Journal of Mechanical Engineering and Sciences
ISSN (Print): 2289-4659; e-ISSN: 2231-8380
Volume 11, Issue 2, pp. 2755-2769, June 2017

DOI: https://doi.org/10.15282/jmes.11.2.2017.16.0250

Thermal phenomenon of glass fibre composite under tensile static and fatigue loading

Jefri Bale[1*], Emmanuel Valot[2], Olivier Polit[2], Claude Bathias[2], Martine Monin[3] and Tresna Soemardi[4]

[1]Department of Mechanical Engineering, Universitas Nusa Cendana,
85001 Kupang, Indonesia
[*]Email: jefri_bale@staf.undana.ac.id ; jefri_bale@yahoo.com
Phone: +628113830900; Fax: +62380881557
[2] Laboratoire Energétique Mécanique Electromagnétisme (LEME),
Université Paris Ouest, Ville d'Avray, 92410, France
[3]Department of Material Characterization and Validation,
PSA Peugeot Citroën, Garenne Colombes (La), 92250, France
[4]Laboratory of Mechanical & Biomechanical Design,
Department of Mechanical Engineering, Universitas Indonesia, 16424 Depok, Indonesia

ABSTRACT

The aim of this study is to understand the thermal phenomenon of unidirectional Glass Fibre Reinforced Polymer (GFRP) composite under static and fatigue (tensile) loads. This study used a rectangular shaped GFRP composite and consisted of specimens with and without a circular notch. Under static test, the constant displacement rate was applied. Under fatigue test, frequency and amplitude of stress were explored to study the fatigue properties and damage evolution of the specimen. Thermography was used in real-time observation to obtain the temperature profile on the external surface of the specimens. This experimental method showed that the thermal phenomenon gave a good detection of the damage appearance of GFRP material under static loading. Moreover, thermal phenomenon gave a good correlation with the energy dissipation under fatigue loading. Thermal phenomenon successfully determined the high cycle fatigue strength of GFRP composite. This study concluded that thermal phenomenon observed by Infra-Red (IR) camera has successfully demonstrated the damage propagation and the strength behaviour of GFRP composite due to tensile loading in both static and fatigue conditions. The IR camera can then be used to determine the damage evolution and the strength prediction based on the thermal phenomenon on the external surface of the GFRP composite.

Keywords: Thermography; GFRP; tensile; static loading; fatigue loading.

INTRODUCTION

Early study about fatigue failure development of fibre reinforced plastic composite was conducted by analysing the stiffness reduction and failure propagation which was divided into three stages [1, 2]. Other perspective of fatigue damage behaviour between composite and metals was explained by Bathias [3]. In composite, fatigue damage is not related to plasticity, which has a very different behaviour compared to metals where its fatigue damage is strongly related to cyclic plasticity. At the mesoscopic level, the fatigue damage is multidirectional and the damage zone, much larger than the plastic zone, is related to the complex morphology of the fracture. Due to the complex behaviour of composite, several studies have been undertaken to gain more understanding of fatigue failure behaviour in GFRP experimentally. Glass fibres are mostly used as reinforcement for polymeric matrix composites. Their main advantages are low cost, high tensile strength, high chemical resistance, and insulating properties [4]. who studied about the fatigue behaviour of continuous glass fibre reinforced plastics to evaluate the micromechanisms that occurred during fatigue and how damage accumulated throughout the sample lifetime found that damage accumulation during fatigue had a stiffness reduction patern characterised by matrix cracking, delamination and fibre failure where matrix cracking was identified as the major factor causing reduction in the stiffness of laminates [4-12]. These cracks were seen to have penetrated the fibre bundles before failure, and propagated by debonding of the fibre/matrix interfaces. The observation using SEM showed that both the fibres and the resins failed in a brittle manner. The fatigue life performance, stiffness degradation and micro mechanisms have been investigated for glass fibre reinforced polypropylene. From microscopic observations, it could be concluded that the better fatigue resistance of glass fibre reinforced plastic can be attributed to the greater interfacial strength and the resistance to debond propagation [13]. The effects of lay-up design and the rise of the temperature of the composite specimens on fatigue perfomance were investigated [14-17]. The results showed that the fatigue strength qas strongly influenced by the layer design and the temperature rise on the surface of the specimens when reaching a maximum value at failure or the damage parameter E presented a nearly linear relationship with the rise of temperature. Under static and fatigue loading, the material properties of fibre orientation can give significant effects on the strength of fibre glass reinforced composites [18-22]. Other factors of loading rate, mean stress, load frequency, crack density, thickness and fibre volume can also affect the behaviour of fibre composites under fatigue loading [23-25].

In order to avoid large safety factors from being applied, damage propagation during the component lifetime must be monitored. So, it is possible to replace components before the final failure. Undergoing different failure types such as matrix cracking, fibre–matrix debonding, delamination, fibre breakage should be quite evenly distributed within the entire material volume [26]. Consequently, monitoring and diagnosis of the early detection of these different forms of damage growth require the application of a contactless method in real-time operation, i.e a non-destructive method. Thermography is an experimental technique of Non-Destructive Test (NDT) that allows for the monitoring of surface while the equipment is online and running under full load. This contactless method is an excellent condition monitoring tool to assist in the reduction of maintenance costs on mechanical equipment and provide an accurate damage assessment in several industries such as the military and aerospace [27-30]. The benefit of infrared thermography in composite field is the viscosity of the matrix which is heated more than the metal. It helps find the first microscopic damage early and identify more individual degradation mechanisms, transverse cracks, interface cracks, fibre cracks, etc [22, 31, 32]. Fibrous composites are considered as very successful targets for the application of thermography due to their thermal and emissive properties [33]. The application of NDT thermography in damage analysis of fibre composite was conducted by previous authors. The development of a thermography approach based on thermal maps over a surface of a specimen to determine the fatigue limit is known as the Risitano method [34]. The authors proposed that the fatigue limit could be determined by plotting the stabilisation temperature (in a few thousand cycles) against the applied stress and finding the value of the fatigue limit as the intercept of the curve on the stress axis. In the case of composite material, friction between fibre and matrix, the different damage mechanisms of fibre breaking, fibre-matrix debonding, matrix cracking, etc, were associated to the visco-elasto-plastic behaviour of matrix. generating a significant amount of heat which was converted in a significant temperature increase for low and high stress levels [35, 36]. Compared to the traditional Wöhler S-N curve, the Risitano method does not need to use a large number of specimens and it has a very efficient albeit time-consuming procedure, which consequently offers a considerable saving in cost [36].

