Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 7 (2017) 283–290

Structural Integrity Procedia

www.elsevier.com/locate/procedia

3rd International Symposium on Fatigue Design and Material Defects, FDMD 2017, 19-22 September 2017, Lecco, Italy

Damage Detection using Infrared Thermography in a Carbon-Flax Fiber Hybrid Composite

Raghu V Prakash[a]*, Monalisha Maharana[a]

[a]*Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai – 600036, India*

Abstract

Hybrid polymer composites are used in many secondary load carrying structures and use of natural fibers for hybridization is one of the options. However, in view of the higher levels of mismatch in strength between synthetic fibers and natural fibers, the failure modes of hybrid natural fiber composites are different. Advanced non-destructive test methods such as infra-red thermography are employed for damage detection. The present paper discusses the detection of damage in hybrid natural fiber composite laminates using active thermography method. Carbon and Flax fiber reinforcements are considered for this study. Specimens of hybrid composites prepared by hand lay-up technique were subjected to impact loading and post-impact fatigue loading to study damage progression through infra-red thermography. The laminates are tested for cooling response under transmission mode and reflection mode of thermal imaging for the test conditions of pristine specimen, impact damaged specimen, and fatigue cycled specimen after impact damage. It is observed that there is a secondary heating of specimens near the impact damaged zone when the active thermography is done in the transmission mode; the de-lamination defect can be more easily detected when the heating is from the damaged side and the measurement is from the opposite side using transmission mode.

Peer-review under responsibility of the Scientific Committee of the 3rd International Symposium on Fatigue Design and Material Defects.

Keywords: Infrared Thermography; Damage detection; Cooling response; Hybrid Polymer Composites

* Corresponding author. Tel.: +91-44-2257-4694; fax: +91-44-2257-4652.
E-mail address: raghuprakash@iitm.ac.in; raghu.v.prakash@gmail.com

Peer-review under responsibility of the Scientific Committee of the 3rd International Symposium on Fatigue Design and Material Defects.
10.1016/j.prostr.2017.11.090

1. Introduction

Up-front detection and consequent prevention of component failure is a crucial demand in the transportation and power sectors. Non-destructive testing (NDT) has emerged as one of the most widely used methods across the industries to detect damage in components without affecting the maintainability or serviceability of the components. Various NDT technologies have been developed to characterize damage and predict failure in components built out of several advanced materials that include polymer composites. Conventionally polymer matrix composites use synthetic fibers, such as, Glass fibers, Carbon fibers, Kevlar fibers; these have high strength and are used in safety critical primary structures such as aircraft structures. However, from the view point of bio-degradability, natural fibers are being considered these days for polymer composite systems. The disadvantage with natural fibers is the lower strength compared to synthetic fibers as well as variability in properties based on the geographical location of sourcing. As recourse, hybridization of fibers is considered as the viable option and the resultant hybrid composite is utilized in many secondary structures. The mechanical properties play an important role while one uses these composite systems. The general failure mechanisms can still be classified as under: fiber failure, matrix failure, de-lamination, de-bonding etc. The hybrid composites are inhomogeneous by nature and are susceptible to inherit defects induced during the processing; hence, exhaustive experimental validation needs to be done on these materials to prevent catastrophic failures. Many of the mechanical property tests are conducted under static conditions, but, they do not reflect the real-time behavior under service conditions, such as fatigue loading, mild impact loading. To overcome this, it is essential to have NDT technologies that can be used to understand the behavior of the materials when they are subjected to in-service loading. Infrared (IR) Thermography technique is one of the most widely used NDT methods to detect failure in materials (Wong et al (1999), Maldague (2001) and Bagavathiappan et al (2013)); the IR technique is in-situ and can be used for online condition monitoring. Infrared thermography works on two basic principles: a) active thermography where the test specimen is heated up (or) thermally activated using an external source and the cooling response is monitored and b) using passive thermal imaging where the heat emitted by a specimen in response to a mechanical loading is monitored.

