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Non-Destructive Evaluation of Small Aircraft Wing Adhesive Joints using Pulse Infrared Thermography Method

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Abstract. In this article we examine possibility of using active infrared thermography as a non-traditional non-destructive evaluation method for an adhesive joints testing. The attention was focused on the load bearing wing structure and related structural joints, specifically the adhesive joints of wing spar caps and skins on the wing demonstrator of a small sport aircraft made mainly of carbon composite. The pulse thermography method using flash lights optical excitation was tested. A modified differential absolute contrast method was used to process the measured data to reduce the effect of heat source inhomogeneity and surface emissivity. The tested method proved a very good ability to detect defects in the adhesive joints. The achieved results are easy to interpret and use for qualitative and quantitative evaluation of the adhesive joints of thin composite parts.

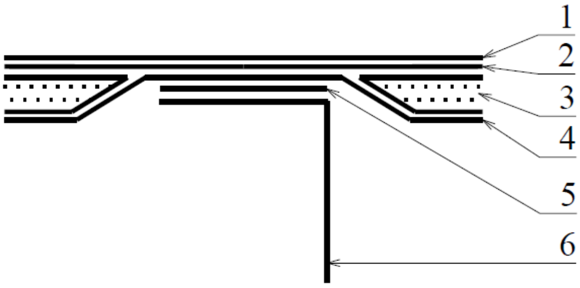
Introduction

The aim of an experimental work was to evaluate bonding quality of the small composite aircraft wing adhesive joints. The all-composite wing is assembled from the pre-cured carbon/epoxy composite (CFRP) parts using the Hysol 9394 two component epoxy adhesive system. The work was focused on the joints of wing skin to spars and ribs.

One of the less common Non-Destructive Evaluation (NDE) methods was used, namely Pulse infrared Thermography (PT). This method allows inspection of specific areas of the tested object with direct graphical output. It is suitable for the finding of flaws and voids located close to the surface. In the case of the performed tests, defects of the adhesive joints were expected at a depth of 0.5-2 mm below the tested surface. They would be difficult to detect using other standard NDT methods.

Experimental specimen

The test sample was the right half of the wing of the small composite aircraft demonstrator. The wing was used for a development static structural strength testing. Its structure consists of the spars and ribs made of CFRP. The wing skins are made of a sandwich structure consisting of a carbon sheet and a foam core. The outer skins are additionally covered with a thin layer of surfacer made of glass/epoxy composite (GFRP). Wing skins are glued to the load bearing structure using the Hysol 9394 epoxy adhesive. The scheme of the bonded joints configuration in the tested areas is pictured in Fig. 1.



no.	description	material
1	surfacer	AeroGlide (CFRP)
2	outer skin	TeXtrem (GFRP)
3	foam	Rohacel
4	inner skin	TeXtrem (GFRP)
5	adhesive	Hysol 9394
6	spar (rib)	GFRP

Fig. 1: Bonded joint configuration

Experimental method description

PT method is based on the principle of heating the sample from one side by a short thermal pulse (for example halogen light flash) and subsequent monitoring of the cooling curve at each point of the surface using an infrared (IR) thermal camera. By sending a pulse, the heat wave begins to propagate through the material. The surface cools due to heat wave propagation (conduction) into the material in the depth direction, but also due to convection and radiation losses. If there is a defect underneath the surface with different thermal effusivity than the base material (delamination, cavity or void in an adhesive joint), the heat wave will be reflected back to the surface and the cooling process will change at this point. This behaviour of surface cooling curves is demonstrated in Fig. 2. Defects that occur at a greater depth will appear on the thermogram with time delay [1, 2]. Fig. 3 shows an example of the time evolution of thermograms for different moments after the excitation pulse. The figure shows a time-sequential drawing of deeper layers of the adhesive joint. At time $t = 5\ s$, the poor quality of the joint can be seen due to inappropriate technology (the adhesive bead wasn't compressed and spread sufficiently). At the same time, it can be seen that due to lateral diffusion, thermograms lose their sharpness with increasing time.

