# NONDESTRUCTIVE EVALUATION OF IMPACT DAMAGE IN GLASS AND CARBON REINFORCED COMPOSITES BASED ON INFRARED THERMOGRAPHY METHODS

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## Abstract

*Application of active infrared thermography has been demonstrated on carbon and glass polymer composites. Several image processing methods have been applied on damaged specimens, demonstrating abilities of thermography as a non-destructive testing method. From comparison of similar impacted glass and carbon reinforced specimens, conclusions considering impact resistance have been made. Image processing and enhancing methods, such as gradient based method, Daubechies wavelet image processing, Fourier and Complex Morlet wavelet transforms, are approaches enabling better damage detection and evaluation than raw infrared image.*

## 1. Introduction

Carbon reinforced polymers (CRP) and glass reinforced polymers (GRP) are materials of particular interest in aerospace and vehicles industries as durable, lightweight and generally advantageous materials. Still, their low resistance to impact damage force producers to protect most exposed parts with metal sheet layers (e.g. aluminum or titanium alloy on CRP based airplanes such as Boeing 787 Dreamliner). On mutually similar CRP and GRP specimens impact damage was simulated by free fall EN DIN 6038 impactor enabling same impact energy for both CRP and GRP specimens. Details about experimental setup have been explained in [1]. Impact loading sequence has been acquired by the cooled middle-wave infrared (IR) camera positioned on side of specimen opposite of impact. Cooled middle-wave IR camera enabled acquisition of sharp IR images up to frequencies of 700 frames per second. Damaged specimens have also been evaluated by means of Thermoelastic Stress Analysis [2,3], providing information about losses of specimen carrying capacity. Several image filtering and enhancement methods have been used as tools of active thermography as a non-destructive testing (NDT) method. Active thermography is based on analyzing images obtained after heat wave propagation caused by heat sources as Xenon flesh lamp, or in this case 1 kW halogen lamp. Testing specimens used herein are: a) 3.12 mm thick CRP plate made of 4 layered 0/90° bi-directional 400g/m$^2$ 12 K carbon fabric in the 2K epoxide matrix, and b) 2.2 mm thick GRP pate made of 4 layered 0/90° 490 g/m$^2$ roving.

## 2. Impact

Observed in IR spectrum, figures 1 and 2 depict; i) moment before impact, ii) elastic loaded specimen (colder/darker zones), iii) elastic with first damage appearing, and finally iv) unloaded and damaged specimen where heat generated by irreversible damage remains for certain period. Thermal distribution and generated heat (Fig. 3) showed that CRP is characterized by larger damage zone. Micro-image of damaged zone shows that damage of GRP is concentrated to zone where there is matrix and glass fiber rupture. Matrix damage zone of CRP specimen is larger with no carbon fiber rupture. This proves that impact energy was, for the CRP specimen, redirected from carbon fibers to the polymer matrix, causing larger damage zone.