It is reported in the literature that composites exhibit thermo-mechanical behavior – i.e., application of an external load induces heat in the specimen. Muneer et al (2009) have utilized this to measure the temperature response during tensile loading in a glass fiber reinforced plastic (GFRP) by passive thermography technique and indicated that the temperature response is sensitive to prior damage. Chrysafi et al (2017) have suggested that active thermography is more suited compared to passive thermography for polymer composite specimens. Active thermography using halogen lamp heating has been used to detect the appearance of defects in adhesively bonded joints in a study conducted by Carosena and Giovanni (2010). Harizi et al (2014) have used active thermography and cooling response as a tool to detect the presence of damage in a polymer matrix composite.

For the purpose of active thermography, two types of specimen heating and resultant temperature response are considered: i) heating of the specimen and the temperature measurements are done on the same surface, also referred to as reflection mode, and ii) temperature measurements are carried out on the surface that is opposite to the heating surface, also referred to as transmission mode. Figure 1 presents schematic of the reflection and transmission mode for pristine and impacted specimen respectively.

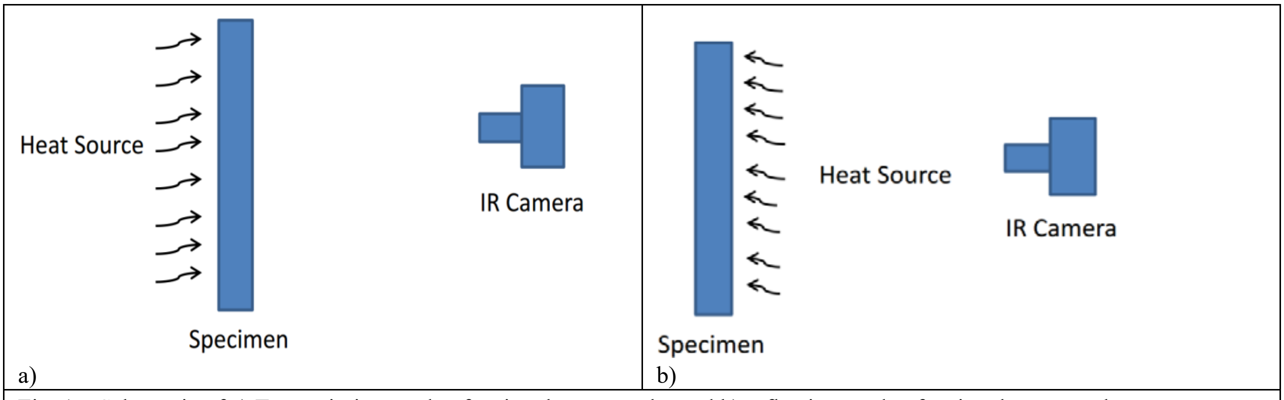


Fig. 1 – Schematic of a) Transmission mode of active thermography and b) reflection mode of active thermography.

The objective of this paper is to study the damage characteristics of hybrid polymer composite specimen in un-impacted (pristine) state as well as under low velocity impacted condition and fatigue damaged state thereafter, both in the reflection mode as well as in the transmission mode. Hybrid natural fiber polymer composite specimens, made up of Carbon fiber Mat and flax fiber mat are used in this study.

2. Experimental Procedure

2.1 Laminate Preparation and Specimen Extraction

The hybrid composite laminates were prepared by hand lay-up technique. A base layer of wax-coated Mylar ® sheet of 300 mm x 300 mm was placed in a sheet mold having a nominal height of 2.5 mm. Over this, a layer of uni-directionally stitched Flax fiber Mat was placed in between two woven Carbon fiber mats (of 480 GSM). Typical fiber diameter for Flax fibers varies between 60 – 110 microns. An epoxy resin mix, comprising of Epoxy LY556 and Araldite® hardener, was applied after placement of each layer of the mat. The top layer was made up of Mylar ® sheet. Compression molding was carried out at a pressure of 10 bar at ambient room temperature. This was followed by curing at room temperature for 24 hrs. The configuration of the fibers was [$0^{\circ\,(Carbon)}/90^{\circ\,(Carbon)}/0^{\circ\,(Flax)}/90^{\circ\,(Carbon)}/0^{\circ\,(Carbon)}$]. The Mylar sheets were peeled off after the curing of the laminate. As the resulting laminate was thin (~ 2.1 mm), the tensile specimens as per dimensions shown in Fig. 2 were extracted as per ASTM D638-2015 standards using a CNC router; rectangular specimens with dimensions 200 mm x 45 mm were also extracted using the CNC router.

