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A COMPARISON OF COMPOSITE SPECIMENS DAMAGE AREA MEASUREMENTS PERFORMED USING PULSED THERMOGRAPHY AND ULTRASONIC NDT METHODS

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ABSTRACT

Carbon fiber reinforced plastics (CFRPs) are widely used in aerospace structures due to their high stiffness, strength and good fatigue properties. They are however vulnerable to loads perpendicular to their plane and, while impacted, can suffer significant internal damage decreasing their overall strength. Detecting and sizing such damage is an important task of the non-destructive inspection (NDI) methods. This study was conducted to detect and quantify damage in a set of six impacted even rectangular CFRP specimens designed from a MiG-29 vertical stabilizer's skin. The inspection was done using the ultrasonic (UT) method (based on mobile scanner – MAUS V) and the pulsed infrared thermographic (IRT) method. Each specimen's inside and outside (impacted) surface was inspected separately with IRT, while the outside surface was then inspected with UT. UT provided the most precise measurements of the damage area, while the IRT inspection of the outside surface (which would be accessible on a real aircraft structure) provided underestimated values due to the damage's depth and geometry.

Keywords: NDT,NDI, ultrasonics, infrared thermography, CFRP, BVID, impact damage, composite structures.

INTRODUCTION

Aircraft structures are subjected to damage during service. Numerous cases of damage can occur on ground resulting from a tool drop, collision with airfield equipment etc. Supervision of aircraft structural elements' condition is necessary in order to ensure their safe operation. Non-destructive inspections are conducted to detect damage without altering the object's properties and functionality.

Composites are a group of structural materials used in production of aircraft structural elements. Nowadays, composite elements constitute a large percentage of mass of airplanes such as Boeing 787 or Airbus A350. They are present in military aircraft structures, the vertical stabilizers of the MiG-29 fighter jet are a representative example. The material utilized in these structures consists of multiple unidirectional carbon pre-preg layers and is called Carbon Fiber Reinforced Plastic- CFRP. CFRPs are used due to their low mass, high in-plane strength and good fatigue properties. However, when used in the aircraft skin, CFRP's layered structure makes them vulnerable to loads perpendicular to the plane, which can result in impact damage. Unlike metal structures, on which dents or cracks caused by impacts compromising an element's strength are visible, composite materials can suffer extensive internal damage that manifests only as a small indentation or is invisible from the outside. An impact can lead to creating a complex damage mode, consisting of matrix cracks, fiber fracture, and a delamination – a separation of adjacent fiber layers [2] (Fig. 1). This failure mode can significantly reduce the material's strength, especially compression strength [2],[7]. Such damage is described as barely visible impact damage (BVID).

The area of delamination between subsequent layers in the impacted composite increases with depth. It is important to measure the dimensions of the largest delamination in the impacted area as it helps in determining the damage's effect on structural strength. To perform this task non-destructive inspection methods such as the ultrasonic method (UT) and infrared thermography method (IRT) can be utilized.

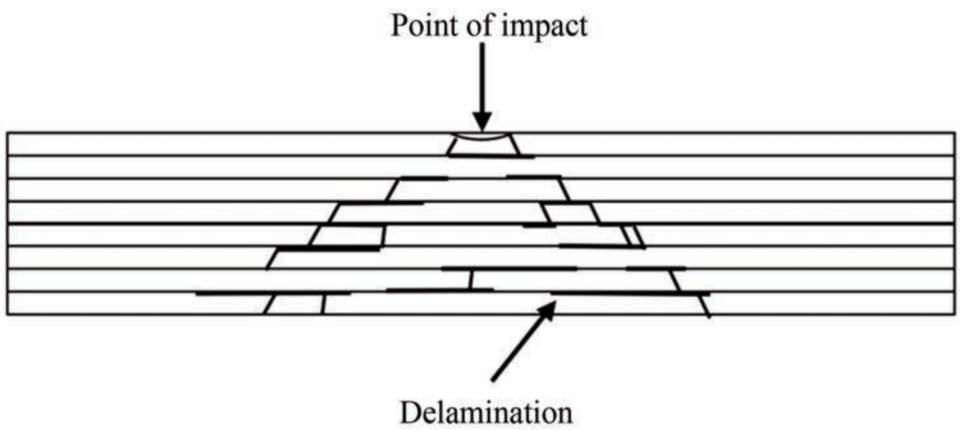


Figure 1. Cross-section of impacted CFRP panel, e.g. aircraft composite skin.

