Glass/Phenolic laminates

5. Conclusions

Low velocity impact response of 5mm thickness E-glass/ epoxy and E-glass/phenolic was compared at three impact energies viz. 50, 125, 175J and drew the following conclusions.

a) Both E-glass/epoxy and E-glass/phenolic laminates show similar performance above the threshold energy; whereas below the threshold energy E-glass/phenolic laminate show higher energy absorption.

b) E-glass/phenolic laminates have shown more damage area compared to E-glass/epoxy laminates at all impact energies.

c) For low velocity impact applications E-glass/epoxy laminate show better performance in terms of less damage area than the E-glass/phenolic laminates and the results are confirmed by NDE analysis also.

d) Failure analysis of laminates reveal that laminates have undergone brittle failure and energy was absorbed through various damage modes like indentation, matrix crack, fibre breakage and delamination.

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