The investigation on the damage mechanisms of composite material with thermography analysis under fatigue loading was also conducted by Toubal et.al [37]. The evolution of the temperature consisted of three stages. In the first part, the variation in the temperature was due to frictions (fibres/fibres and fibres/matrix) and the damages which started and were propagated during the fatigue test. In the second part, the temperature reached a balance due to the saturation in the damage, which then led to a sudden increase of temperature corresponding to the rupture. Studies were also performed to investigate the evolution of composite damage under static tensile tests by using the thermography method with different fibre orientations of E-glass respective to the loading direction. These studies showed that the thermography method can locate the failure due to the rupture of fibre by detecting the hottest point of the specimen and it is very useful for early diagnostics of structures under real conditions [38, 39]. Colombo et.al [40] in their study about mechanical characteristics of GFRP by thermography, categorised thermal behaviour of fibre composite into elastic behaviour, non-elastic behaviour and final breakage. In elastic period, temperature showed a decreasing trend since the input energy is stored and absorbed by composite material. In non-elastic behaviour and final breakage period, the temperature increased suddenly and non-linearly due to the energy released that caused the final failure of the composite specimen. Recently, several authors studied about the thermomechanical behaviour of fibre composite in terms of damage behaviour [41-47]. The results indicated that temperature response was related to the physical damages of fibre composite. Considering the relationship between physical damages and temperature response, it is therefore important to provide an experimental analysis method with thermography and conventional approach for damage behaviour of fibre reinforced composites; a particular category is the glass fibre reinforced polymer which is the object of this work. This kind of composite has long unidirectional fibre glass as reinforcement and a polymer matrix. The objective of this study is to have the thermal phenomenon from NDT thermography observation of glass fibre/epoxy composite during the tensile static and fatigue loading.

METHODS AND MATERIALS

This section describes the materials used and experimental prosedure to understand the mechanical and damage behaviour of GFRP composite by determining various mechanical properties testing and NDT observation.

Material

The material used for the study was the unidirectional glass fibre reinforced polymer composite. In order to facilitate the wetting of fibres, epoxy resin was selected. The composite laminate consisted of 10 layers of unidirectional glass fibre (0.24 mm thickness of layer) that contained 60% of nominal fibre volume throughout the thickness as the reinforcement and epoxy resin was employed as the matrix. The orientation of fibre was 97% perpendicular and 3% parallel against the tensile loading direction. The specimens were rectangular specimen with dimensions of 200 mm x 25 mm x 4 mm and bonded with glass/epoxy tabs of 50 mm. There were two types of GFRP composite specimen used in this study as seen in Figure 1.

(a) Rectangular specimen without hole

(b) Rectangular specimen with 5 mm in diameter of hole at its center

Figure 1. GFRP composite specimens.

Experimental

This experiment was divided into two stages.Tensile static testing on GFRP composite without hole and observed with IR camera.Tensile fatigue testing on GFRP composite with hole and observed with IR camera. Test was carried out with a servo-hydraulic testing machine, the INSTRON Machine 8501 with a capacity of 100 kN. The machine was equipped with a standard load cell and mechanical grips. The global longitudinal strain of the specimen was measured based on the crosshead displacement and the local longitudinal strain was measured using an electric uni-axial strain gauge with a gauge length of 5 mm attached to a specific position of the specimen surface. Static tensile tests were performed under a constant cross-head speed of 1 mm/min. Fatigue tests were performed under load control and at a stress ratio, R, equal to 0.1, i.e., tension loading and constant 3 Hz of frequency (ASTM D 3479). Various maximum stresses were used for the fatigue tests. The test specimens were allowed to cycle until failure occurred or until a predetermined number of cycles was reached. Moreover, rapid test of fatigue loading with same parameters was also conducted to determine the high cycle fatigue strength and fatigue life utilising IR camera that referred to the Risitano's method. This rapid fatigue test used one specimen for each test of maximum stress until reaching 10000 cycles. Once the 10000 cycles were reached, the test was stopped, then continued with the next maximum stress. In following the temperature changes on the specimen surface, an Infra-Red camera of FLIR A325sc was used for the tests. Control of the camera and data recording were done with the FLIR R&D software. The FLIR R&D software was able to measure temperature change in various shapes and dimensions such as spots, lines, and area as well as when using various palettes of colours and shades. The camera resolution was 320 x 240 pixels with a detector type of uncooled microbolometer. Camera spectral range was 7.5 to 13 µm, whereas the temperature range was from -20°C to +120°C with ± 2°C or ± 2% accuracy of reading. The camera was provided with the automatic correction of emissivity and atmospheric transmission based on distance, atmospheric and relative humidity. IR camera was placed approximately 30 cm of fix distance in front of the specimen surface; therefore, it was possible to obtain full-field thermal maps of the specimens during the tests. This thermography observation did not use an external heat source. In this case, the thermal images acquisition were set at 30 Hz. Figure 2 shows the experimental set up.

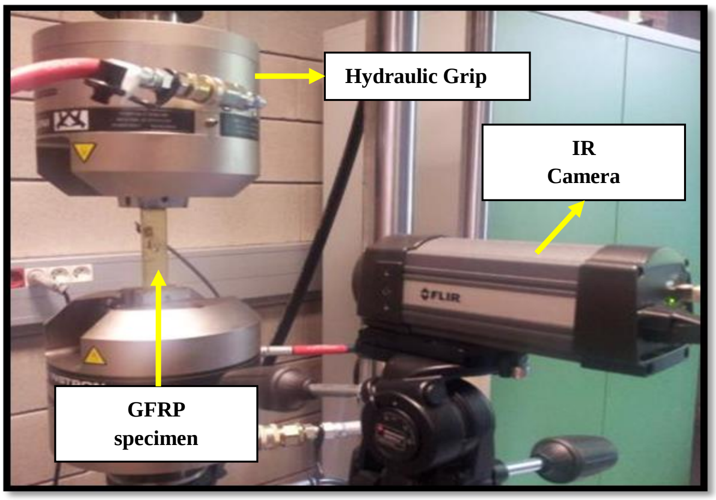


Figure 2. Experimental set up.

