Characterization of Defects in Curved CFRP Samples using Pulsed Thermography and 3D Finite Element Simulation

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Abstract

We present results obtained from Pulsed Thermography on curved components made up of CFRP. In the specimens inclusions of Teflon stripes with different sizes and orientation are positioned at different depths. Especially in the curved regions, it is important to separate defect-related effects on the surface temperature from effects due to the complex sample shape like curvatures or edges. The usage of 3D finite element simulation, taking into account anisotropic heat conduction and inhomogeneous heat excitation as well as orientation dependent heat absorption, makes it possible to interpret the thermographic result in order to reduce geometry effects.

Keywords: Active Thermography, Complex Structure, Finite Element Simulation

1. Introduction

The lightweight construction, used increasingly in the aviation industry, resulted in the development and optimization of new material systems in the field of composites. These tendencies, in turn, require new methods and concepts of Non-Destructive Testing (NDT), which in the manufacture of safety-critical components is of uttermost importance. Among experts [1, 2], Active Thermography is considered to be an NDT method for present and future challenges.

A wide range of different techniques of thermal excitation and signal processing have been reported in the literature. Depending on the material, structure and the damages surveyed different approaches of Active Thermography are used. For aircraft composite assessment Pulsed Thermography combined with optical excitation sources provided excellent results on the basis of flat panels. As composites are used more frequently in complex shapes there is an increasing requirement for the inspection of curvatures, corners and stiffeners, as well [3]. Defects in these regions have a much more critical influence on the mechanical properties than defects in flat regions. Furthermore, the presence of curvatures and corners pose serious difficulties on ultrasonic inspection methods, so Pulsed Thermography seems to be more appropriate for inspection of complex shaped structures. In such structures the temperatures after thermal excitation are influenced not only by material and defect properties but also by geometry effects and details of the excitation conditions. Thus the evaluation procedures used in the case of simple geometries would lead to a mixture of geometry related effects and flaw related effects when applied to complex shaped specimens.

In this paper we present a comprehensive analysis, including finite element (FE) simulations and specific measurements on reference specimens in order to take geometry and excitation effects into account.

2. Analysis of geometrically dependent measurement and excitation features

For realistic FE-simulations precise values of thermal excitation parameters are required [5]. The angular dependence of optical parameters like the emissivity has been measured for different test specimens. In order to determine how the energy of the excitation is distributed over the inclined surface we performed parameter studies. All parameters derived in this work are specified for the flash lamp BLÄSING G 6000Z. It is, however, possible to characterize other flash lamps with reflectors as well.

Angular dependence of infrared measurement

Due to the dependence of the emissivity $\varepsilon$ on the viewing angle $\theta$ (figure 2), the shape of the surface affects the results of infrared measurement. In addition, the spectral range and material properties influence the angular dependence of the emissivity. Thus temperatures $T_{\text{IR}}(\theta)$, measured by means of our thermography system (FLIR Thermacam® PM695), have been acquired for different materials, including black painted aluminum, cardboard and composite materials like Carbon Fiber Reinforced Plastics (CFRP), in the spectral range of 7.5 to 13 $\mu$m and for angles $\theta$, ranging from -90° to 90°. In Figure 1 the expression $g(\theta) = (T_{\text{IR}}(\theta)-T_{\text{amb}})/(T_{\text{IR}}(\theta=90°)-T_{\text{amb}})$ is plotted versus angle $\theta$, where $T_{\text{amb}}$ indicates the ambient temperature. This plot indicates a nearly constant emissivity for an angle between 0° to 45° for all materials. For angles higher than 60° the emissivity is decreased and so reliable infrared measurements are no more possible. As a result we observed that the materials surveyed exhibit an almost identical angular dependence of $\varepsilon$. Although most of the results presented below have been obtained from cardboard, they can be transferred to CFRP or other materials as well.
Heat source characterization

The amount of optically induced thermal energy depends on several factors. Since that the absorptivity of the sample surface is equal to the emissivity, the absorption also depends on the viewing angle, spectral range and temperature. As can be seen in figure 1 the range of constant emissivity or absorptivity, respectively, is between an angle of 0 and 45°. For this reason all following models are derived for a range of θ from 0° to 45°. Further the influence of the distance and normal angle between heat source and the specimen was investigated. Figure 2 shows the experimental setup and a typical temperature profile of a tiled surface. Due to its low heat capacity and thickness (0.6 mm) a thin cardboard is used as test specimen because lateral heat diffusion, convection and radiation can be neglected. The infrared temperature measurement is carried out in transmission mode to prevent reflections.

\[
\Delta T(x,y,t) = \phi \text{(specimen)}
\]

Fig. 2. Experimental setup and measured temperature profile on specimen surface (cardboard) along the x-axis

2.2.1. Local energy distribution of flash light

The induced intensity integrated over time and area equates the input energy, which causes an intensity proportional temperature rise. A 6 kJ – flash excited the cardboard whereas the distance \(d\) between heat source and specimen is varying from 23 cm to 48 cm in steps of 2.5 cm. The temperature profiles are plotted at the maximum temperature 1.8 sec after thermal excitation. For comparison of temperature profiles measured at different distances between heat source and the test specimen, a plot versus angle \(\Phi\) is used (figure 2). According to figure 2 the angle \(\Phi\) is calculated by the following equation

\[
\phi = \arctan \left( \frac{\pm \sqrt{x^2 + y^2}}{d} \right)
\]  

where \(d\) denotes the distance from heat source to the specimen and \(x\) and \(y\) denote the local position on the specimen surface, respectively.