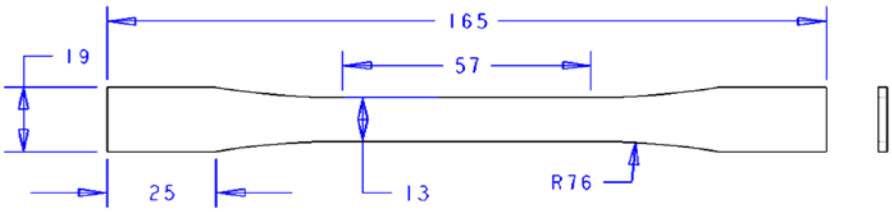


Fig. 2 – Schematic of test specimen used for the study. All dimensions are in mm.

2.2 Impacting and Fatigue Testing of the Specimen

The tensile specimens were impacted with an energy of ~ 5 J (low velocity of ~ 1.4 m/s) using a Drop-Impact test set-up (Fig. 3). A 5.2 kgf hemispherical impact head, with a nominal diameter of 16 mm, was used to impact the specimen. The rectangular specimens were impacted with ~10 J input impact energy. These impacts were sufficient to impart a Barely Visible Impact Damage on the specimen (BVID).

2.3 Active IR Thermography

A Micro-Epsilon Infra-red (IR) camera (Model: TIM 160) was used to monitor the specimen response after it was heated using a halogen lamp for a time period of 20 s at different configurations, such as rear side heating (Transmission mode) and front side heating (Reflection mode). Figure 4 presents the photograph of experimental set-up. The cooling response in Transmission mode as well as in Reflection mode was obtained at both the impacted region and the non-impacted region of the specimen for the following conditions:

i) Carbon Fiber Mats, ii) Flax Fiber Mats, iii) Pristine Hybrid natural fiber composite specimen, iv) 5 J Impacted and Fatigue Damaged Specimen, and v) 10 J Impacted Specimen (Rectangular specimen).

The 5 J impacted and fatigue damaged specimen was subjected to a constant amplitude tension-tension fatigue cycling with loads ranging between 1.0 – 0.1 kN till 260,000 cycles. Table 1 presents the stiffness value of the 5 J impacted specimen before the commencement of fatigue cycle and after subjecting the specimen to 2,60,000 cycles. It may be noted that the stiffness values of a pristine specimen (un-impacted, no fatigue-damage) during loading and unloading part of fatigue cycles were estimated as 41.1 kN/mm and 41.9 kN/mm respectively. A load window of 10-50% of P_{max} was considered for the loading part of the fatigue cycle and a load window of 90-50% of P_{max} was considered for the unloading part of the fatigue cycle to estimate the corresponding stiffness values.

Fig. 3 – Drop Impact tester used for impacting specimens.

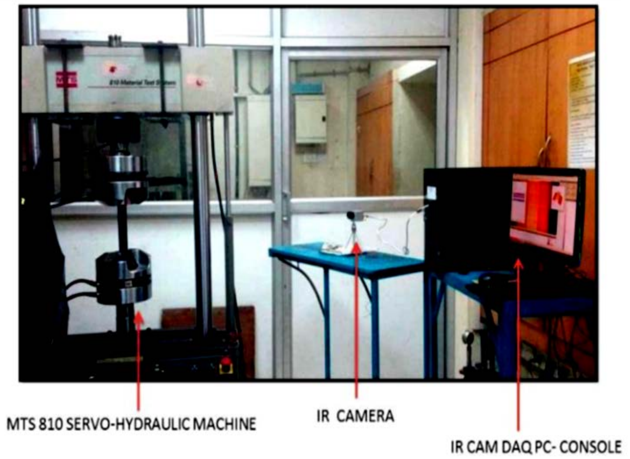


Fig. 4 – Infrared imaging and MTS 810 servo-hydraulic test system used for the experiments.