RESULTS AND DISCUSSION

Static Results

During the test, specimen surface was also observed by the IR camera to follow the evolution of temperature. Figure 3 shows the thermal images up to the final failure. In order to follow the evolution of temperature during the test, the area profile was used at several areas of specimen surface to study all changes of the maximum temperature until the final failure, as seen in Figure 4.

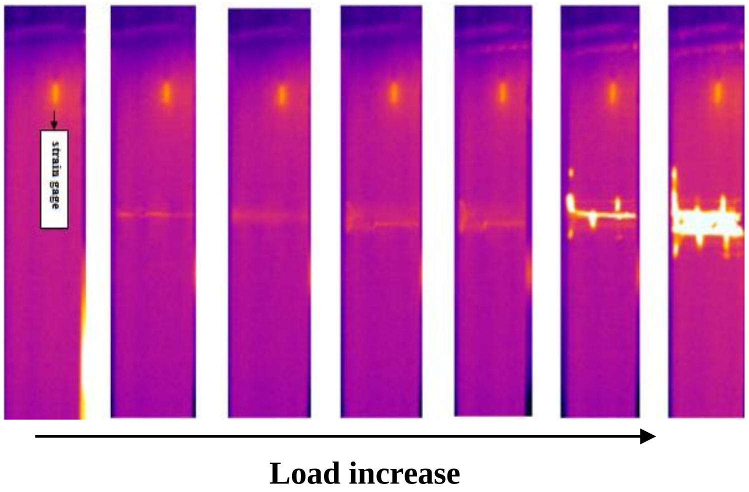
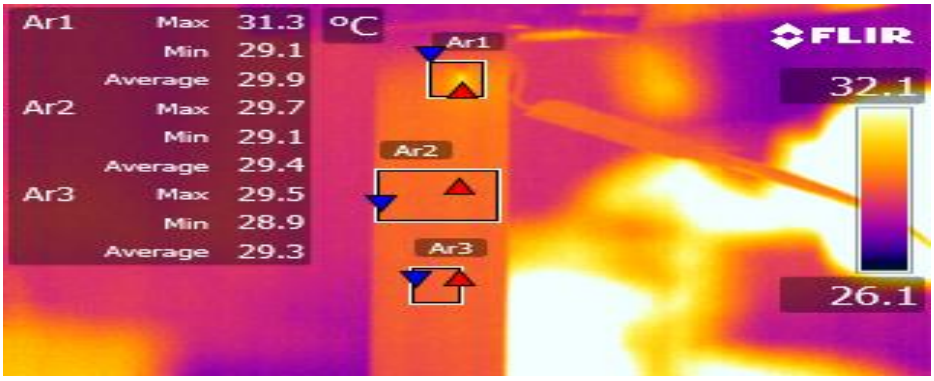
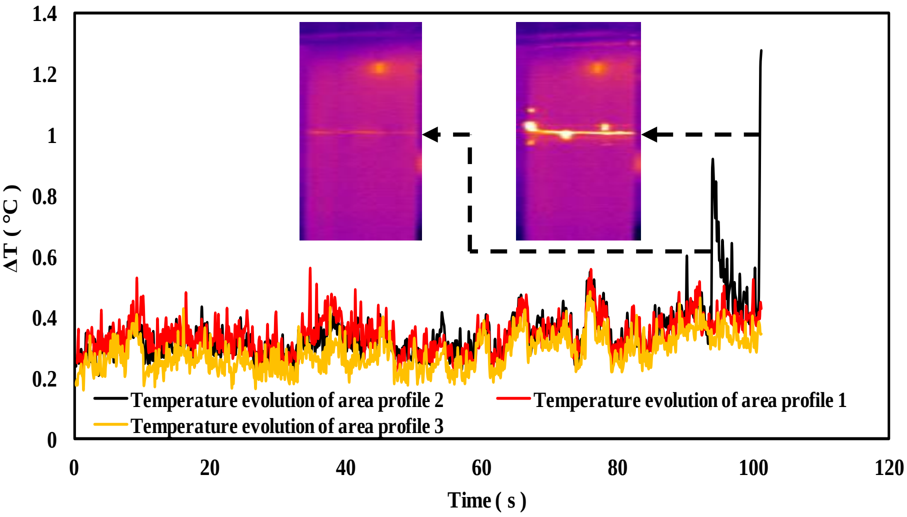


Figure 3. Thermal images of GFRP composite without hole.

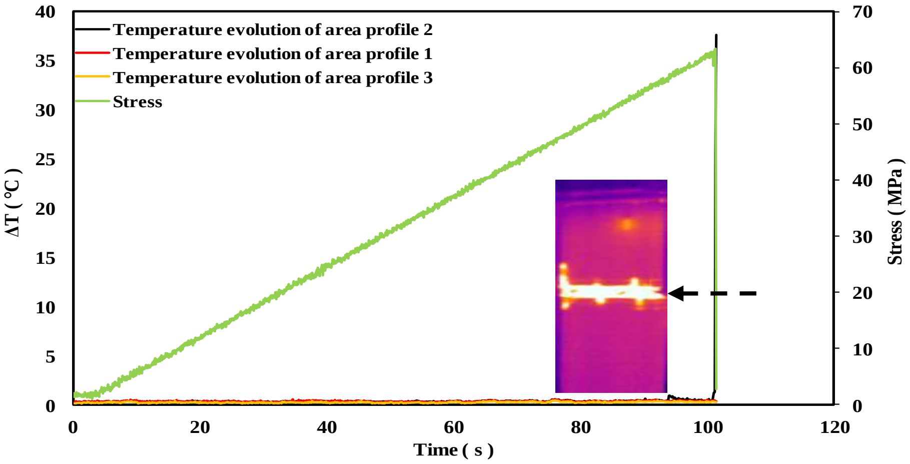
From Figure 4 above, all the temperature surfaces (ΔT) detected by the IR camera varied between 0.2 – 1.3 °C. From the comparison between thermal images and temperature change during the test before the final failure, ΔT above 0.6 °C was clearly shown by several peaks of temperature profile related to the presence of macro damage. When damage occurred, it represented the energy which was gradually released. The energy that has been absorbed Was sufficient to create macro-cracks, enlarging the pre-existent ones, and also to create new inner and surface cracks. The heat generated from the energy release was then detected by the IR camera that showed an increase in temperature in the area of damage [41].



a) Temperature image observation / profile area



b) Before final failure



c) Until final failure

Figure 4. Temperature evolution of GFRP composite without hole.

