Comparative Investigation of Pulse Thermographic and Shearographic Testing of Composite Materials

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Abstract. New materials like fibre reinforced plastics, fibre reinforced ceramics and other composites as well as new integral structures make it difficult or impossible to use the standard methods for nondestructive testing. Therefore a great variety of new test methods has been developed in the last years. Among these new methods are pulse thermography and shearography. Both methods are fast in application and analysis, non-contacting and can use multiple possibilities of exciting the object under investigation. Although relatively young these methods have demonstrated great potential and have been proven indispensable for a number of material problems. This study shows the results of both nondestructive methods in application of testing new material composites and structures, partly in comparison to scanning ultrasonic testing. Tests were carried out with monolithic laminate and sandwich compound specimens with artificial defects like drilled flat holes, interlaminate patches and impact damages. Further investigations were done with real aircraft components. Results show that both methods have individual advantages and disadvantages concerning the great variety of damages observed for material composites. Therefore both methods should be rather considered as supplement and used in combination and not as competitive test methods.

1. Introduction

For decades the basic testing methods like ultrasonic testing, eddy current testing, magnetic particle testing, penetrant testing and radiography were sufficient for nondestructive testing of aircraft structures and components made of conventional metallic materials. New materials like fibre reinforced plastics, fibre reinforced ceramics and other composites as well as new integral structures make it difficult or impossible to use the standard methods for nondestructive testing. Therefore a great variety of new test methods has been developed in the last years. Among these new testing methods are pulse thermography and digital shearography.

Both methods have numerous advantages: They are fast in application and analysis, whole-field imaging, non-contacting and can use multiple possibilities of exciting the object under investigation. Both methods have demonstrated great potential for revealing subsurface defects in composite materials. Therefore these test methods are gaining more and more acceptance and face official introduction by the aircraft and automotive industry in the near future. This study shows the results of both nondestructive methods in application of testing new composite materials and structures in comparison to each other.
2. Experimental

2.1 Pulse Thermography

In active thermography the front surface of a measuring object is heated either instantaneously or continuously while an IR camera monitors changes in the surface temperature [1]. The use of numerous excitation sources for heating the test object is possible. In this study optical flash lamps for instantaneous heating were used. The basic principle of pulse thermography is visualized in Fig. 1. The sample surface is heated with a pulse of electromagnetic radiation from flash lamps. Radiation energy is absorbed at the object surface and converted into heat, which penetrates the bulk of the object. The presence of subsurface defects obstruct this heat flow resulting in an accumulation of heat energy at the defects and in locally higher surface temperatures in comparison to non-damaged areas. These hot spots cause a nonuniformity in the infrared radiation from the object surface, which is detected by the IR camera. With the help of a PC with a frame grabber card infrared images of a whole surface cooling process are recorded, digitalized and analyzed. The deeper the defects are located under the surface, the later the corresponding indications appear in the thermal images of the cooling process. Therefore the recording of a whole sequence of images is necessary.

The investigations were carried out with a FLIR SC 3000 IR camera. This long wave IR camera with the sensitivity of its GaAs quantum well detector in the 8 – 9 µm wavelength region has a nominal thermal resolution of 30 mK. For data acquisition and analyzing a computer system with the ThermoLab software from the T-ZfP Company was used. This software allows a great variety of image processing methods, e.g. depiction of time-temperature curves, computing of temperature differences in regard to the initial state, normalized temperature distributions, temperature gradients, pulse-phase analysis and more. Each of two flash lamps used for these tests released an energy of 3 kJ in a few milliseconds.

![Figure 1: Schematic drawing of the pulse thermography principle](image-url)
2.2 Digital Shearography

Digital shearography is a laser-optical method using an interferometrical measuring technique. The basic scheme is depicted in Fig. 2. According to the common sense of interferometry, two beams with an identical wavelength are required for the purpose of interference. These beams are obtained from one laser by using a beam splitter [2, 3]. A distinguishing feature of shearography is the use of a self-reference interference system. Instead of using an additional reference beam, shearography utilizes a shearing device to bring the light waves from two points P1 and P2 of the object surface into one point on the image plane. The result is an interference image called speckle interferogram. The intensity distribution of the speckle pattern is then recorded by a CCD camera, digitalized and saved by a frame grabber device in a PC. Speckle patterns of the area of interest are taken for an unloaded and a loaded state of the object. Mechanical load can be introduced into the test object by heat, vacuum or vibration. Due to the mechanical load the surface is strained, which leads to a change of the speckle pattern. This is especially true for regions with subsurface damages like delaminations showing bulging normal to the surface. Afterwards the difference of both intensity distributions (speckle patterns for the loaded and unloaded condition) is computed resulting in a fringe pattern called shearogram. One can mathematically show that a shearogram pattern is a measure for deformation gradients of the surface in direction of optical shear. In a shearogram a defect can be easily identified as characteristical butterfly pattern, which shows a change of deformation between two points. By use of an additional mathematical operation, the phase-shifting process, the shearographic fringe-patterns are transformed into so-called phase images, which show defect indications more clearly. A great advantage of the shearography method is its relatively low sensitivity to rigid body movements.