Table 1: Variation in the stiffness of a 5 J impacted sample with application of fatigue cycles

Number of Fatigue Cycles	Loading Cycle Stiffness, kN/mm	Unloading Cycle Stiffness, kN/mm
0	28.07	27.73
260000	21.02	21.16

In some of the cases, the specimens were subjected to a mild compressive load to verify if the cooling response is influenced by the application of load, similar to the work of Prakash and Sudevan (2016), in a study pertaining to thermo-mechanical response of Carbon fiber composite laminates. It is presumed that the de-laminations at the damage region would broom which could cause the change in cooling response at the region of interest. The impact damaged face was kept either facing the infrared camera (or) was behind the camera during the experiments.

3. Results and Discussions

3.1 Fiber Mat cooling response and Pristine Laminate cooling response

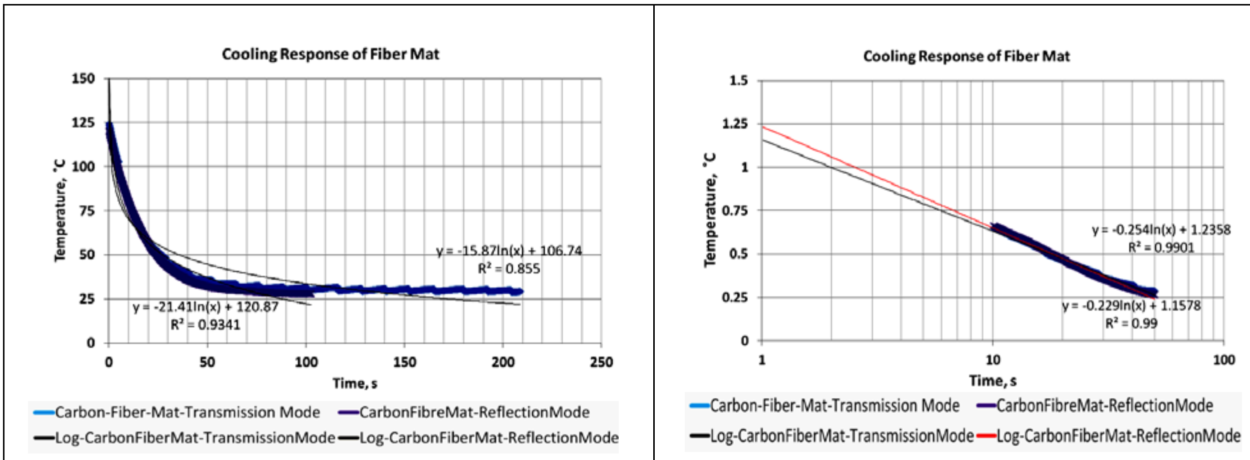
Figure 5a presents the cooling response of carbon fiber mat in the reflection and transmission mode. A logarithmic fit of cooling response was made and it is noted that there is not a significant difference between the transmission mode and reflection mode of cooling for the Carbon fiber mat that was chosen for this study. Similar observation was made with respect to Flax fiber mat. As the temperature at the beginning of cooling response could not be held constant for all the cooling response trials, the temperature-time response was normalized with reference to the temperature at the start of cooling response and the normalized temperature-time response was used for fitting this function. The normalized temperature vs. time data plotted in log-linear graph is shown in Fig. 5b. The logarithmic constants do not show much of a difference between the transmission and reflection mode for the carbon fiber mat as well as for the natural fiber mat. However, one could note that the logarithmic fit is not exact; in an attempt to look into this aspect, the best fit response was sought and it was noted that a double exponential representation of temperature-time response showed the best fit. The temperature at any instant (T(t)) is given by the following equation:

$$\mathrm{T(t)} = ae^{bt} + ce^{dt} \tag{1}$$

Where t = time and a, b, c and d are constants of exponential fit. Table 2 presents the constants for the double exponential fit for the temperature-time response.