Each of the peak of temperature indicated different types of initial macro damage. We found that ΔT ≈ 0.9 °C was directly associated with the appearance of macro matrix cracking and ΔT ≈ 1.3 °C was related with the appearance of interfacial failure or splitting. The higher temperature of splitting was in fact due to absorbing more energy of damage [48]. From the temperature evolution during the tensile test, the presence of macro damage indicated the area of final failure which was concentrated in the region of the failure area. In sum, the initial macro damage provoked the occurrence of catastrophic or final failure of the specimen that induced the highest peak of temperature at ΔT ≈ 37 °C.

Using the information of strain propagation that occurred when this initial macro damage occurred, thermography and strain gage confirmed the presence of initial macro damage which happened before the catastrophic or final failure of the specimen as seen in Figure 5. The damage appearances were shown with a small discontinuity in the strain curve and also higher increase of temperature at the same time. It can be noted that the combination of this exprimental method of thermography observation by IR camera and strain propagation by strain gage under static tensile loading can give good local information and excellent correlation with local strain from the strain gage about the early damage appearance and propagation, as well as damage type and damage location until a rupture based on the temperature profile and strain value of GFRP composite [42].

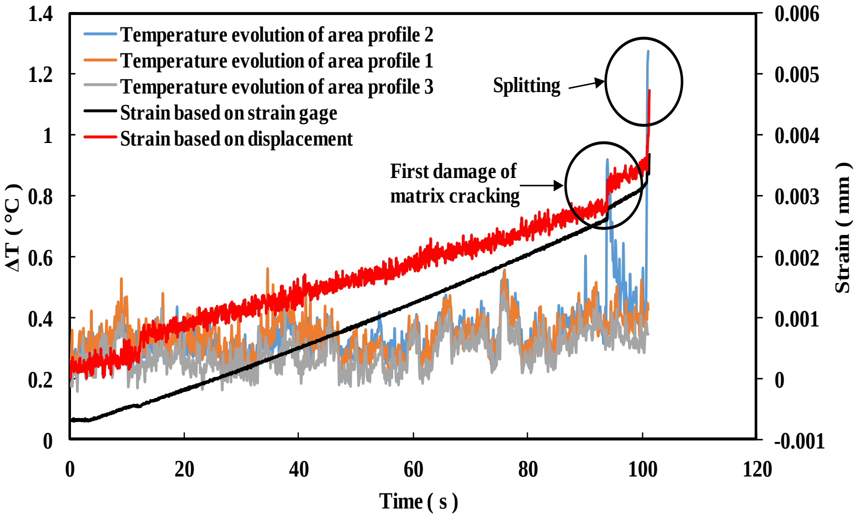


Figure 5. Strain and temperature evolution of GFRP composite without hole

Fatigue Results

During the fatigue tests, IR camera was used to follow the temperature changes on the specimen surface. Figure 6 represents the temperature changes at the edge of the hole during the fatigue test with 65% of UTS. From Figure 6, all the temperature surface (ΔT) detected by IR camera varied between 0.2 – 39 °C. From the comparison between thermal images and temperature change during the test before the final failure, ΔT ≈ 0.9 °C which was clearly shown by the peak of temperature profile related to the presence of the first macro damage of matrix cracking. After that, the temperature was shown to reach a stable period of the increase trend [37]. The temperature profile had a gradual increase trend with the slope ≈ 0.001 °C/cycle until around 200 cycles and continued to increase with a slightly higher slope ≈ 0.002 °C/cycle. The temperature increased until around 800 cycles. The trend of temperature experienced a significant increase at the final period.