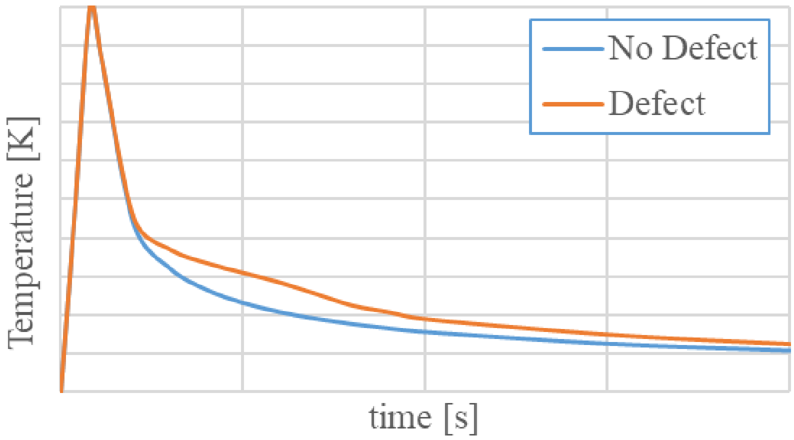


Fig. 2: Surface cooling curves

The disadvantage of this method is the sensitivity to the unevenness of the heat source and the distribution of emissivity on the surface, which can be partially eliminated by subsequent postprocessing.