Figure 6 presents the plot of temperature-time response with logarithmic fit for normalized data as well as data obtained through the two exponents fit for the carbon fiber mat. It can be noted that the slope of the first exponent term is almost the same as that of the logarithmic fit of base data and the second exponential term has a very small slope. It can be surmised that the first term of exponential term represents the heat transfer from the front face of the specimen, while the second term represents the heat transfer from the rear side of the specimen upon removal of active heat source from the halogen lamp.

Figure 7 presents the cooling response of the two types of fiber mats used in this study as well as that of the finished laminate of 2.1 mm thickness. It is noted that in case of pristine laminate, the cooling response (in the normalized temperature format) is showing a difference between the transmission and reflection mode. The temperature appears to increase by a small amount in the transmission mode (up to a time period of about 8 seconds) and thereafter cools, whereas the slope of the cooling response in reflection mode is steep up to the same time period. A similar response was observed in our earlier work (Prakash and Sudevan, 2016) that dealt with woven Carbon fiber mat polymer composites. Table 2 presents the constants of exponential fit for the natural fiber and built-up laminate in transmission and reflection mode.



a) b)

Figure 5 – a) Cooling response of Carbon fiber mat under Transmission and Reflection Mode and b) Normalized cooling response of Carbon fiber mat under Transmission and Reflection Mode.

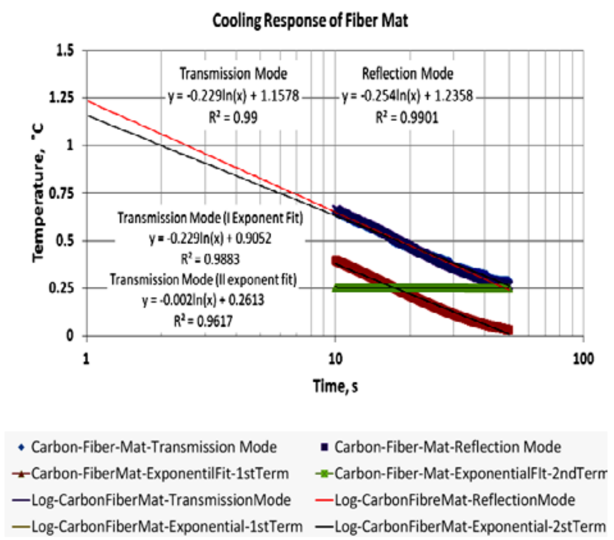


Fig. 6 – Cooling response of Carbon Fiber Mat in Transmission and Reflection Mode

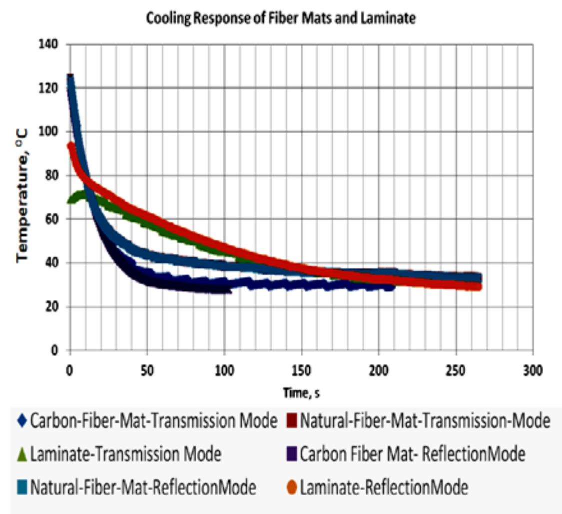
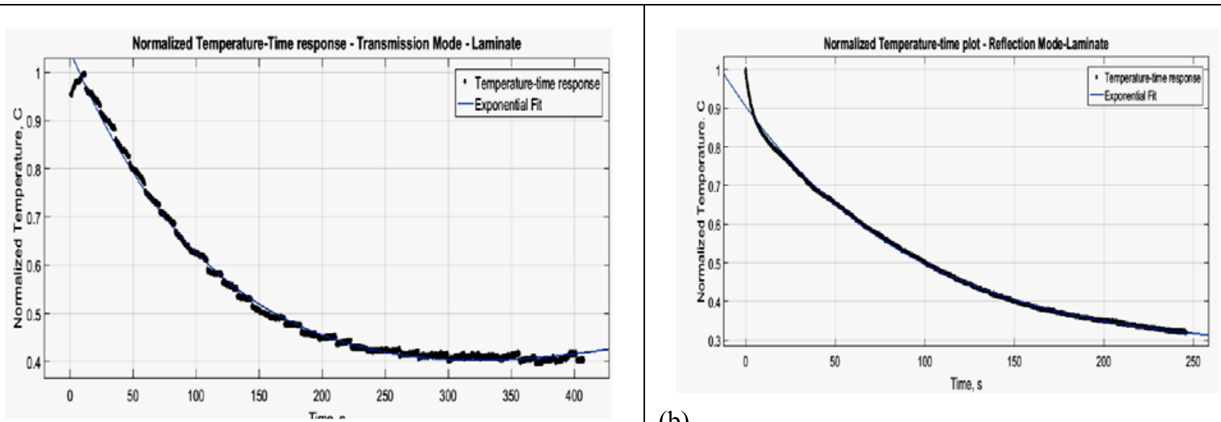