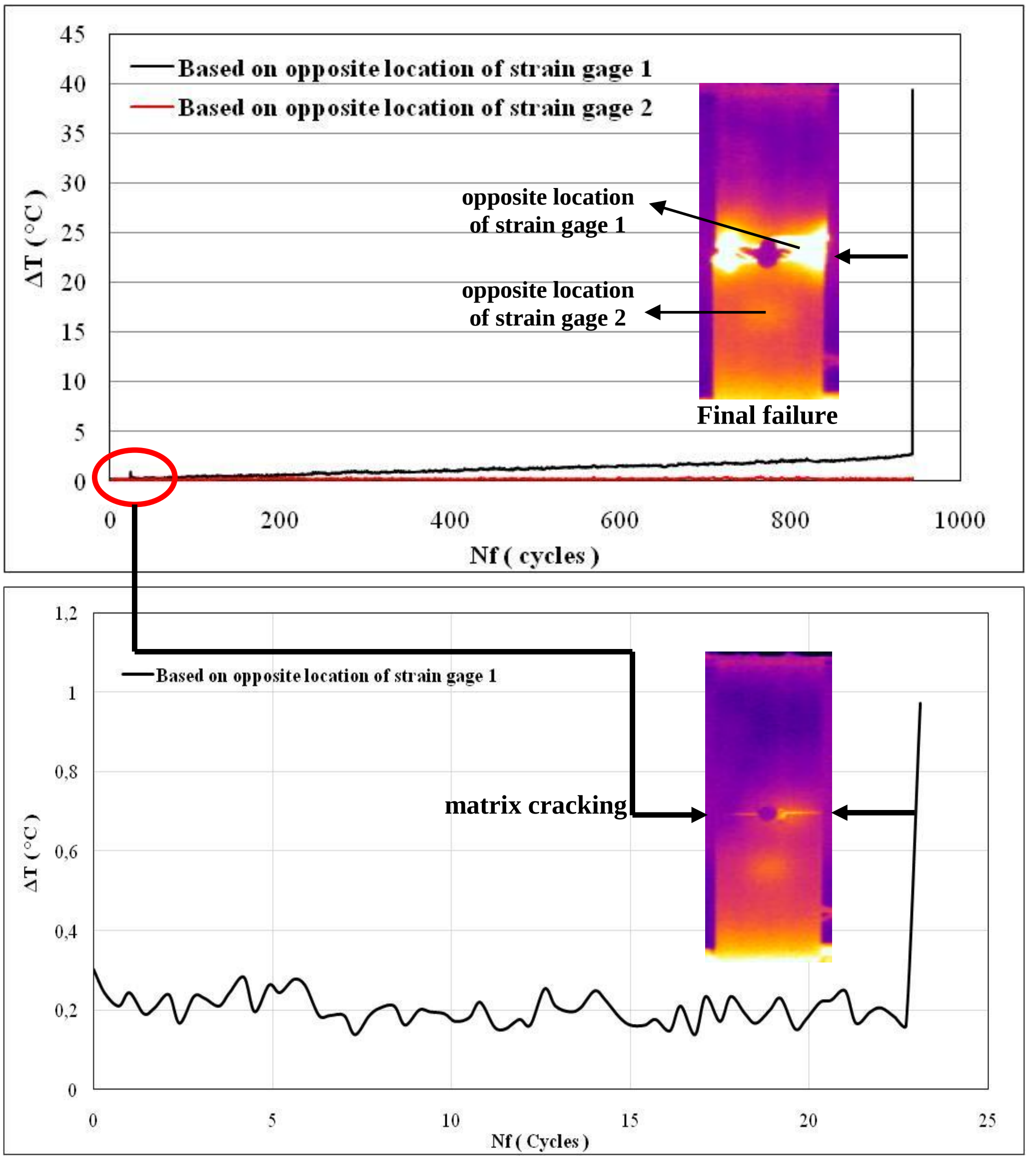


Figure 6. Evolution of surface temperature of GFRP composite.

With three times of higher slope, at 0.006 ^{o}C/cycle until reaching the rupture, ΔT suddenly increased and reached the highest $\Delta T \approx 39$ ^{o}C at one cycle. The temperature evolution was then compared with the damage evolution as seen in Figure 7. From the temperature and damage evolution during the tensile fatigue test (Figure 6 and Figure 7), the presence of damage was indicated by temperature change on the specimen surface during the test that existed and concentrated at the hole. Meanwhile, the temperature evolution at other areas of specimen surface that were far from the hole did not show an increase of temperature or relative to have the same temperature from the beginning of the test until the rupture of the specimen [47]. When damage occured, it represented the energy which was gradually released. The heat generated from the energy release was then detected by the IR camera that showed an increase in temperature in the area of damage. The evolution of the temperature can be categorised in four stages. In the first part, the initial increase of temperature was possibly due to the micro cracking in matrix [47]. In the second part, a sudden increase in temperature was caused by the first appearance of macro matrix cracking. After that, the temperature reached a slowly increasing trend due to the stable growth of matrix cracking as part of the third stage [47]. The final part, a significant increase trend of temperature could be due to fibre/matrix debonding as the interfacial failure in splitting the form and finally provoking the occurrence of fibre fracture which was dealing with the rupture of the specimen [47]. It can be noted that the combination of this exprimental method of thermography observation by IR camera and strain propagation by strain gage can give a good confirmation with local strain from gage detection on the damage appearance and evolution of GFRP composite with holed specimen under tensile fatigue loading.

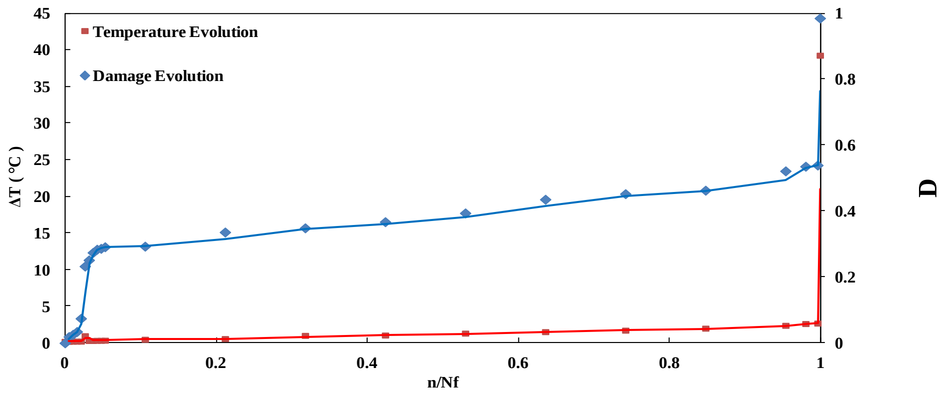


Figure 7. Temperature and damage evolution of GFRP composite with 60% of UTS.

Rapid Analysis of Fatigue Strength

The purpose of this analysis is to determine the fatigue strength based on experimental results by means of IR camera and energy dissipated in a unit volume of material. Thermographic approach that relies on the use of an IR camera, as originally called the Risitano method has shown to be useful for the determination of high cycle fatigue strength (HCFS) of composite material [34, 48, 49]. The main advantage of this method provides a rapid determination of HCFS that is a very efficient time-consuming procedure and provides substantial saving of fatigue test costs [49-51]. This test was conducted using GFRP composite with a holed specimen and under the loading frequency of 3Hz and R = 0.1. Using the IR camera, a temperature profile for specimen surface was used as a function of the number of cycles for a test with different load levels. The fatigue tests were conducted until 10000 cycles to have a stable or a plateau profile of temperature evolution as is seen in Figure 8.

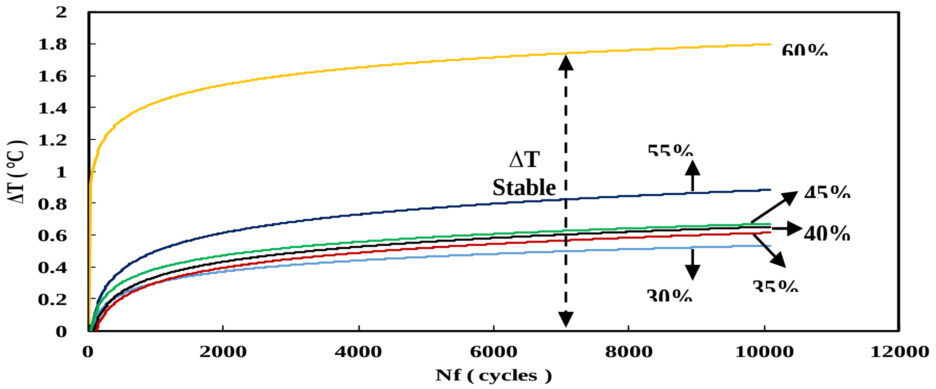


Figure 8. Temperature profile of GFRP composite for each load level.