PURPOSE OF WORK

The work's objective is to size the damage area of the impacted composite specimens using two NDI methods: ultrasonic and thermographic, and to compare the results obtained. The point of such comparison is not calculating probability of detection (POD – such comparisons can be found in [3],[8]), but determining the capability of the methods used to provide measurements reflecting the actual size of damage to legitimize of using them as a general or detailed aircraft structures inspection method.

METHODS USED

NDI methods used in this work are the pulse-echo ultrasonic method and pulsed infrared thermography. These methods are approved and widely used in NDI of aerospace composites [1],[3],[4],[5],[6],[8],[9].

Pulsed infrared thermography

Infrared thermography is based on analyzing the temperature field of an inspected object's surface[8],[9]. A technique used in this work is pulsed thermography – the object is heated with a pulse generated by two xenon flash lamps. Subsequently, the temperature is registered using an infrared camera. The temperature field of the homogenous undamaged material is going to be uniform. If a foreign object inclusion, thickness change, a crack or other discontinuity is present in the material, the heat flux is going to be affected. In effect, the surface temperature in the vicinity of the discontinuity is going to be different from the pristine area's temperature. Delamination is one type of damage that can be detected using this method as the separation of layers parallel to the object's surface creates a barrier disrupting the heat flux deeper into the material. The main limitations of this method are the size and depth of a defect. The limit that can be found in literature is often described as approximately 5 mm or 0.2” [8]. The advantages of a thermographic method are associated with its being a non-contact and fast method of inspection, and its ability to inspect complex geometry parts.

Ultrasonic method

The second method used is the pulse-echo ultrasonic method. It involves emitting a mechanical wave into the inspected object and collecting it after it is reflected from the material's back surface. In the pulse- echo technique, the ultrasonic probe acts both as a pulser and a receiver. An ultrasonic wave reflected from a wall opposite to the inspected surface returns to the probe. The returning wave's energy and time of travel provide information on the detected surface's location. If a discontinuity is present between the material's inspected and bottom surfaces, the ultrasonic wave will be reflected and returned to the receiver more quickly. Delamination of a composite creates interfaces between fiber layers and can be detected using the ultrasonic method. This method can provide very precise information on the size, type and depth of damage or defect, particularly when used with a scanning device in a B-scan or C-scan mode. The method's drawbacks are associated with its lower speed compared to thermography and the need to use a coupling (e.g. water, oil, USG gel). Scanning systems and phase arrays can improve the quality and speed of inspection, but are limited by the object's geometry, curvature and physical obstacles such as rivet heads.

INSPECTION

Inspected specimens

Six flat rectangular CFRP specimens of dimensions 150 x 100 mm and average thickness of 4.5 mm were inspected. The specimens were cut out from the composite skin of the MiG-29 fighter jet's vertical stabilizer. The composite stringers bonded to the internal surface of the specimens were removed. The specimens were initially inspected using the pulsed thermographic method to check for the presence of damage. Afterwards, the center point of each specimen was impacted with the energy of 15 J. The specimens were impacted on their outside surface. They were produced as part of the "MIG" project run by the Air Force Institute of Technology for the Polish MoD. The project aim is to develop end experimentally verify the repair technology used for the MiG-29's CFRP and sandwich structures.

Equipment

Pulsed infrared thermography method:
Inspection device: Thermal Wave Imaging Inc. EchoTherm
Excitation method: xenon flash lamps. Heat pulse energy 2 x 2.5 kJ
Infrared camera: FLIR SC7000
Inspected object to camera distance: 30 cm
Inspected object's temperature registration time: 10s.

Specimens were inspected one at a time. Each specimen was inspected twice: firstly the outside surface, the impacted one, was inspected, and after letting the specimen cool down, the inspection of the inside surface was carried out.

Pulse-echo ultrasonic method
Inspection device: Boeing Mobile Automated Scanner- MAUS V
Probe type: normal, single transducer
Frequency: 5 MHz
Probe diameter: 0.25"

The specimens' outside surface was inspected. The inspection of the specimens' inside surface was not possible due to the presence of composite stringers' remnants and surface damage caused by the impactor. USG gel was applied for coupling, and the impact point was secured with tape to prevent the gel from ingress into the damaged structure.