Fig. 7 – Cooling response of Fiber Mats and Laminate in Transmission and Reflection Mode

Table 2 – Double Exponential Constants (as per Eqn. 1) for the cooling response of fiber mats

Material	a	b	c	d	R^2
Transmission Mode					
Carbon Fiber Mat	0.7434	-0.06247	0.2561	-0.000368	0.9988
Natural Fiber (Flax) Mat	0.6475	-0.07185	0.337	-0.0008379	0.996
Hybrid Laminate	0.8549	-0.007558	0.1897	0.001698	0.9957
Reflection Mode					
Carbon Fiber Mat	0.7931	-0.0575	0.2135	0.0008653	0.9998
Natural Fiber (Flax) Mat	0.6455	-0.07459	0.3448	-0.0009871	0.9974
Hybrid Laminate	0.6624	-0.00985	0.2428	0.0002869	0.9976

The cooling response of hybrid laminate alone is shown in Figure 8 for clarity of secondary heating and subsequent cooling response of laminate. It is noted that the temperature increases by a small amount in the transmission mode (up to a time period of about 8 seconds) and thereafter cools (Fig. 8a), whereas the slope of the cooling response in reflection mode is steep up to the time period of 8 seconds (Fig. 8b). The increase in temperature for the initial few seconds in transmission mode could be due to the initial heat transfer from the rear surface of specimen to the front surface by conduction mode of heat transfer and the same is captured by the front face of the infrared camera. Once the front surface temperature has stabilized, there is heat loss from the front and rear surface of the specimen. Possibly the heat transfer from the rear surface is the reason for the second exponential response of the specimen in the temperature-time response. In all subsequent experiments, cooling responses were monitored both in Transmission mode as well as in Reflection mode, but for the sake of brevity, transmission mode results alone will be presented in the later parts of this paper. In case of impacted specimens, there are two options: to have the impacted side facing the camera (or) have it facing behind the camera.

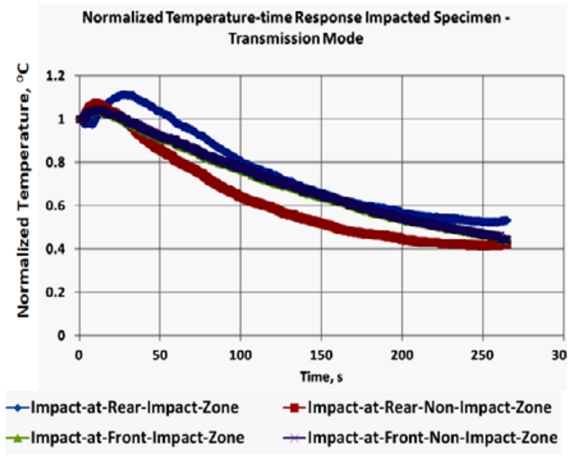


(a) (b)