According to the Risitano method, the high cycle fatigue strength of material can be determined from the intersection of temperature profile ΔT_{stable} of different stress levels obtained by separately fitting the experimental data for low and high stress amplitudes on the x -axis, respectively (for stress levels below and above the expected fatigue limit). From Figure 8, after 50% of load level, there was a significant or higher increase of temperature compared to under 50% of load level. This load level was then used to categorise the stress level of below and above, which showed the characteristic of bilinear profile used for this method. Figure 9 shows how the HCFS was determined using a graphical procedure based on the thermography method. It was noted that this method is a true in situ measurement technique. Thermography is a measurement technique which provides the information (image, profile, distribution) of the temperature on the surface of the examined object in real time [36, 37, 49]. The deformation of solid materials is almost always accompanied by releases of heat. When the material becomes deformed or is damaged and fissured, a part of energy is necessary and the propagation of the damage is transformed in an irreversible way into heat [52].

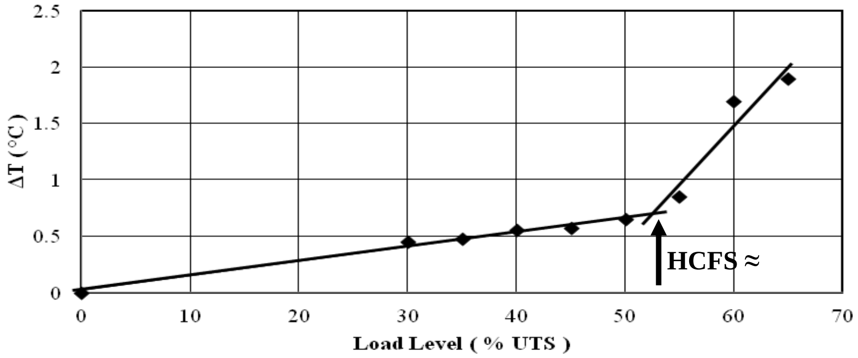
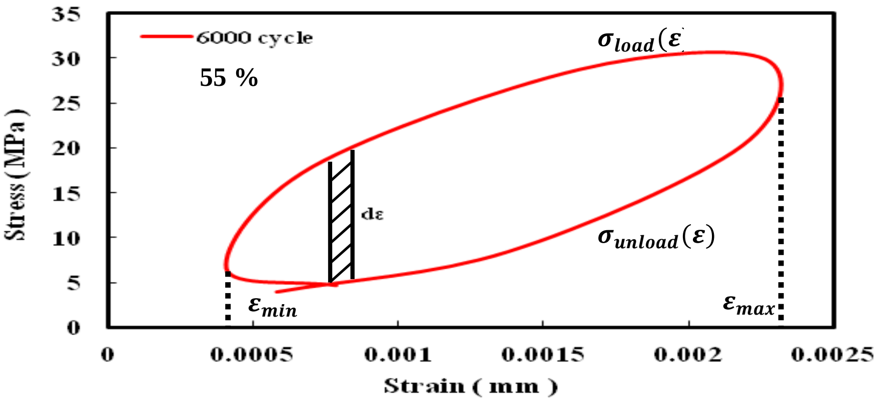


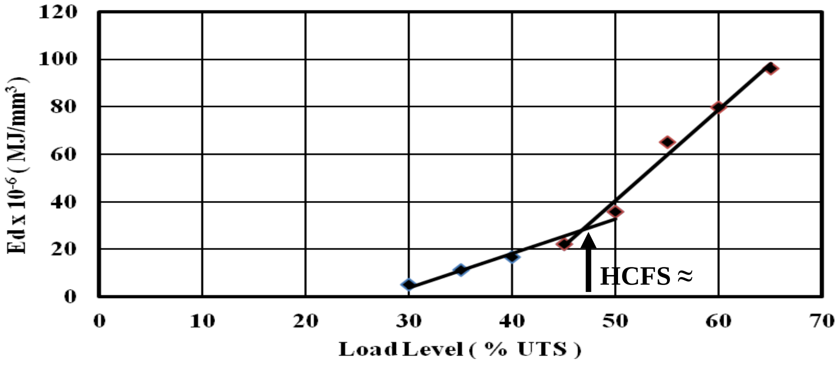
Figure 9. HCFS of GFRP composite by thermography method.

Figure 9 confirms the HCFS of 53 % of UTS, and it can be noted that HCFS was determined by the thermography approach successfully applied for the GFRP composite material. Furthermore, an investigation for a quantitative characterisation based on intrinsic energy dissipation was presented to validate the accuracy of the thermography approach. The energy dissipation was identified as the area enclosed by a hysteresis loop for a particular cycle according to the cycle in the ΔT_{stable} period, as illustrated in Figure 10(a). Next, a plot of energy dissipation per unit volume as a function of the load was created to determine HCFS as seen in Figure 10(b).

The HCFS of ≈ 48% of UTS obtained by energy dissipation in Figure 10 was found to not differ significantly to that obtained using the thermography method in Figure 9. From the comparison result of HCFS based on thermography and HCFS based on energy dissipation, the thermography method showed good correlation of following the damage behaviour with the conventional approach, which is a key finding to study the damage behaviour of unidirectional GFRP composite. Furthermore, a plot in Figure 11 was established between energy dissipation per unit volume and ΔT_{stable} for each load level of fatigue test to obtain the relationship between thermal dissipated detected by IR camera and energy dissipated from the hysteresis heating. The relation between stabilisation temperature profile and the energy dissipation during fatigue test can be approximated by a linear function with a data correlation factor, R^2 close to 1. It can be said that the increasing of temperature detected by the IR camera on the specimen surface as a result of thermal dissipated was in fact due to energy dissipation of the material. The main mechanisms causing energy dissipation could be attributed to the damage appearance of matrix cracking, interface cracking/friction among others, and fibre fracture [37, 50]. Or in other words, thermography method exists where the damage is characterised by the temperature increase during fatigue testing due to the hysteresis heating [36].



a. Hysteresis loop during 55% of UTS



b. Energy dissipation as a function of load level

Figure 10. Hysteresis loop and energy dissipation for GFRP composite.