For our investigations we used a Q 800 shearography system of the Dantec-Dynamics Company in combination with the Istra 800/810 data acquisition and analyzing software. Mechanical load was introduced by means of heating with two halogen lamps.

![Figure 2: Schematic drawing of digital shearography](image)
3. Results

Comparative tests with pulse thermography and shearography were carried out with monolithic laminate and sandwich compound specimens with artificial defects like drilled flat holes and interlaminate patches. Further investigations were done with a real aircraft component with an impact damage.

3.1 Thermographic and shearographic investigations of monolithic composite specimens

A first test set of specimens consisted of CFRP panels with artificial flaws. These panels were produced by utilizing the prepreg method. The prepreg material used was Hexcel 8552/IM7 with single layers of unidirectional fibre orientation. Each panel consisted of 48 single layers and had a unique laminate thickness of 6 mm. The specimens with a monolithic, quasi-isotropic laminate structure had a layer sequence given by 

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\begin{bmatrix}
45/0/-45/90
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Different kinds of specimens with additional features of a realistic aircraft structure were produced. The different structures were:

- **Structure 1:** CFRP laminate, thickness 6 mm
- **Structure 2:** CFRP laminate, thickness 6 mm with additional copper mesh layer
- **Structure 3:** CFRP laminate, thickness 6 mm with additional copper mesh layer, GFRP layer and paint coating with thickness of approximately 50 µm

The additional GFRP layer of structure 3 specimens is intended as a means of protection against wear. Investigations with panels of structure 2 and 3 were carried out to investigate the influence of lightning protection mesh and paint coatings on the defect detectability. It was assumed that these additional features would strongly reduce the detectability of defects with increasing depth and decreasing size of defects. In each panel flat holes were drilled as artificial flaws. The holes were arranged in a matrix shown in Fig. 3 and had four different diameters of 5, 10, 15 and 20 mm. Two different types of panels of each structure were made. For **type A** panels the depths of the hole bottoms varied from 0.5 mm to 2.5 mm and for **type B** panels from 3.0 to 5.5 mm.

![Figure 3: Arrangement of flat drilled holes in CFRP panels](image)
Fig. 4 to 6 depict the results of thermographic investigations. The images show the normalized temperature difference to a reference image at the beginning of the cooling sequence. As expected and clearly visible from the images the detectability is reduced with decreasing size and depth of the flaws. The deeper and smaller the flaw, the more diffuse is the thermal indication and thermal noise is increasing. Furthermore there is a certain influence of additional layers on the detectability. This influence is relatively small for structure 2 panels with additional copper mesh only in comparison to panels structure 1 without copper mesh: For type A panels of both structures all flaws are clearly visible except the flaw with 5 mm diameter and a depth of 2.5 mm. For both type B structures the results are very similar. Flaws with a diameter of 20, 15 and 10 mm can be observed in both cases down to depths of 4.5, 4.0 and 3.5 mm, respectively. Flaws with a size of 5 mm are not visible at all.
With additional GFRP and paint layers the depth of detection is reduced at least by 0.5 mm for flaws with a diameter of 20, 15, 10 mm. For flaws of 5 mm diameter the reduction is even greater and comes out to 1.5 mm. Flaws with a diameter of 20, 15, 10 and 5 mm are now visible down to 4.0, 3.5, 2.5 and 1.0 mm. Additionally thermal noise is further strongly increased.

Shearographic results are visualized in Fig. 7 to 9. The images on the left hand side depict the fringe patterns, while on the right hand side the so-called phase images are shown. Only results for type A panels are described, because not a single flaw of type B panels could be found by shearographic testing. As phase images in Fig 7 to 9 present the detectability of drilled flat bottom flaws is clearly worse for shearography than for thermography. For struc-
ture 1 panels a clear butterfly indication could only be found for the single flaw with a diameter of 20 mm in a depth of 0.5 mm, while shadowy indications are visible for 20 and 15 mm diameter defects down to 1.5 mm depth and for 10 mm defects down to 1 mm depth. Flaws with 5 mm diameter could not be found at all. Amazingly for the panel with additional copper mesh layer (structure 2) the number and type of flaws that could be recognized were the same as for the structure 1 panel, but the contrast of indications became much better than for panel structure 1. For structure 3 panel the visibility and number of flaws detected were further increased. Now clear butterfly patterns were recognized for defects of 20, 15 and 10 mm diameter to a depth of 1 mm, while weak indications of 20 and 15 mm defects were found down to a depth of 2 mm. Finally one can notice that for investigated panel structures the contrast and depth of detection increased with additional copper mesh, glass fibre and paint layers on top of the CFRP panels.