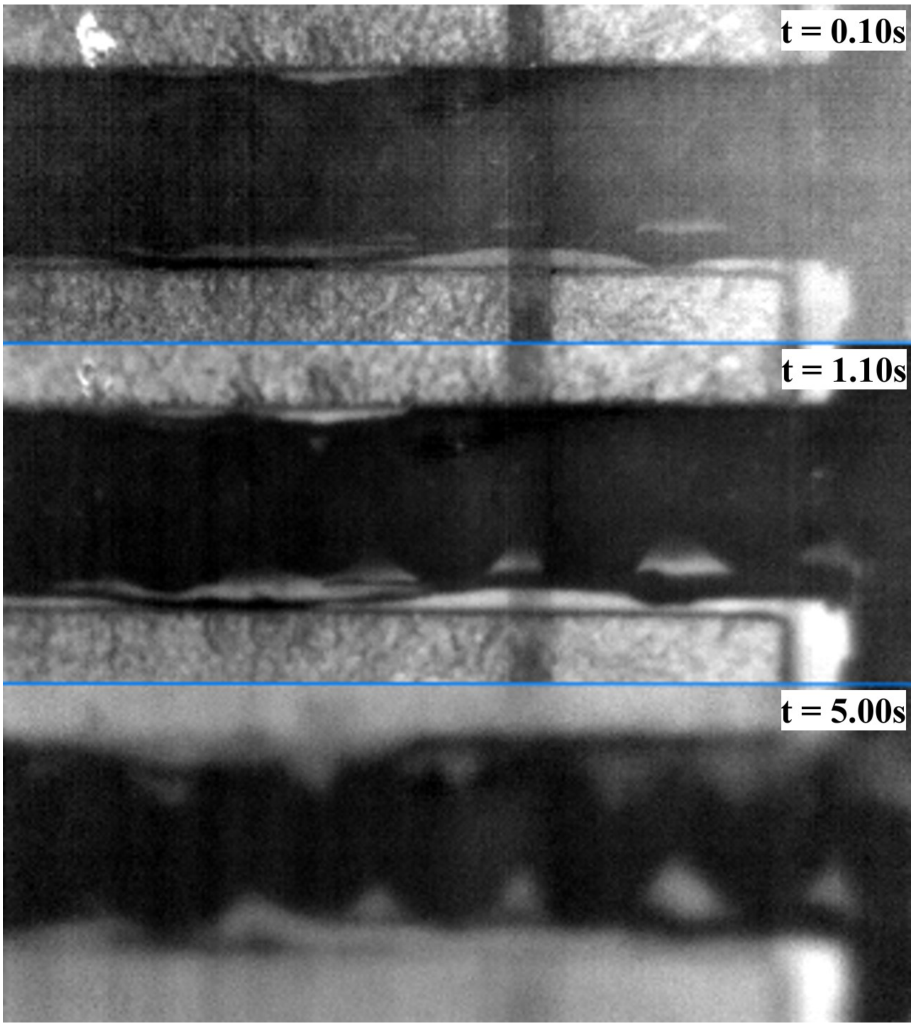


Fig. 3: Sequence of thermograms of the bonded joint

Experimental system description

A modular test system was designed and used for the PT non-destructive testing (NDT) method. The basic hardware elements of this system consist of a FLIR A325SC bolometric uncooled IR camera (resolution 320x240 pixels, NETD <50 mK, maximum scanning frequency 60 Hz), instrument unit equipped with PC for test control and data recording and two flash lights (2x 1200 Ws).

The instrument unit works as the communication interface between the PC, IR camera and excitation lights. It consists mainly of the cDAQ measuring and control system from National Instruments, equipped with analog output cards (for excitation light control) and digital input/output, as well as other necessary auxiliary electronics.

A program created for this purpose in the LabView environment from the National Instruments was used to control the tests process and record the measured data. Processing and evaluation of the obtained data was performed in the MATLAB environment from the MathWorks company.