RESULTS

Thermographic inspection results

During each inspection, after generating a heat pulse, the EchoTherm system registers a series of images of the inspected surface's temperature field. For each measurement, one image of the series showing the largest damage area was chosen as representative. Each measurement took approximately 30 second to 1 minute, including specimen positioning.

The results obtained with the thermography method are presented in Figure 2. For each measurement, one image in grayscale is shown. Different shades of gray represent different values of temperature's first derivative. The damage is visible in the central area of each specimen, as shaded areas clearly differ from the surrounding material.

The metal rivets remaining in the structure are visible close to the specimens' edges.

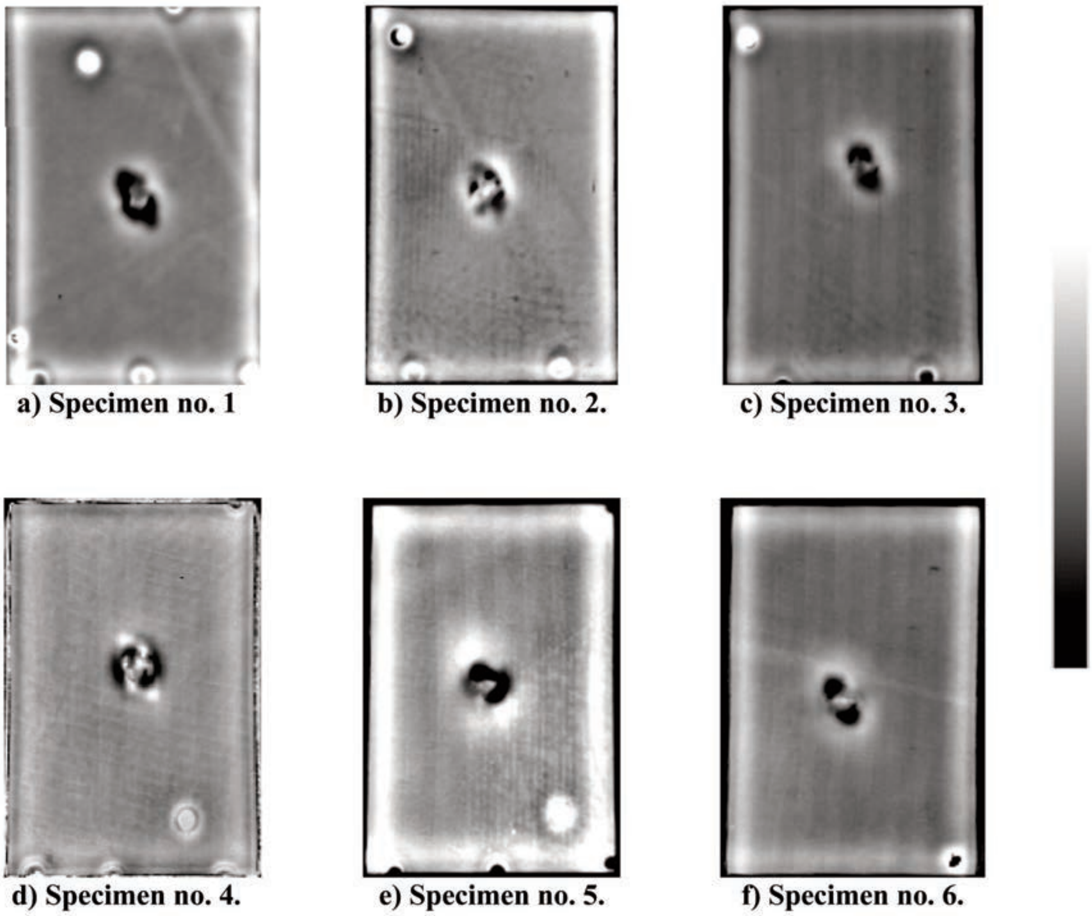
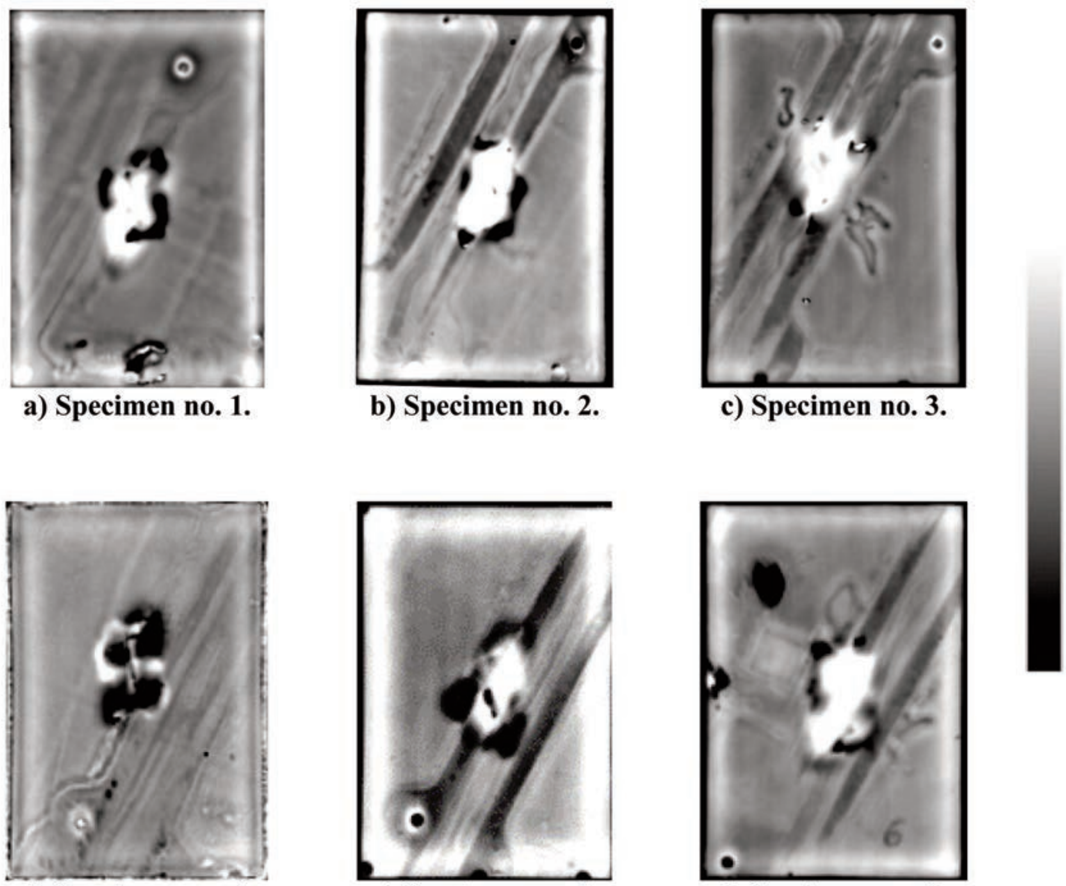