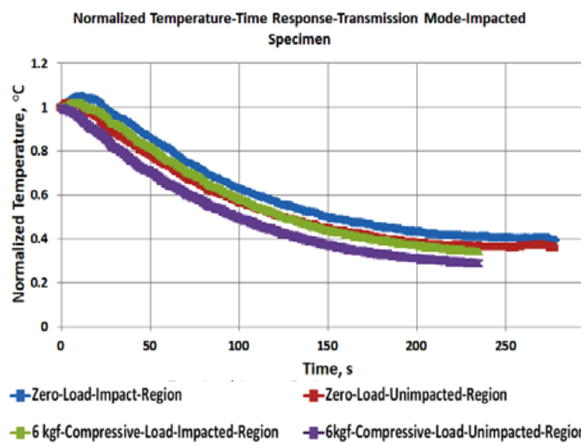
Figure 8- (a) Cooling response of Hybrid natural fiber laminate in pristine state in transmission mode and (b) in reflection mode

3.2 Impacted and Fatigue-damaged Sample

Figure 9a presents the normalized cooling response comparison under Transmission mode (rear heating) between the impacted region and non-impacted region of a 10 J impacted specimen. The impacted region was kept either in front of the IR camera or on the rear side of the IR camera. It is noted that the difference between impacted and non-impacted region can be seen clearly when the impacted region is kept on the rear side of the specimen. A time delay was observed for the peak temperature to be attained in the impacted region and this also results in a shift along the time axis in the cooling response as a function of time. The increase in magnitude of peak temperature and delayed cooling response could be due to the trapping of heat inside the impact region which gets released after a time delay during cooling response. Figure 9b presents the normalized cooling response for the case of specimen under zero load conditions and with mild compressive load (6 kgf compressive loads). It can be noted that the application of compressive load did not significantly alter the cooling response to aid damage detection. Perhaps, an application of a mild tensile load could have resulted in change in cooling response, as was found in our earlier studies (Prakash and Sudevan, 2016).



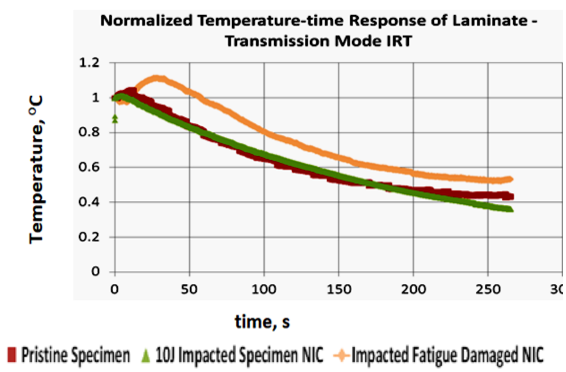
a)



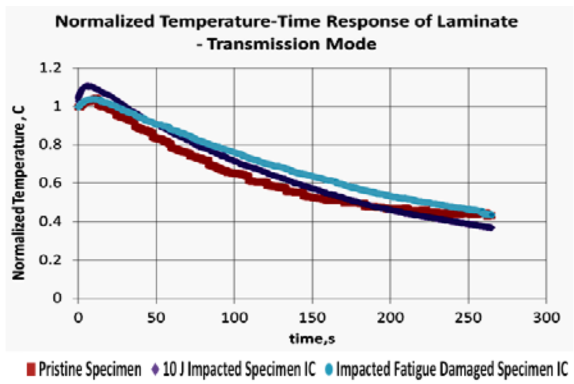
b)

Fig. 9 – a) Normalized temperature-time response for the impacted zone and unimpacted zone for a hybrid natural fiber laminate with impact either in fronr face or in the rear face, b) the effect of mild compressive force application on the cooling response of the laminate.

Figure 10a presents the cooling response in the transmission mode for a pristine, 10 J impacted laminate and 5 J impacted and subsequently fatigue cycled laminate. The impact damaged side was kept close to the heating source (i.e. impact side was not facing the IR camera). As seen in the figure, there is an initial heating in the specimen in transmission mode before cooling starts. The extent of time it took for heating from initial condition (also termed as time delay for cooling response) was higher in case of impact damaged and fatigue cycled specimen. This could be because of extensive de-lamination that had taken place in the fatigue damaged specimen compared to impacted specimen. Figure 10b presents the cooling response for the same set of specimens where the impact side was facing the IR camera. The time delay for the commencement of cooling response in this case was much less compared to the impact side not facing the camera.



a)



b)

Fig. 10 – Normalized temperature-time response for the unimpacted (pristine) specimen, 5 J impacted and fatigue damaged specimen and 10 J impacted hybrid laminate specimen – a) impact region at the rear side of camera and b) impact region in the front face of the camera.