3.2 Investigations of a sandwich composite specimen

A further main focus of tests were investigations of a CFRP sandwich specimen with honeycomb core. This specimen had a 16 mm thick honeycomb core and 1 mm thick front and rear side laminate skins and a great variety of artificial defects. Fig. 10 gives an overview of the different types of defects, while Fig. 11 presents the diameters, types and distribution of the flaws. These defects can be divided into following types:

(1) adhesive, front side: circular fillings of polyamid foam and honeycomb with size of 5, 10, 20, 30, 40 and 50 mm
(2) honeycomb core, front side: 8 mm depression of core with circular fillings of polyamid foam and honeycomb with size of 5, 10, 20, 30, 40 and 50 mm at the upper side
(3) honeycomb core: circular fillings of polyamid foam and honeycomb with size of 5, 10, 20, 30, 40 and 50 mm
(4) honeycomb core: heat damage in the middle of the core and circular honeycomb fillings with size of 20 and 30 mm
(5) honeycomb core, front side: 8 mm depression of core with circular fillings of polyamid foam and honeycomb with size of 5, 10, 20, 30, 40 and 50 mm at the rear side
(6) adhesive, rear side: circular fillings of polyamid foam and honeycomb with size of 5, 10, 20, 30, 40 and 50 mm
(7) rear side skin defect of layer sequence in rear side skin

Figure 10: Different kinds of artificial defects in a CFRP sandwich specimen with honeycomb core
The results of thermographic and shearographic testing are shown in Fig. 12. The thermal and shearographic images had to be put together from four different shots, because the region of interest was larger than the field of view of the IR camera and the CCD camera, respectively. A comparison shows clearly better results for thermography. With pulse thermography all of the surface-near defects in the upper side glue (type (1)) were found independent of the filling, even the smallest with 5 mm diameter, while shearography was able to find only the bigger defects with a diameter of 40 and 50 mm. Pulse thermography achieved the better results also for the detection of defects in the different depth of the honeycomb core. It was possible to detect defects filled with polyamide foam at the upper side of the core (type (2)) with diameters from 20 to 50 mm, but only the biggest defect with a honeycomb filling became visible. The shearographic method could only detect the type (2) defects filled with polyamide foam and with diameters of 30, 40 and 50 mm. Both methods had problems to find defects with ho-
neycomb fillings. This is especially true for defects in deeper regions of the core. All of the type (3) defects filled with polyamid foam throughout the whole core could be observed by thermography, but none of the defects with a honeycomb filling was detected. For shearography the result was even worse: Only the defects with a polyamid filling and diameters of 30, 40 and 50 mm were found, but not the smaller ones. While thermographic testing was able to find the two heat damaged defects in the middle of the core (type (4) with 20 and 30 mm diameter), shearographic testing showed only a weak indication for the 20 mm flaw. Filled defects at the rear side of the honeycomb core (type (5)) with diameters of 30, 40 and 50 mm were observed by both methods only as weak and faint indications. All defects in deeper regions were not visible from the front side with both methods.

3.3 Inspection of a main landing gear flap

Additionally to composite specimens with artificial flaws a real damaged aircraft component was examined with both test methods. Fig. 13 left shows a main landing gear flap of an aircraft which suffered an impact damage. This component consists of a honeycomb sandwich structure. The right side of Fig. 13 gives a detailed look at the damage area which is emphasized by a red line, while no signs of a damage are visible at the surface. This damage area was firstly recognized by manual ultrasonic testing.

Fig. 14 and 15 show the results of the thermographic and shearographic inspection, respectively. There is relatively good agreement with ultrasonic findings. Size and shape of the damage are similarly recognized with all three methods. With thermographic testing the right part of the impact damage showed only a weak indication, observed in thermal images at a later stage of the cooling process, which means that the corresponding damage should exist in a greater depth of the component. With shearographic testing the observed damage extension normal to the edge of the gear flap is somewhat smaller than found with both other methods while the linear damage extension along the edge was correctly indicated. Nevertheless pulse thermography and digital shearography proved a quick and reliable means for the qualitative detection of the impact damage.