Figure 2. Outside surface. Thermographic inspection result.

Below, in Figure 3 (a÷f), the thermographic results of the specimens' inside surfaces are shown. For each specimen, the damage area visible on the inside surface is clearly larger than the one visible on the outside surface. Besides the rivets, the remnants of composite stringers, located at an angle to specimens' edges, and the irregular shapes of the remaining adhesive can be seen.



a) Specimen no. 1. b) Specimen no. 2. c) Specimen no. 3.

d) Specimen no. 4. e) Specimen no. 5. f) Specimen no. 6.

Figure 3. Inside surface. Thermographic inspection result.

Ultrasonic inspection results

The ultrasonic inspection results are presented in Figure 4 (a÷f) in the form of a C-scan mode as 2D color maps. Each color represents a different depth of detected surface. Black color marks areas with increased signal attenuation, where no reflected signal was registered, or it was too attenuated to be registered. Inspection of a single specimen took approximately 10 minutes.

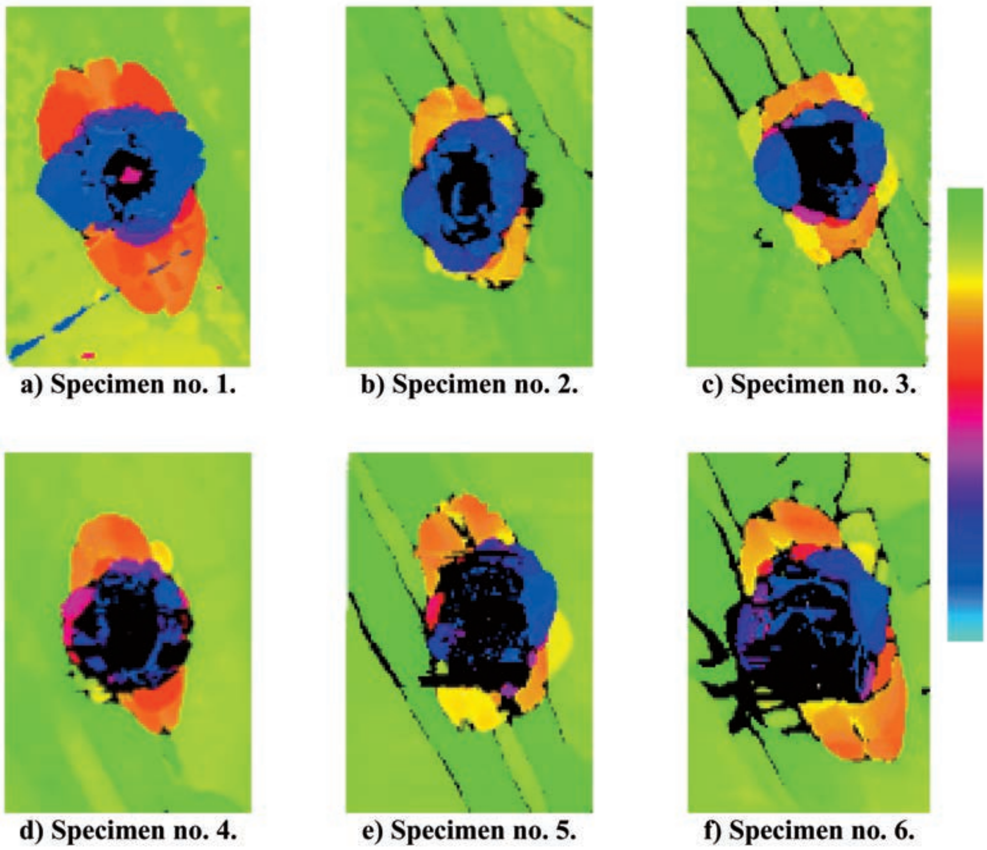


Figure 4. Ultrasonic inspection result.

SUMMARY

Figs. 5÷7 show the sizing of the damage area. A two-dimensional projection of the damage onto the specimen's surface is measured and described as a detected damage's surface area. The inspection results measured this way are presented in Table 1. A graph depicting differences between the results obtained with both methods used is shown in Fig. 8. For each specimen, the ultrasonic method gave the highest value of the measured damage surface. The thermographic inspection of the specimens' inside surface provided lower values in every case, ranging from 74 to 88 percent of the ultrasonic measurement results. Inspecting the outside (impacted) surface of the specimens gave the lowest values of the damage surface area, ranging from 29 to 45 percent of the ultrasonic measurement results.

The ultrasonic method is volumetric, which means that a single-sided access to objects enables inspection of its entire thickness. A single measurement can therefore detect discontinuities located close to the inspected surface, as well as the ones located deep in the material. Scanning resolution can be adjusted. Scans in this work were created with 0.02" ≈ 0.5 mm resolution.

Differences between the results obtained with thermographic inspection for inside and outside surfaces of the specimens are significant and caused by the damage geometry- the largest areas of fiber layers' separation are located near the inside surface (3.5 ÷ 4.2 mm deep), and can remain undetected during inspection of the outside surface. The presence of a paint layer can also be a factor. The irregular shape of the damage also affects the precision of determining its size.

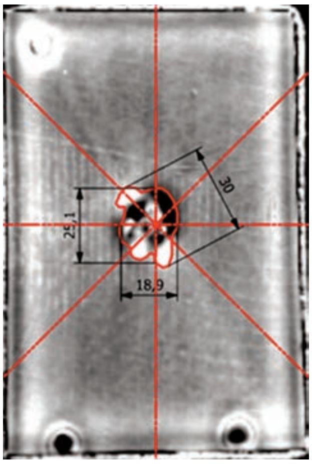


Figure 5. An example of damage dimensioning- thermographic method, outside surface.

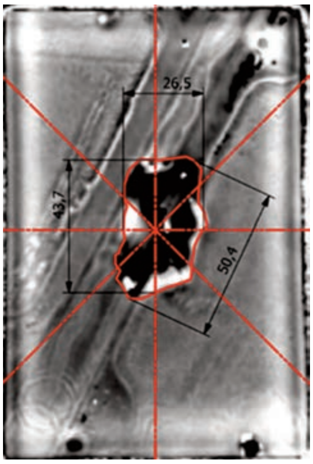


Figure 6. An example of damage dimensioning- thermographic method, inside surface.