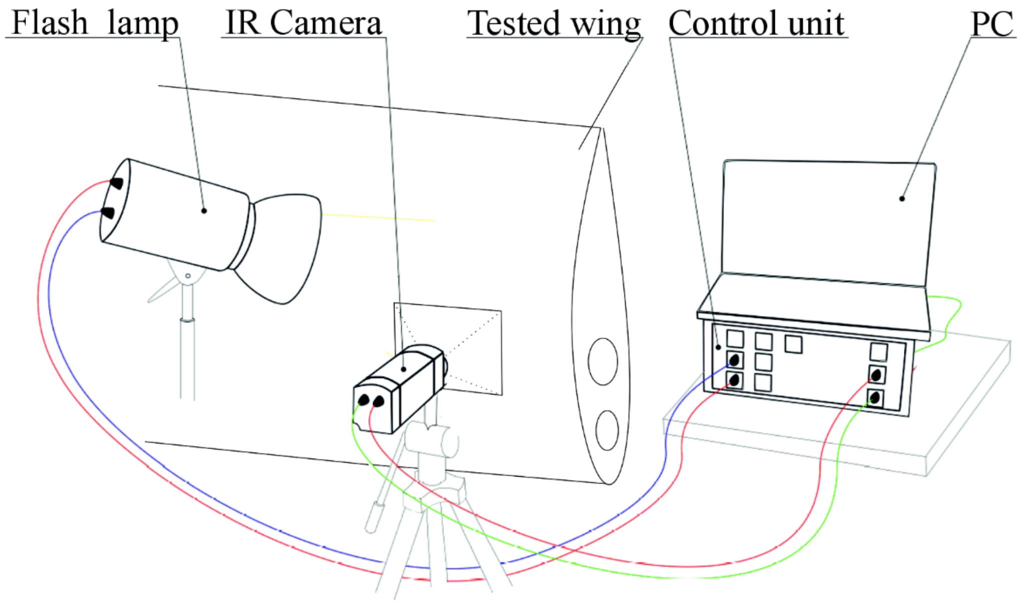


Fig. 4: Experimental configuration

Experimental data evaluation

A modified Differential Absolute Contrast (DAC) method was used to process the measured data. It allows partial elimination of heat source unevenness and of emissivity distribution on the surface. The DAC method compares the temperature of the tested place with the defect with the theoretical value of the temperature in case the defect does not occur in the tested place. This theoretical temperature is calculated on the basis of the 1D form of the Fourier equation of heat conduction in a semi-infinite medium from the measured temperature at a time when the temperature defect does not manifest itself [3]. The standard DAC method works with the temperature in time just before the manifestation of the defect, which, however, usually requires manual intervention of the test operator. The modified DAC method, on the other hand, uses the temperature taken from the end of the measurement. The thermal contrast is calculated according to (1), which describes relation of temperature $T_{(t)}$ at the observed time t and the temperature $T_{(t')}$ at steady state at the end of the measurement at time t' for each individual pixel of the record.

$$\Delta T_{DAC}(t) = T(t) - \sqrt[b]{\frac{t'}{t}}T(t')\ [K] \tag{1}$$

Parameter b represents the steepness of the cooling curve shape correction factor, which is given by the properties of the examined material, especially the rate of surface cooling after excitation (standard DAC method uses $b = 2$). This parameter must be determined experimentally in order to gain the greatest possible contrast. [1]

Results and Discussion

The following figures show examples of the test results. Each individual image covers the tested area with a size of approx. 320x240 mm, which at a given resolution of the IR camera represents a resolution of 1x1 mm for each pixel of the image. The final images were adjusted so that the grayscale range covers the entire range of evaluated data (from white to black). Fig. 5 and 6 show a representative selection of images on which the test results are demonstrated with an explanation of the individual indications.

The area of the adhesive joint of wing tip rib (right) and the front wing spar cap on the lower wing skin side is pictured in Fig. 5. The red lines mark the area of the front wing spar for the PT NDT evaluation process. The blue lines mark the area of the sandwich foam core reinforcements of the wing skin. From the point of view of the adhesive joint evaluation, the critical places are represented by the lighter shade of corresponding colour (A), which can be interpreted as the voids in the adhesive joint. The indication marked with the D in the figure represents an overflow of excessive adhesive outside the joint area. Indication B is caused by overlapping of the top layers of the surfacer and thus its local doubling. Indication C represents the region of resin accumulation in the place where foam core ends and sandwich skins are joined together.

Fig. 6 represents the area of the front wing spar at the fuel tank location on the upper wing skin side. Again, the places with the voids in adhesive layer are clearly visible (A). The use of two types of different adhesives is visible in the bonded area (B). This is because the need for the increased resistance to the influence of fuel in the fuel tank area (use of C-resin type). Indication C represents the local reinforcement in the area of fuel tank lid by adding one layer of fabric to the outer skin lay-up.