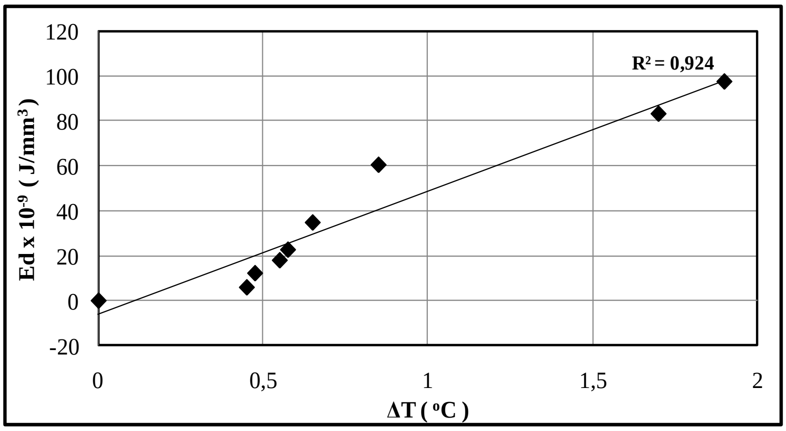


Figure 11. Energy dissipation versus ΔT_{stable} of GFRP composite for different load level.

CONCLUSIONS

This paper has presented the experimental results of thermal phenomenon based on the application of the previously established rapid thermographic technique to determine the damage behaviour under static and fatigue tensile loading and high cycle fatigue strength of unidirectional glass fibre reinforced polymer composite. The findings indicated that the thermal phenomenon observed by the infra-red camera gave a good local information about early damage appearance and propagation, as well as damage type and damage location until rupture based on temperature profile of GFRP composite under tensile static loading. Under tensile fatigue loading, the damage appearance and evolution of GFRP composite were successfully followed by the thermal phenomenon. In terms of fatigue strength, thermal phenomenon can be successfully used to determine the HCFS of GFRP composite. Therefore, it can be concluded that thermal phenomenon is effective for characterisation of mechanical strength and identification of damage behaviour of GFRP composite under static and fatigue conditions. Further studies are recommended on the combination of several non-destructive testing methods to obtain more correlation data of GFRP composite behaviour in terms of mechanical strength and damage mechanisms.

ACKNOWLEDGMENTS

This work is funded by PSA Peugeot Citroën in France and LEME laboratory of University of Paris Ouest Nanterre-La Défense as a collaboration project number 01564_11_00380 *confidentiel* PSA / Paris 10. Thanks to the Ministry of Research, Technology and Higher Education of the Republic of Indonesia for the financial support under DDIP Program.

REFERENCES

[1] Schulte K. Damage monitoring in polymer matrix structures. Le Journal de Physique IV. 1993;3:C7-1629-C7-36.

[2] Talreja R. Damage and fatigue in composites–a personal account. Composites Science and Technology. 2008;68:2585-91.

[3] Bathias C. An engineering point of view about fatigue of polymer matrix composite materials. International Journal of Fatigue. 2006;28:1094-9.

[4] Haque MM, Hasan M. Mechanical properties of betel nut and glass fibre reinforced hybrid polyethylene composites. International Journal of Automotive & Mechanical Engineering. 2016;13(3): 3763-72.

[5] Dyer K, Isaac D. Fatigue behaviour of continuous glass fibre reinforced composites. Composites Part B: Engineering. 1998;29:725-33.

[6] Toumi RB, Renard J, Monin M, Nimdum P. Fatigue damage modelling of continuous E-glass fibre/epoxy composite. Procedia Engineering. 2013;66:723-36.

[7] Jollivet T, Peyrac C, Lefebvre F. Damage of composite materials. Procedia Engineering. 2013;66:746-58.

[8] Belmonte E, De Monte M, Hoffmann C-J, Quaresimin M. Damage initiation and evolution in short fiber reinforced polyamide under fatigue loading: Influence of fiber volume fraction. Composites Part B: Engineering. 2017;113:331-41.

[9] Maragoni L, Carraro P, Peron M, Quaresimin M. Fatigue behaviour of glass/epoxy laminates in the presence of voids. International Journal of Fatigue. 2017;95:18-28.
[10] Abdul Majid M, Daud R, Afendi M, Amin N, Cheng E, Gibson A. Stress-strain response modelling of glass fibre reinforced epoxy composite pipes under multiaxial loadings. Journal of Mechanical Engineering and Sciences. 2014;6:916-28.
[11] Roundi W, El Mahi A, El Gharad A, Rebière J-L. Experimental and numerical investigation of the effects of stacking sequence and stress ratio on fatigue damage of glass/epoxy composites. Composites Part B: Engineering. 2017;109:64-71.
[12] Gamstedt EK, Berglund LA, Peijs T. Fatigue mechanisms in unidirectional glass-fibre-reinforced polypropylene. Composites Science and Technology. 1999;59:759-68.
[13] Rotem A, Nelson HG. Fatigue behavior of graphite-epoxy laminates at elevated temperatures. Fatigue of Fibrous Composite Materials: ASTM International; 1981.
[14] Curtis P. A review of the fatigue of composite materials. RAE Technical Report TR87031; RAE (now DRA): Farnborough, UK. 1987.
[15] Harris B, Reiter H, Adam T, Dickson R, Fernando G. Fatigue behaviour of carbon fibre reinforced plastics. Composites. 1990;21:232-42.
[16] Ferreira J, Costa J, Reis P, Richardson M. Analysis of fatigue and damage in glass-fibre-reinforced polypropylene composite materials. Composites Science and Technology. 1999;59:1461-7.
[17] Al-Alkawi HJ, Al-Fattal DS, Ali A-JH. Types of the fiber glass-mat on fatigue characteristic of composite materials at constant fiber volume fraction: Experimental determination. Al-Khawarizmi Engineering Journal. 2012;8:1-12.
[18] KA Z, RH J, SNR R, AA A, O B, MB A. Study on fatigue life and fracture behaviour of fibreglass reinforced composites. Journal of Mechanical Engineering and Sciences. 2016;10:2300-10.
[19] Mortazavian S, Fatemi A. Effects of fiber orientation and anisotropy on tensile strength and elastic modulus of short fiber reinforced polymer composites. Composites Part B: Engineering. 2015;72:116-29.
[20] Nyman T. Composite fatigue design methodology: a simplified approach. Composite structures. 1996;35:183-94.
[21] Hadzreel MAM, Aisha ISR. Effect of reinforcement alignment on the properties of polymer matrix composite. Journal of Mechanical Engineering and Sciences. 2013;4:548-54.
[22] Zakaria KA, Jimit RH, Ramli SNR, Aziz AA, Bapokutty O, Ali MB. Study on fatigue life and fracture behaviour of fibreglass reinforced composites. Journal of Mechanical Engineering and Sciences. 2016;10:2300-10.
[23] Bernasconi A, Davoli P, Basile A, Filippi A. Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6. International Journal of Fatigue. 2007;29:199-208.
[24] Tanaka K, Kitano T, Egami N. Effect of fiber orientation on fatigue crack propagation in short-fiber reinforced plastics. Engineering Fracture Mechanics. 2014;123:44-58.
[25] Gagel A, Lange D, Schulte K. On the relation between crack densities, stiffness degradation, and surface temperature distribution of tensile fatigue loaded glass-