It would imply that it would be appropriate to use impact side not facing the camera (i.e. rear side) and heat the specimen in transmission mode (i.e. from rear side) to obtain clear distinction in terms of cooling response for damaged FRP specimens. The exponential constants in both these cases provide a confirmation of the same.

Further work is in progress to correlate the defect (location and size) using X-ray computed tomography and thermographic response of the material. It is also proposed to numerically model the heat flow problem to understand the cooling response in the presence of delamination. Possibly experiments with insulated rear side of the specimen with heating from the front face (reflection mode) would help to understand the extent of heat transfer from the front and rear surfaces.

4. Summary and Conclusion

This paper presented the results of an experimental work concerning the cooling response of hybrid natural fiber laminate subjected to impact damage as well as post-impact fatigue damage. The cooling response was monitored using active infrared thermography technique with active heating carried out either in the transmission mode or in the reflection mode. In addition, the thermal response of bare Carbon fiber mat and Flax fiber mat is also characterized. Based on this study, it can be concluded that, in general, transmission mode of active thermography provides a clear indication about the presence of defects compared to reflection mode. In case of impact damaged specimens, placing the damage in the rear-side and heating from rear-side provides a clear indication of damage presence. The cooling response is best described by a double exponential response, which presents the information regarding heat transfer from the heating side as well as heat transfer from the other surface. Use of mild compressive load in case of a defective laminate did not improve the defect tracking ability through the active thermography technique

5. Acknowledgments

This work was carried out as part of the Master's degree dissertation work of the second author from TVS Motor Co. Ltd - Hosur, Tamil Nadu, India.

6. References

ASTM Annual Book of Standards, Volume 15.03, 2015, ASTM, West Conshohocken, PA, USA

Bagavathiappan, S., Lahiri, B. B., Saravanan, T., John Philip, Jayakumar, T., 2013, "Infrared thermography for condition monitoring – A review", Infrared Physics & Technology, 60 (2013) 35–55

Carosena, M., Giovanni, M. C., 2010, "Impact damage in GFRP: new insights with infrared thermography", Composites: Part A, Vol 41, pp 1839-47.

Chrysafi, A. P., Athanasopoulos, N., Siakavellas, N. J., 2017 "Damage detection on composite materials with active thermography and digital image processing", International Journal of Thermal Sciences, 116 (2017) 242-253

Harizi, W., Chaki, S., Bourse, G., and Ourak, M., 2014, "Mechanical damage assessment of Polymer-Matrix Composites using active infrared thermography", Composites: Part B, Vol. 66 (2014), 204-209.

Maldague, X., 2001, Theory and Practice of Infrared Technology for Nondestructive Testing, 1/e, John Wiley and Sons, New York,2001.

Mohamed Muneer, K. M., Prakash, Raghu V., and Krishnan Balasubramaniam, 2009, "Thermo-mechanical Studies in Glass/Epoxy Composite Specimen during Tensile Loading", World Academy of Science, Engineering and Technology, 3 (2009), 08-26.

Prakash, R. V., Sudevan, D., 2016, "Post-impact Thermo-mechanical response of Woven mat composites subjected to tensile loading", ASME International Mechanical Engineering Congress and Exposition, Volume 14: Emerging Technologies; Materials: Genetics to Structures; Safety Engineering and Risk Analysis: V014T11A003, doi:10.1115/IMECE2016-66343

Wong, B. S., Tui, C. G., Bai, W., Tan, P. H., Low, B. S., and Tan, K. S., 1999, "Thermographic Evaluation of defects in composite materials: Insight", Non Destructive Testing and Condition Monitoring, 1999, 41 (8): 504-9.