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A complex approach to the development of the method and equipment for thermal nondestructive testing of CFRP cylindrical parts

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ABSTRACT

Composite materials are being increasingly used in high-tech industries, such as aerospace, automotive manufacture and building inspection. Thermal nondestructive testing (TNDT) has become an accepted method for composite inspection. However, the majority of investigations have dealt with flat or slightly-curved composite components with a thickness of up to 5 mm. Particular studies have been devoted either to NDT modeling with an emphasis on some theoretical issues, or they have been based exclusively on experimental results. There has been some recent interest in the use of composite materials in the nuclear industry. Some critical parts, including centrifuge components, have been made of carbon fiber reinforced polymer (CFRP) composites. The working conditions in a centrifuge include radioactivity and high rotational speed, and the composites used in centrifuges must have very uniform thermal properties and must be free of defects.

This paper describes a complex approach to the TNDT of cylindrical parts made of CFRP by starting from thermal properties measurement, theoretical modeling and preliminary experiments, and finishing with the technical requirements for the development of practical equipment capable of operating in both laboratory and industrial conditions.

The objects tested were CFRP cylinders with a diameter of 150 mm and a wall thickness of 4–6 mm, and they contained some artificial defects of varying size and depth. Both one- and two-sided test procedures have been analyzed for spot, line and uniform heating. Ultrasonic excitation has also been used as an alternative stimulation technique.

In a one-sided test, the depth detection limit has been about 4 mm. Similar results have been observed in the case of ultrasonic stimulation, but the practical implementation of ultrasonic IR thermography to the inspection of cylindrical parts requires further exploration.

In a two-sided test, even fairly mild heating resulted in the reliable detection of all defects independent of their size and depth.

In all test cases, the highest signal-to-noise ratio occurred after applying the technique of principal component analysis.

1. Introduction

Composite materials are being increasingly used in high-tech industries, such as aerospace, automotive manufacture and building inspection. For example, the proportion of composites on civilian airliners has been growing rapidly since the 1970s and is now about 50% on both the B787 and A350. On some modern military aircraft, over 82% of fuselage panels are made of composites. Carbon fiber reinforced polymer (CFRP), or 'graphite epoxy' composites having high mechanical strength at temperatures up to 100°C are ubiquitous in aircraft wing and fuselage components.

There has been some recent interest in the use of composite materials in the nuclear industry. Some critical parts, including centrifuge components, have been made of CFRP [1]. Centrifuges are high-speed rotational machines that perform isotopic separation of uranium in gaseous form. The working conditions in a centrifuge include radioactivity and high rotational speed, and these can be even more challenging than those in aviation. Composites used in centrifuges must have very uniform thermal properties and must be free of defects.

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The most common defects in composites are delaminations and disbonds. Delaminations are separations between layers of a composite laminate, and disbonds are usually a separation between the composite facesheet and honeycomb reinforcement in a sandwich panel. Also, incomplete repairs to composites can result in a variety of defect types. Finally, impact damage and water ingress may occur during use.

In all these cases, the role of nondestructive testing (NDT) cannot be underestimated. A general comparison of NDT methods in the inspection of large composite structures and a bibliography of NDT of composite materials were written by Burleigh [2,3]. Various aspects of characterization of defects in CFRP were discussed by Balageas et al. [4], Maierhofer et al. [5], Montesano et al. [6] and Goidescu et al. [7]. General features of active thermal NDT of composites were summarized by Maldague [8] and Vavilov [9,10].

Thermal NDT (TNDT) works well on CFRP composites due to the following: (1) the absorption/radiation properties of these composites are similar to that of a blackbody in the infrared (IR) wavelength band, (2) their thermal conductivity provides reasonable temperature signals at easily-observable times, (3) due to the laminate structure of CFRP and sandwich panels, all defects are in-plane and they produce thermal resistance to the flow of heat through the panel, and (4) TNDT is a fast, non-contact technique which, unlike the more widely used ultrasonic inspection method, does not require exposing the material to water. Composite materials can absorb water and this is undesirable, as it can cause corrosion of a metallic honeycomb or other metallic materials, it adds weight, it causes changes in the mechanical properties of the laminates, and it could freeze during use.

TNDT has become an accepted method for composite inspection and it is now a standard method in ASNT (American Society of Nondestructive Testing), DGZfP (German Society of Nondestructive Testing) and other certifying organizations. TNDT can sometimes provide quantitative NDT data. An example of this in the aerospace industry is the investigation of the Colombia space shuttle catastrophe that occurred in 2003 [11]. Another example was the US X-33 launch vehicle program [12]. In this program, TNDT was proven to be more efficient than the ultrasonic method because: (1) the TNDT scan rate was much higher than that of the ultrasonic method, (2) TNDT inspection cost was less than that of ultrasonic inspection, (3) TNDT could be performed in the factory area where the parts were fabricated, making it unnecessary to move the parts to the ultrasonic test laboratory, (4) ultrasonic inspection exposes the CFRP facesheet to water, which diffuses through the surface and becomes trapped inside the panel; TNDT does not expose the parts to water and if a part is tested by ultrasonic methods and water gets inside, TNDT can be used to verify the removal of the water, (5) the location of the defects detected by TNDT could easily be marked on the surface of the parts, and (6) TNDT was able to find defects that had not been detected by ultrasonics.