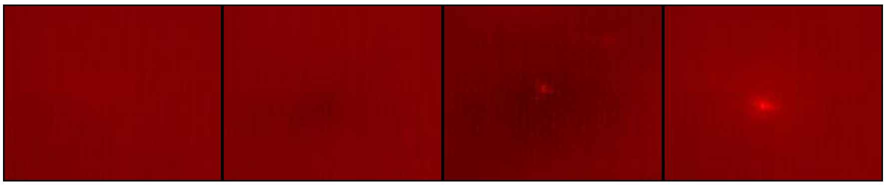

**Figure 1.** Loading sequence of GRP specimen

**Figure 2.** Loading sequence of CRP specimen

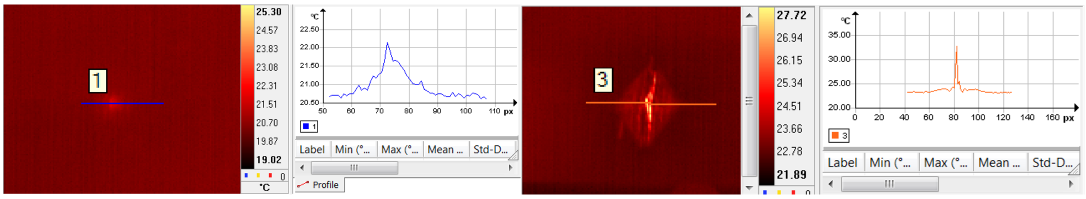


**Figure 3.** Post impact temperature distribution for GRP (left) and CRP (right) zone of damage

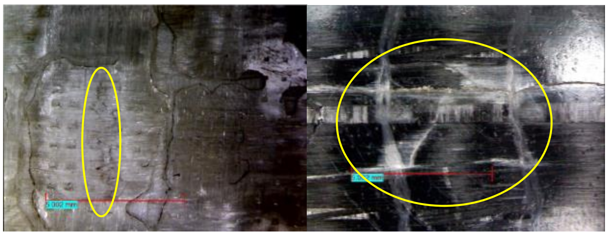

**Figure 4.** Zone of damage for GRP (left) and CRP (right) specimen impacted by the same impact energy

## 3. Thermoelastic stress analysis

The Thermoelastic stress analysis of cyclic loaded specimen is showing stress distribution around damaged zone and stress redirection from the damaged to non-damaged zone. Damage zone is zone with no load carrying capacity.

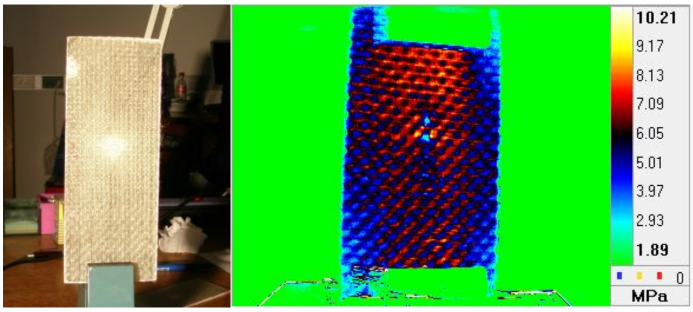


**Figure 5.** GRP specimen and stress distribution near damaged zone of loaded specimen

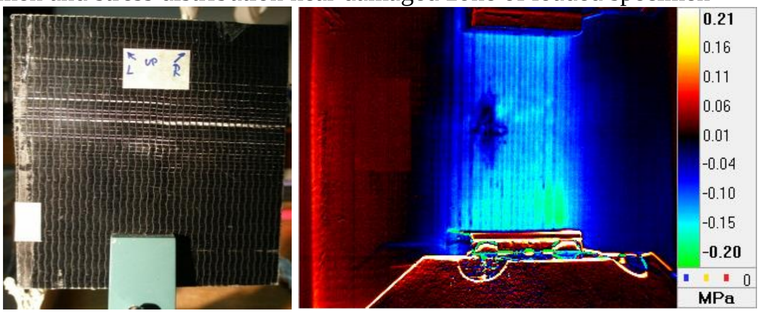


**Figure 6.** CRP specimen and stress distribution near damaged zone of loaded specimen

TSA analysis results confirm conclusion from chapter 2, i.e. damaged zone for the case of CRP is larger than for the case of GRP specimen.

## 4. Thermography as a NDT tool in damage detection

Active thermography based on a halogen lamp as a heat impulse source is a NDT method providing images of thermal obstacles in material such as material anomalies, damage (fractures, cracks, delamination), inclusions and changes in material thickness. Raw image obtained for thermal camera (Fig. 7) does detect material damage, but often additional image processing has to be performed in order to ensure more precise damage detection, enabling detection of anomalies with weak thermal contrast. Typical examples are osmotic process degradation detection in polymer boat hulls characterized by weak thermal contrast [4]. CRPs, due to higher thermal conductivity of carbon fibers, are showing weaker contrast of damage zone. Another problem with raw thermal image is influence of unequal heating that significantly influences thermal reading. Thus, four methods of image enhancement are presented herein.