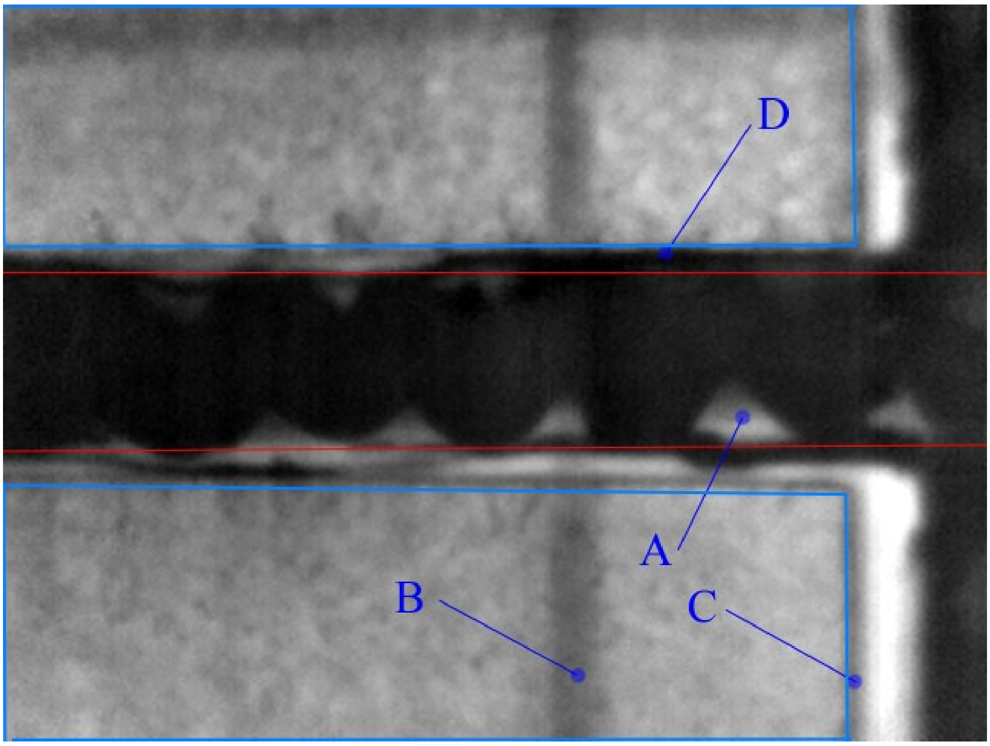


Fig. 5: Results of PT NDE method – adhesive joint of the front wing spar and the wing tip rib on the lower wing skin

Due to the fact that no etalons with artificial defects were available for testing, an additional comparison of the NDT findings with the actual condition of the adhesive joint at the failure area was performed after the static strength test of the wing demonstrator. In the area of the main wing spar, the CFRP wing skin was removed to the depth of the adhesive joint. Fig. 7 shows a comparison of the NDT findings with the actual condition of the adhesive joint. The individual color circles mark the corresponding defects of the joint. The performed NDT measurement shows a good agreement with the actual condition of the joint. The smallest detected defect (marked in red) is about 3 mm in diameter. Due to the resolution of the IR camera, this dimension can be considered as the smallest detectable defect in the adhesive joint for a given test configuration. Except for defects in the adhesive layer, the use of two adhesives (Hysol and C-resin) is clearly visible in the picture. In the lower half of the picture, two vertical cracks caused by a failure during the strength test of the wing demonstrator can be also seen.