fibre non-crimp-fabric reinforced epoxy. Composites Part A: Applied Science and Manufacturing. 2006;37:222-8.

[26] Wang X, Chung D. Fiber breakage in polymer-matrix composite during static and fatigue loading, observed by electrical resistance measurement. Journal of Materials Research. 1999;14:4224-9.

[27] Ley O, Godinez V. Non-destructive evaluation (NDE) of aerospace composites: application of infrared (IR) thermography. Non-Destructive Evaluation (NDE) of Polymer Matrix Composites: Elsevier; 2013. p. 309-36e.

[28] Suratkar A, Sajjadi A, Mitra K. Non-destructive evaluation (NDE) of composites for marine structures: detecting flaws using infrared thermography (IRT). Non-Destructive Evaluation (NDE) of Polymer Matrix Composites: Elsevier; 2013. p. 649-68e.

[29] Yang B, Huang Y, Cheng L. Defect detection and evaluation of ultrasonic infrared thermography for aerospace CFRP composites. Infrared Physics & Technology. 2013;60:166-73.

[30] International A. Standard Practice for Infrared Flash Thermography of Composite panels and Repair Patches Used in Aerospace Applications. West Conshohocken, PA: ASTM International; 2014.

[31] Khan MM, Dixit G. Erosive wear response of SiCp reinforced aluminium based metal matrix composite: Effects of test environments. Journal of Mechanical Engineering and Sciences. 2017;14:2401-14.

[32] Haris A, Tay TE, Tan VBC. Experimental analysis of composite bolted joints using digital image correlation. Journal of Mechanical Engineering and Sciences. 2017;14:2443-55.

[33] Pastuszak PD. Characterization of defects in curved composite structures using active infrared thermography. Procedia Engineering. 2016;157:325-32.

[34] La Rosa G, Risitano A. Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical components. International Journal of Fatigue. 2000;22:65-73.

[35] Meneghetti G, Quaresimin M, De Monte M. Fatigue strength assessment of a short fibre-reinforced plastic based on the energy dissipation. Proceedings of the 16th International Conference on Composite Materials; 2007.

[36] Steinberger R, Leitão TV, Ladstätter E, Pinter G, Billinger W, Lang R. Infrared thermographic techniques for non-destructive damage characterization of carbon fibre reinforced polymers during tensile fatigue testing. International Journal of Fatigue. 2006;28:1340-7.

[37] Toubal L, Karama M, Lorrain B. Damage evolution and infrared thermography in woven composite laminates under fatigue loading. International Journal of Fatigue. 2006;28:1867-72.

[38] Kutin M, Ristić S, Puharić M, Vilotijević M, Krmar M. Thermographic testing of epoxy-glass composite tensile properties. Contemporary Materials. 2011;2:88-93.

[39] Libonati F. Damage analysis of composites by means of thermography. Youth Symposium on Experimental Solid Mechanics2010.

[40] Colombo C, Libonati F, Vergani L. Study of the mechanical characteristics of GFRP by thermography. ICCS; 2011.

[41] Bale J, Valot E, Monin M, Polit O, Bathias C, Soemardi T. Experimental analysis of thermal and damage evolutions of DCFC under static and fatigue loading. Journal of Composite and Advanced Materials. 2016;26:165-84.

[42] Bale J, Valot E, Monin M, Laloue P, Polit O, Bathias C, et al. Damage observation of glass fiber/epoxy composites using thermography and supported by acoustic emission. Applied Mechanics and Materials: Trans Tech Publ; 2014. p. 187-90.

[43] Vergani L, Colombo C, Libonati F. A review of thermographic techniques for damage investigation in composites. Fractural and Structural Integrity. 2014;27:1-12.

[44] Harizi W, Chaki S, Bourse G, Ourak M. Mechanical damage assessment of glass fiber-reinforced polymer composites using passive infrared thermography. Composites Part B: Engineering. 2014;59:74-9.

[45] Shardakov I, Shestakov A, Bykov A. Delamination of carbon-fiber strengthening layer from concrete beam during deformation (infrared thermography). Frattura ed Integrità Strutturale. 2016:331.

[46] Ghadermazi K, Khozeimeh M, Taheri-Behrooz F, Safizadeh M. Delamination detection in glass–epoxy composites using step-phase thermography (SPT). Infrared Physics & Technology. 2015;72:204-9.

[47] Chrysafi A, Athanasopoulos N, Siakavellas N. Damage detection on composite materials with active thermography and digital image processing. International Journal of Thermal Sciences. 2017;116:242-53.

[48] Fargione G, Geraci A, La Rosa G, Risitano A. Rapid determination of the fatigue curve by the thermographic method. International Journal of Fatigue. 2002;24:11-9.

[49] Montesano J, Fawaz Z, Bougherara H. Use of infrared thermography to investigate the fatigue behavior of a carbon fiber reinforced polymer composite. Composite structures. 2013;97:76-83.

[50] Bale JS. The damage observation of composite using non destructive testing (NDT) method: Paris 10; 2014.

[51] Lipski A. Rapid determination of the Wöhler's curve for aluminum alloy 2024-T3 by means of the thermographic method. AIP Conference Proceedings: AIP Publishing; 2016. p. 020004.

[52] Quaresimin M. Fatigue of woven composite laminates under tensile and compressive loading. Tenth European Conference on Composite Materials; 2002.