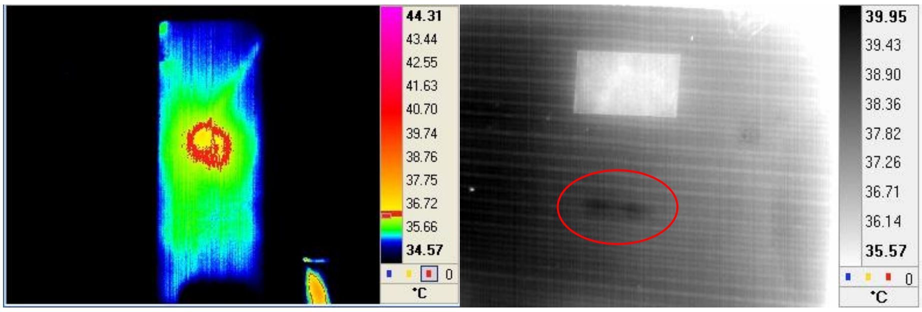


**Figure 7.** Raw thermal image after pulsed heating for GRP (left) and CRP specimen (right)

Two methods, gradient based image processing [5] and Daubechies wavelet transform [6], are based on processing a single thermal image. These methods can be used as additional image processing methods applied on other two transform methods. Two transforms, Fast Fourier transform (FFT) [7-10] and Complex Morlet wavelet transform (CWT) [11, 12] are transforming images of whole cooling sequence, thus enabling extracting more detailed NDT information. All these functions and transforms are standard mathematical tools available in Matlab software.

### *4.1. Gradient based image processing*

Gradient based image processing [5] is function that enables locating thermal zones where sudden change in temperature level occurs. This is robust and reliable method applicable to cases with strong thermal contrast. Method fully eliminates strong influences of unequal heating that often makes raw image evaluation hard and confusing. Drawback of method is that weak thermal contrast is sometimes lost together with unequal heating noise, e.g. here presented CRP specimen case where anomaly is hardly detectable after gradient function processing (Fig. 8).

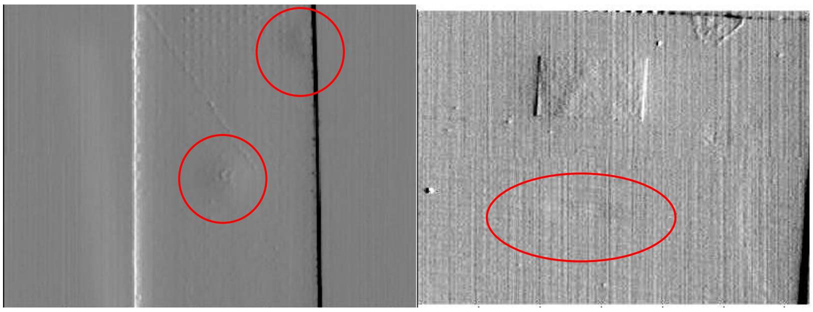

**Figure 8.** Gradient based image processing of GRP (left) and CRP (right) specimen.

### *4.2. Daubechies wavelet image processing*

Daubechies wavelet image processing is powerful method providing strong thermal contrasts even for weak raw image contrast, but often happens that method provides noisy images. The method can be applied as 1D and 2D image processing [6]. If noise is not a problem, mostly 2D Dabuechies wavelet is appropriate method for GRP and CRP. Combining this method together with gradient based image processing is suggested as approach in NDT [6]. Both images in Figure 9 are obtained by 2D Deubechies wavelet with 5 vanishing moments and approximation 2 [6].

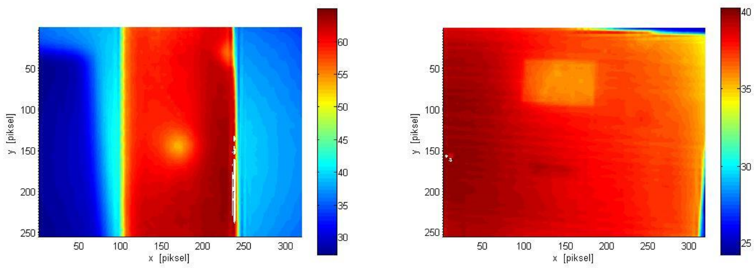


**Figure 9.** 2d Daubechies db5a2 wavelet image processing of GRP (left) and CRP (right) specimen.

### *4.3. Fast Fourier transform*

FFT is often used transformation methods providing amplitudegrams and phasegrams of sequence of images. It transforms sequence of images from time domain to real and imaginary domain, i.e. amplitudegrams and phasegrams. Amplitudegrams are giving information similar to raw image and amplitudegrams are not used in NDT, thus they are not presented herein. Phasegrams are relieving anomalies providing strong contrast. From whole set of images (displayed as function of frequency *f*) the one with best contrast has to be selected. For detecting anomalies on different depths of material, as phasegram frequency is depth dependent, several phasegrams have to be considered.