In aviation, TNDT inspections generally remain qualitative because of a lack of data that correlates the severity of defects to measured inspection parameters [13].

However, the majority of investigations have dealt with flat or slightly-curved composite components with a thickness of up to 5 mm, which is typical of aircraft panels. Particular studies have been devoted either to NDT modeling with an emphasis on some theoretical issues, or they have been based exclusively on experimental results.

This paper describes a complex approach to the TNDT of CFRP cylindrical parts used in nuclear engineering applications. Filament-wound composite parts for this application are fairly inhomogeneous, and TNDT modeling should include anisotropy. In addition, CFRP cylinders allow only one-sided access; therefore, the determination of detection limits is an important issue. Also, when cylindrical specimens are heated by optical radiation, for example, by means of Xenon flash or quartz lamps, strong reflections are observed along specimen axis and minimizing the effect of this requires the use of a sophisticated data processing technique. In this study, we start from thermal properties measurement, theoretical modeling and preliminary experiments, and finish with a technical proposal for the development of practical equipment to operate in both laboratory and industrial locations.

2. Test objects and inspection procedures

The objects to be tested are CFRP cylinders with a diameter of 150 mm and a wall thickness of 4–6 mm (Fig. 1). The most typical defects in such parts are delaminations with the accepted detection limit 10 × 10 mm by lateral size, while the limit requirements to defect thickness, or thermal resistance, have not been elaborated by end-users. The maximum allowed temperature of CFRP is 100 °C.

Due to technological reasons, a candidate NDT technique is supposed to be one-sided, however, at the development stage, a two-sided approach has been also considered. In all procedures, point and line heating, as well as extended uniform heating, have been analyzed to optimize a means of sample thermal stimulation (Fig. 2a–c). Fig. 2d shows the alternative case of powerful ultrasonic stimulation sometimes called ultrasonic IR thermography [14].

The experimental section of this study was accomplished by using FLIR SC7700 M (spectral range of 8–10 μm, image size of 640 × 512 pixels, temperature resolution of 20 mK, acquisition frequency of 115 Hz) and NEC Avio TH-9100 (spectral range of 7–13 μm, image size of 320 × 240, temperature resolution of 50 mK, acquisition frequency of 60 Hz) IR imagers in combination with both line and extended heat sources. Within a spot-scanning approach, temperature acquisition was performed with an Optris LS IR thermometer (spectral range of 7–13 μm, spot size of 1 mm).

Two reference specimens (Table 1) were fabricated by a filament-wound process, and each specimen contained 9 Teflon inserts having sizes of 10 × 20 × 0.15 mm, 20 × 40 × 0.15 mm and 10 × 80 × 0.15 mm. The defects were located at the depths of 1.64, 4.0 and 4.7 mm. Note that Teflon inserts represent delaminations in CFRP.

3. Modeling and optimization of heating procedures

3D modeling allows the calculation of dynamic temperature distributions as functions of heating parameters $\{W$ or $Q, \tau_h\}$, material parameters $\{L, K, \alpha\}$ and defect parameters $\{h, d, l, K_d,$

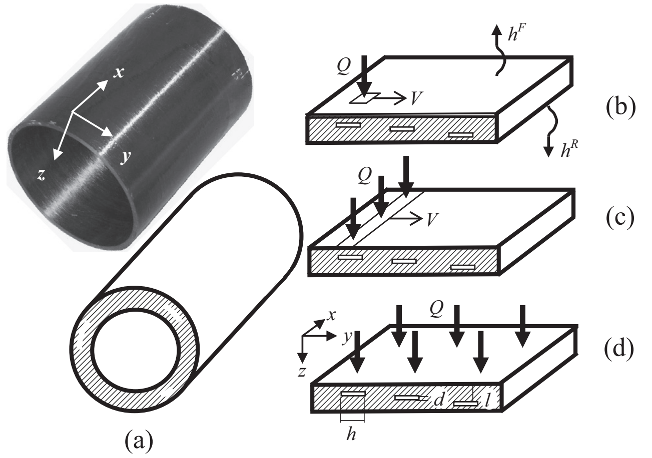

Fig. 1. Modeling heating procedures: a – cylindrical geometry, b–d – spot (a), line (b) and uniform (c) heating, Cartesian geometry.