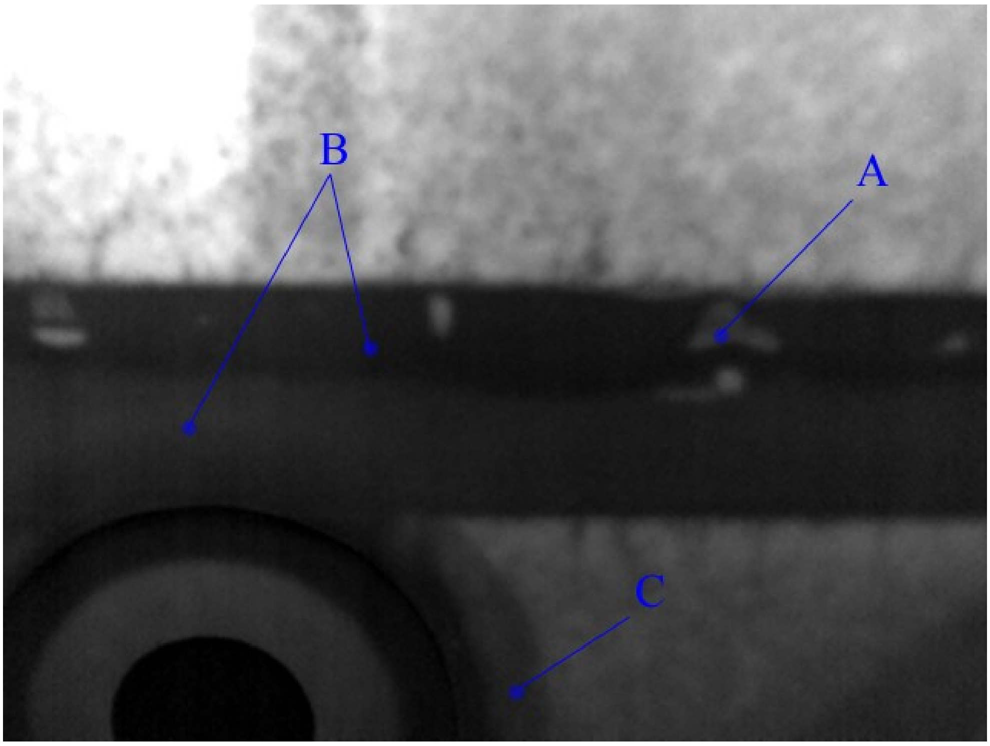


Fig. 6: Results of PT NDE method – adhesive joint of the front wing spar and the upper wing skin in the fuel tank area

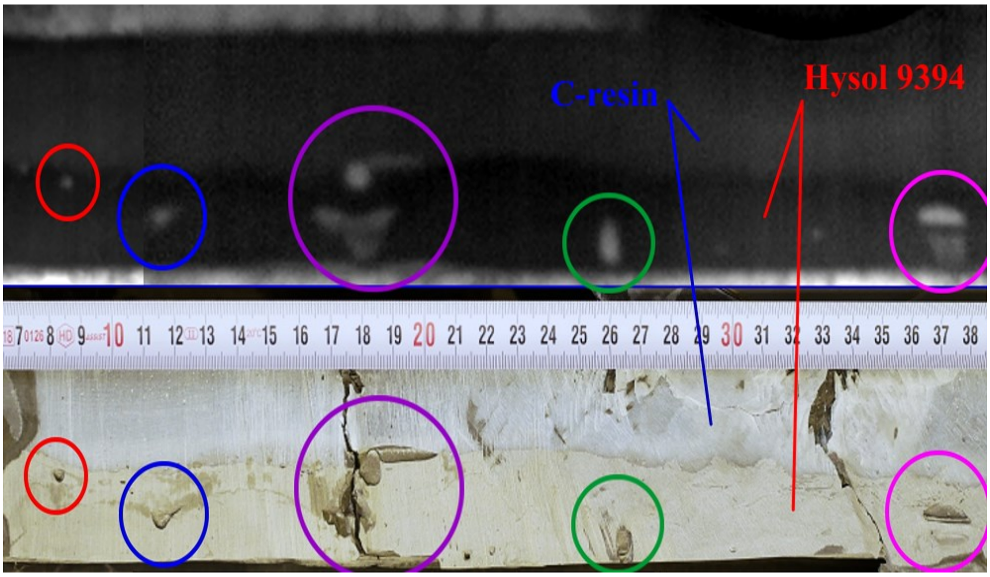


Fig. 7: Comparison of NDT findings (top) with the actual condition of the adhesive joint (bottom)

Fig. 8 shows an overview image (top and bottom view of the right wing) from the test of the entire wing, composed of individual images. The tested area is limited to adhesive joints only. The dark vertical areas represent the adhesive joints of the spar caps to the wing skin. The horizontal areas represent the adhesive joints of the ribs to the wing skin. Areas with insufficient adhesive coverage (brighter areas in the adhesive joints) can be seen practically along the entire length of the adhesive joints of the spar caps with the wing skin. Furthermore, the areas of overlapping of the outer layers of the wing skin or reinforcements of the structural openings in the skin are clearly visible.

Fig. 8: Results of PT NDE method – overview image of the tested wing area (lower wing side on the left, upper wing side on the right)

Conclusions

Described NDE testing method proved very good usability for detection of the flows in the adhesive joints of the wing skins, ribs and the load-bearing beam structure made of thin GFRP. The achieved results are clearly interpretable and usable for qualitative and quantitative evaluation of adhesive joints. Besides defects in an adhesive layer, manufacturing technology defects and inaccuracies such as adhesive overflow, foam inserts misalignments or composite layers overlaps are detectable.

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