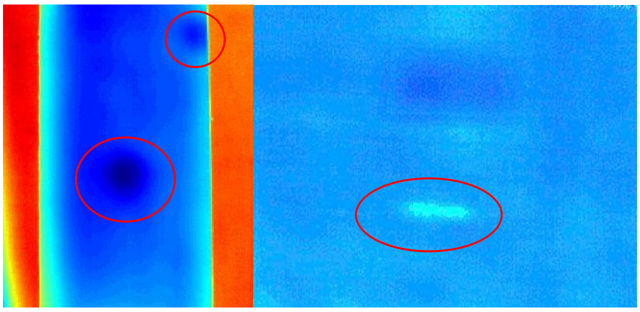

**Figure 10.** FFT phasegram of GRP (*f=0.006 Hz*) and CRP (*f=0,01 Hz*) specimen.

### *4.4. Complex Morlet wavelet transform*

CWT is method similar to FFT. CWT is a continuous wavelet transform, that transforms thermal images from the time domain to the real and imaginary domain, with time as an additional variable that remains variable after CWT transform is performed. As in FFT, amplitudegrams are not of particular NDT interest. In figure 11 the continuous Morlet wavelet transform (M1-0.1) is applied with center frequency *Fc=1* and bandwidth *FB=1.1*. The method showed to provide stronger thermal contrast with less depth dependency from FFT [6]. For here presented CRP case, CWT appeared to be most recommendable approach when CRP materials are evaluated.

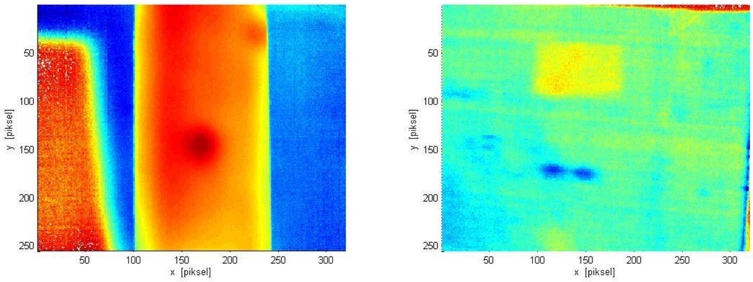


**Figure 11.** CWT phasegram of GRP (*t=40s, scaling factor S=16*) and CRP (*t=8s, scaling factor S=16*) specimen.

## 5. Concluding remarks

Abilities of infrared thermograpy as an emerging NDT tool, have been demonstrated showing reliability of addressed methods. CRP materials, due to high thermal conductivity of carbon fibers, are problematic in IR thermal evaluation due to weak thermal contrast. CWT showed to be proper approach in IR NDT evaluation of CRP materials. As radiography (X ray testing) cannot be performed on CRP materials, leaving ultrasound testing as only reliable method, importance of introducing IR thermography testing to CRP materials is relevant. Demonstrated image processing methods, as recently developed image processing approaches (except Fast Fourier transform), are proper tools when GRPs, and especially CRPs, are evaluated. From NDT results, together with IR thermal imaging of impact and TSA evaluation of impacted specimen, it can be concluded that CRP materials, in contrast to GRP materials, are very sensitive considering impact damage. Impact energy, that is locally absorbed in matrix and fiber rupture of GRP specimen, has different scenario in CRP case where impact energy is not absorbed by carbon fibers, but redirected to matrix, causing larger damaged zone. Local damage of GRP, in contrast to lager damage of CRP, globally is less influencing the carrying capacity of the whole structure. Although load carrying capacity of CRP can hardly be compared to GRP, impact sensitivity of CRP has to be considered.

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