The temperature distributions plotted in figure 3 are normalized with respect to their maxima, respectively and are fitted by a superposition of two Gauss error curves (Eq. 3).

\[
f_\phi(\phi) = a_1 \cdot e^{-\phi^2/b_1} + a_2 \cdot e^{-\phi^2/b_2}
\]
where $a_1$, $b_1$, $a_2$, and $b_2$ denote heat source dependent constants.

The usage of the following constants $a_1 = 0.4215$, $b_1 = 0.08807$, $a_2 = 0.5766$, $b_2 = 0.2884$ allows an exact modeling of the local energy distribution (figure 3). The advantages of this model are that no Look-Up Table is needed, the shape is smoothed and a further interpolation is possible.

Fig. 3. Temperature distribution on a flat panel after flash lamp excitation: varying distances from 23 cm to 48 cm in steps of 2.5 cm

2.2.2. Distance heat source to specimen

The well known $1/d^2$ - dependence can be used for point like heat sources but for the characterization of the deployed flash lamp with reflectors the following model shows better results.

$$f_d(d) = \frac{p_1}{d^2 + q_1 \cdot d + q_2}$$

(4)

where $p_1$, $q_1$, and $q_2$ denote heat source dependent constants.

Fig. 4. Dependence of the maximum temperature on the distance between test specimen and heat source

2.2.3. Influence of surface angle

In the case of inclined planes the excitation energy is distributed over a larger surface and so the temperatures are decreased by a factor of $\cos(\theta)$ (figure 2). In consideration of all effects depending on the local energy distribution and surface orientation, following model is applied:

$$\Delta T = f_{\phi}(\theta) \cdot f_d(d) \cdot \cos(\theta)$$

(5)

This model is verified for declinations up to $\theta = 45^\circ$, since the angle dependent emissivity factor is nearly constant.

Figure 5 shows a comparison of temperature profiles derived from IR measurement and the analytical model (Eq. 5) at two different inclined positions ($30^\circ$ and $45^\circ$). A good correlation between measured and calculated signals is obtained. In Figure 6 a comparison of the two-dimensional local temperature distributions, measured and calculated at $\theta = 40^\circ$, is shown.

The analytical modeling allows a description of the induced intensity by optical thermal excitation, which is proportional to temperature changes. This model is used for calculating the input parameters of the FE-simulation.
Fig. 5. Comparison of measured and calculated temperature profiles on a tilted flat plate (left 45° and right 30°)

Fig. 6. Comparison of local temperature distribution measured and calculated at a θ = 40° tilted flat specimen

3. Test sample

The test specimens examined in this study were curved and flat CFRP panels with Teflon® inclusions. In Figure 7 the dimensioning is shown in a section with inclusion.

Fig. 7. Geometry of the curved and flat test specimen with Teflon® inclusion used for FE – simulations and thermographic measurements

4. Finite element analysis

The transient heating of realistic CFRP flat and curved specimens with varying thermal and geometrical properties was numerically simulated using the finite-element method (FEM). The simulations performed in this study consider realistic heating conditions (see Chapter 2.2), anisotropic thermal conductivity and varying defect sizes and depths. For the sake of simplicity the flaws are simulated as thin air gaps since the Teflon® inclusions are air-filled. A more advanced model is investigated by Vavilov [8].
Model

In Table 1 the thermal properties, which are derived from literature [6], and geometrical parameters are defined for the FE-model. Additionally a position-dependent thermal conductivity tensor is used to simulate the anisotropy heat flux especially in the curved regions. From the temperature transients calculated either for the front or for the rear side of components investigated (transmission mode), we determine the thermal diffusivity and use this quantity as a probe for material properties like porosity or in this work for the existence of defects like Teflon® inclusions.