Figure 13: left: overview of main landing gear flap; right: detail with impact damage area

Figure 14: Thermal image of impact damage area; left early image, right late image
4. Discussion

The results for the investigation of the monolithic CFRP laminate panels and sandwich specimens presented above suggest that both methods are most sensitive to surface-near defects in composite materials. Sensitivity is strongly reduced with increasing depth and decreasing size of defects. This is especially true for shearographic testing of the monolithic CFRP laminate panels. While defects in laminate panels could be detected with pulse thermography down to a depth of 4.5 mm, shearographic testing was limited to defect depths of 1.5 to 2 mm. Furthermore in most cases thermographic indications appeared more clearly than shearographic indications. This difference in capability can be explained by the thermomechanical behaviour of the monolithic laminate material and the different excitation sources used for both methods. Fibre-reinforced laminate material shows a high stiffness and a heat conduction that is higher in lateral direction than normal to the surface because of the fibre orientation. Prolonged thermal load over several seconds by use of halogen lamps and a high lateral heat conduction leads to thermal equilibrium, inducing only small differences in deformation and therefore resulting in a strong limitation of the depth of detection. Deeper defects had only little influence on thermomechanical surface deformation. So it seems that heating with halogen lamps is not the best way to induce mechanical deformation for carrying out shearographic testing of fibre-reinforced components.

With regard to thermographic testing the lateral heat conduction of composite materials reduced the contrast of indications while thermal noise was increased. The lateral conduction also limited the depth of detection for this method. But its limiting influence seems to be smaller than for shearographic testing, because a short and intensive heating by flash lamps was used, resulting in a strong thermal non-equilibrium. Amazingly an additional copper mesh layer on top of the panel resulted only in a small increase of thermal noise, while the depth of detection was not affected. It can be supposed that the fraction of the surface not covered by copper and absorbing heat directly was still great enough for a sufficient heat flow in normal direction, while lateral heat flow in the copper mesh plays only a minor role. Firstly with further GFRP and paint layers on top the depth of detection and contrast of indications is clearly reduced because of thermal equalizing processes in these layers.

Amazingly the results of shearographic tests of monolithic CFRP laminate specimens showed a contrary result, which is still unclear: Additional layers of copper mesh, GFRP and paint led to a better contrast of indications and a better detectability of deeper flaws. Perhaps this can be explained by the differences of thermal expansion of the different layers at the interfaces, resulting in greater deformations in the vicinity of defects.

Similar results were observed for investigations of the sandwich composite specimen. Both methods were able to find defects between the front side laminate skin and honeycomb core and defects in different regions of the honeycomb core. In general thermographic testing
proved to be more sensitive in detecting the smaller defects (5, 10, 20 mm diameter) in different depths of the specimen than shearographic testing, while shearographic testing found in most cases only the bigger ones (30, 40 and 50 mm). This can be explained by the higher deformation of the material and the lower influence of lateral heat conduction in the vicinity of the larger defects. Nevertheless both methods had problems to find defects consisting of honeycomb fillings in the core. In comparison to indications of defects consisting polyamid foam fillings the contrast is clearly worse. This is not astonishing because honeycomb fillings represent no real change of thermal resistance and thermomechanical behaviour equally. So it seems that both methods are not the optimal choice to find vertical cracks in a honeycomb core. Furthermore results suggest that it is very difficult or impossible to find defects between the honeycomb core and the rear side laminate skin or in the rear side skin, respectively. So one can conclude that with optical excitation and only one-sided access to measuring objects with sandwich composite structure non-destructive testing is limited to prove defects located in positions from the front side skin to the back side of the core.

In regard of the impact damage in the main gear flap non-destructive testing with pulse thermography and digital shearography showed a good agreement of qualitative results. Thermographic testing could give some qualitative information about the depth of defects by analysing the development of the cooling process. The deeper the defects are settled in the component, the later the corresponding indications appeared in the thermal image. On the other side shearography was also able to detect the impact. The observed damage extension normal to the edge of the gear flap is somewhat smaller than found with both other methods. This can be explained by an increase of the wall thickness with increasing distance to the edge of the component, which means a higher stiffness of the structure and therefore a smaller deformation of component parts far from the edge by optical excitation.

5. Conclusions

This study investigated the capabilities of pulse thermographic and digital shearographic testing with optical heating for the detection of defects in monolithic laminate and sandwich CFRP composite objects. In summary one can say that both test methods proved a quick and reliable means for the qualitative detection of surface and near-surface damages in fibre-reinforced composite components. Thermography showed comparatively better results in regard of finding smaller and deeper defects. This could be explained by the influence of lateral heat conduction which is strong in CFRP composites especially in combination with a prolonged heating as in the case of shearographic testing with halogen lamps. Therefore it seems that optical heating is not the best way to generate mechanical deformation in fibre-reinforced materials. Other methods of inducing mechanical load (e.g. low pressure or vibration) should be more suitable. Corresponding investigations with digital shearography are underway. Nevertheless it seems that this method has a greater potential for the testing of sandwich composites than for monolithic laminate composites because of the lower stiffness.

6. References