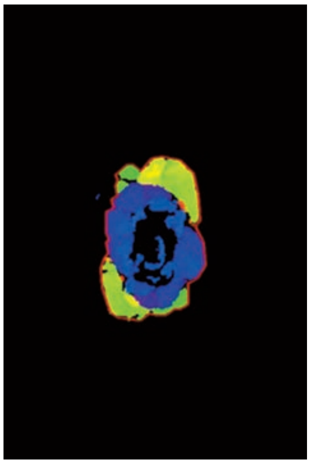


Figure 7. An example of damage dimensioning- ultrasonic method.

	Damage area measured		
Specimen no.	**Ultrasonic method [cm²]**	**Thermographic method- outside surface [cm²]**	**Thermographic method- inside surface [cm²]**
1	16,1	7,0	14,2
2	13,6	5,1	10,7
3	15,1	4,2	12,4
4	15,6	5,2	12,5
5	17,4	7,8	13,4
6	17,6	5,0	13,1

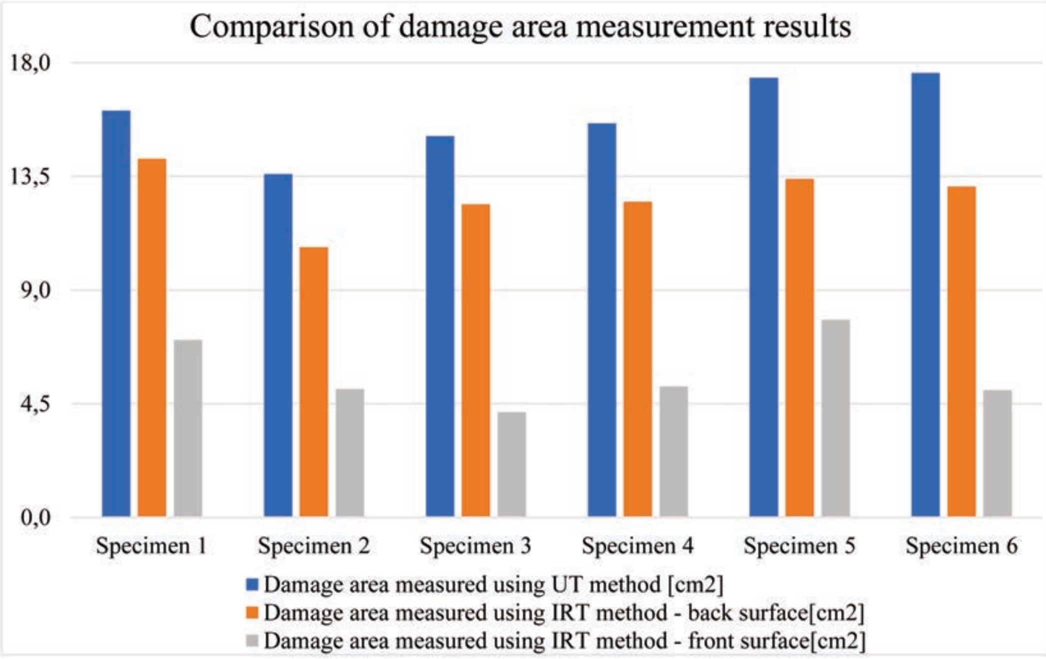


Figure 8. Comparison of damage area measurement results.

CONCLUSIONS

The most precise results were obtained with the ultrasonic method. The thermographic inspection of the outside (impacted) surface provided underestimated results, due to the geometry of the damage. It is reasonable to expect that, with the devices and parameters utilized in this work, an inspection of a real structure would provide underestimated data as well. It has to be pointed out, however, that in spite of the lower precision of damage measurements, all impacts were detected using this method.

Due to the significant underestimation of the damage surface area, the pulsed thermography method in the presented setup should rather be used as a general-inspection method whose purpose is to quickly examine the condition of the structure and to locate damaged areas. Moreover, its capability to inspect objects of complex geometry and curved surfaces, commonly found on military aircraft, confirms its legitimacy in this role. The ultrasonic method remains a more suitable choice when it is necessary to determine the size of a damaged area, e.g. in elements under supervised operation that requires comparing the results of multiple inspections.

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