| Table 1. Thermal properties and geometrical parameters for the 3D FE-model |
|---------------------------------|---------------|------------|
| Symbol | Value | Unit | Description |
| $k_{n,CFK}$ | 0.64 | W / (K · m) | thermal conductivity (normal) |
| $k_{p,CFK}$ | (1.4,10) · $k_{n,CFK}$ | W / (K · m) | thermal conductivity (parallel) |
| $\rho_{CFK}$ | 1600 | kg / m³ | density |
| $c_{p,CFK}$ | 1200 | J / (kg · K) | heat capacity |
| $k_{Air}$ | 1.2 | W / (K · m) | thermal conductivity |
| $\rho_{Air}$ | 1005 | kg / m³ | density |
| $c_{p,Air}$ | 0.23 | W / (K · m) | thermal conductivity |
| $\rho_{Teflon}$ | 2200 | kg / m³ | density |
| $c_{p,Teflon}$ | 1040 | J / (kg · K) | heat capacity |
| $h$ | 6 | W / (m² · K) | heat transfer coefficient |
| $r_1$ | 8 · 10⁻³ | m | radius (inside) |
| $r_2$ | 12 · 10⁻³ | m | radius (outside) |
| $L$ | 72 · 10⁻³ | m | length |
| $H$ | 49.5 · 10⁻³ | m | height |
| $B$ | 6 · 10⁻² | m | edge length of inclusion |
| $r_F$ | (9.10,11) · 10⁻³ | m | position of inclusion |
| $d_F$ | 0.25 · 10⁻³ | m | thickness of inclusion |

Comparison of thermal diffusivity images in flat and curved geometries

Determining the thermal diffusivity from the numerical simulations of flat and curved specimens with and without Teflon® inclusions makes it possible to differentiate between geometry effects and defect related effects. Figures 7 and 8 show a map of thermal diffusivity values representing quarters of the specimens, respectively. These maps are obtained from a sequence of simulated thermal images taken on a curved and a flat CFRP specimen. Effects of inside (figure 7) and outside (figure 8) thermal excitation on the flaw contrast are demonstrated for two Teflon® inclusions positioned at two different depths. For a quantitative comparison of the flaw size a transformation of coordinate $y^*$ is necessary. The size of the flaw contrast area depends on several but two main factors in curved specimens: on the depth of the inclusion (the same like in flat plates) and on the thermal excitation side, that means inside or outside excitation. In the case of inside excitation (figure 8) the flaw contrast seems stretched up in $y^*$-direction as a consequence of the spreading heat flux. The reverse effect occurs with outside excitation (figure 9). Here due to the concentration of the heat flux the flaw size seems to be decreased, up to 40 % in $y^*$-direction. The full width at the half maximum (FWHM) of flaw contrast curves in $y^*$-direction for several scenarios are shown in Table 2. The results of the numerical simulations give a good imagination of how the lateral extent of the flaw in curved specimens responds to thermal excitation side. In future, we try to find a method to correct the flaw size depending on the radius of the curvature and the depth of the flaw.

| Table 2. FWHM at the diffusivity contrast in $y^*$-direction |
|---------------------------------|---------------|-------------|
| Thermal excitation | Defect depth $r_F$ | FWHM ($y^*$-direction) Flat specimen | FWHM ($y^*$-direction) Curved specimen |
| Inside | 9 mm | 4.97 mm | 6.41 mm (+ 28%) |
| Inside | 11 mm | 5.20 mm | 5.45 mm (+ 4 %) |
| Outside | 9 mm | 5.22 mm | 3.99 mm (- 23 %) |
| Outside | 11 mm | 5.06 mm | 3.02 mm (- 40 %) |
5. Results of pulsed thermography measurements

We have prepared a 4 mm thick, curved CFRP specimen with 8 Teflon inclusions, incorporated intentionally at different depths from 0.5 mm to 3.5 mm with an edge length of 6 x 6 mm. The test specimen is aligned between the flash light and the infrared detector. All measurements are performed with a 320x240 un-cooled FPA IR camera with a dynamic range of 8 bit and a frame rate of 25 Hz. As a fact of the small dynamic range and low acquisition rate all test are performed in transmission mode. In figure 10 a comparison of a contrast temperature image and a thermal diffusivity image is shown. The bright horizontal strip in the middle of the images indicates the curved area where the sample thickness is decreased due to manufacturing tolerances. Additionally, lateral heat fluxes influence the heat transfer in this area through the medium and therefore the calculated values based on the 1D-LDF approach [7] deviate from real values. The thermal diffusivity image for the whole curved CFRP specimen is shown in figure 11. The calculated thermal diffusivity values diverge in the curvature from the values of the flat region approximately by 26%. In a first approach, this deviation can be corrected by a subtraction of a line profile of diffusivity values of a sound area. This approach has been turned out as a very useful empirical method to separate geometry effects from defect related effects under the assumption of relatively slight geometry deviations and homogeneous material properties.
6. Conclusion

From measurements on test specimens we have generated a model for the special excitation conditions including the energy distribution of the light source as well as distance and orientation dependence of the specimens with respect to their energy absorption. These results are used in FE–simulations of components with complex shape. The simulations showed that the size of defects in curved regions may appear bigger or smaller dependent on the direction of the heat flux.

Measurements in transmission have been performed on CFRP specimens with curved areas. Teflon stripes are positioned in the curved region at different depths. The resulting diffusivity images are strongly influenced by geometry effects. The latter, however, can be interpreted by means of simulations in a much better way and they can be reduced by applying appropriate algorithms.
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