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A coefficient clustering analysis for damage assessment of composites based on pulsed thermographic inspection

Yifan Zhao*, Lawrence Tinsley, Sri Addepalli, Jörn Mehnen, Rajkumar Roy

Through-life Engineering Services Institute, Cranfield Manufacturing, Cranfield University, Cranfield MK43 0AL, UK

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ABSTRACT

This paper introduces a coefficient clustering analysis method to detect and quantitatively measure damage occurring in composite materials using pulsed thermographic inspection. This method is based on fitting a low order polynomial model for temperature decay curves, which (a) provides an enhanced visual confirmation and size measurement of the damage, (b) provides the reference point for sound material for further damage depth measurement, (c) and reduces the burden in computational time. The performance of the proposed method is evaluated through a practical case study with carbon fibre reinforced polymer (CFRP) laminates which were subjected to a drop impact test with varying energy levels. A novel method for reducing an entire thermogram sequence into a single image is introduced, which provides an enhanced visualisation of the damage area.

1. Introduction

Composite materials are well known for their high strength-to-weight ratios, low density and corrosion resistant properties in comparison with traditional metallic components. As such, they are applied in a wide variety of contexts, increasingly in automotive and aerospace sectors; where there is a huge requirement to improve system performance through weight reduction. With the rising price of aviation fuel and attitude towards environmental issues, modern aircraft manufacturers are looking out for innovative solutions that can offer better performance without compromising the structural integrity and safety features of the aircraft. Thus the current generation of aircrafts are seeing large introduction of composite components that constitute to about 50% by weight of the aircraft in parts such as engine casings, wing sections, tail plane, control structures and fuselage [1]. However, composites are also well known for their vulnerability to impact damage and their difficulty to repair compared to metal based components. An impact or strike on the surface may cause structural damage that may be exhibited with only a small surface visual profile – this is known as barely visible impact damage (BVID) [2]. Even though the damage is 'barely visible' on the surface, the damage to the structure could severely affect its properties and performance, which may not be apparent from the surface profile of the impact.

A variety of impact sources exist, such as stones, hail, bird strike and even accidental drop of workmen tools during maintenance that can cause impact damage. Literature suggests that bird strikes account for up to 80% of service damage to composites in the aerospace sector [3]. While the surface may appear sound, there may be significant damage hidden in the internal structure, and may not be appreciated on the surface because of a difficult relationship between appearance of surface features and structural integrity of the part [4,5]. When the composite structure is subjected to a minor impact damage that is barely visible on the surface, the damage even at the micro scale can progress to significant structural damage that affects the strength, durability and stability of the composite laminates [6].

In the aviation industry, multiple non-destructive testing or NDT methods are employed, ranging from direct visual inspection, dye-penetrant, magnetic particle, eddy current, radiography to advanced methods such as 3D computed tomography, ultrasound and thermography to capture the health and structural integrity of the component without creating or intensifying any further damage to the component that is being inspected. This diversity of inspection methods requires a range of skills and expertise, providing results with differing margins of error between them.

Thermography has been attracting increasing attention over recent decades as the method involves a rapid, robust, non-contact, non-invasive inspection. Thermography can be divided into two modes: passive and active. The passive mode applies where deviations from normal operation exhibit a change in thermal contrast to be observed by an infrared imager, while active thermography involves the input of an external heat that generates a measurable thermal contrast. This particularly applies where an inspected part is not in use and is in thermal equilibrium with its

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* Corresponding author.
E-mail address: yifan.zhao@cranfield.ac.uk (Y. Zhao).

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surrounding environment, when detection of sub-surface damage and defects is sought, or for the measurement of material thermophysical properties. In order to generate a thermal contrast, heat input is designed to highlight damages and defects either using them to generate the heat signal, as in the case of vibro-thermography, or as an obstruction or conduit to heat flow. Thermography in its varied forms has found applications in many contexts such as condition monitoring of electrical equipment [7], mechanical equipment [8], welds [9], structures [10], and aerospace composites [11,12] and Through-Life Engineering [13].

In infrared thermography, various image processing methods are in common use, from the basics of dealing with fixed pattern noise, vignetting, bad pixels and spatial noise smoothing [14], to thermal contrast algorithms [15] which have been further developed over the years [16]. The Thermographic Signal Reconstruction (TSR) [17] algorithm was a landmark development in pulsed thermography which dramatically increased spatial and temporal resolution of a thermogram sequence and opened up the opportunity for new ways of processing pulsed thermography data. Others have applied Principal Component Analysis (PCA) to thermography, also referred to as Principal Component Thermography (PCT), on TSR coefficients that improved the results from typical averaging filters, with comparable results to Pulse-Phase Thermography [18]. PCA analysis has also been applied to a TSR-type treatment of per-pixel signal data [19] in order to differentiate different delamination sizes and lengths, with sensitivity to delamination opening. Additional study has involved use of skewness parameter [20], and high order statistics, with somewhat consistent performance in signal-to-noise ratio for defects of different size and depth [21]. TSR based analysis processes have previously been explored with exciting developments, involving the transformation of the thermography data into a series of RGB colour images synthesised from TSR polynomial coefficients [22]. The data thus obtained may be plotted for each colour shade to estimate contrast emergence times together with depth scaling, and has been applied to both artificial and real damage features [23]. This specific application has been proven to be quite powerful at extracting multiple features into single images.

This paper is limited to focus on damage detection and corresponding sizing measurement with an application in assessing degradation caused by drop impact. Damage detection is important because a number of commonly used feature depth measurement methods, such as Peak Temperature-Contrast [15] and Peak Temperature-Contrast Slope [24], often require a reference point that is known on a sound material. Ringermacher [24] used the average temperature from the entire surface before flash as reference. This can work well only when the defective region is small and the surface is uniformly illuminated. Curve-fitting based methods, such as Shepard's Peak Second-derivative method [25] and Sun's Least-Squares Fitting method [26,27] require fitting either a high order polynomial model or a complex heat diffusion model. A high order polynomial model can experience the over-fitting problem when the model has too many parameters relative to the number of observations, especially when the data is noisy. Although fitting based on a physical model (the model structure being known) reduces the sensitivity to noise, it requires multiple unknown parameters to be estimated simultaneously using optimisation techniques. However, this can be very time-consuming and sometimes only locally optimal solutions are produced rather than globally optimal solutions. Developing a fast, automatic and reliable technique with high robustness against noise for damage detection is therefore a key goal of the community.

2. Experimental data

2.1. Specimen

Specimens were produced with the dimension of 150 mm × 100 mm × 4 mm, which were made of unidirectional Toray 800 carbon fibres pre-impregnated with Hexcel M21 epoxy resin. The laminates were subjected to a drop impact test with predefined energy levels using a semi-spherical 16mm diameter weight drop machine which employed a drop weight of 2.281 kg, as illustrated in Fig. 1(a). The support used to hold the sample in place was designed by following the instructions given by the standard BS ISO 18352, shown in Fig. 1(b).

The weight impact energy is equivalent to $m \times g \times h$, where m refers to impact mass, here 2.281 kg was used, $g = 9.8\ \mathrm{m/s^2}$ is gravitational acceleration, and h is the drop height. Impact energy is adjusted by changing the height of the drop-weight, details of which are shown in Table 1. The specimens were subjected to represent impact energies of 5, 10, 15, 20, 25 and 30 J respectively. As shown in Fig. 2(a), in all samples, each of the damages are clearly visible from the impacted side, but they are hidden or less obvious from the rear surface, as shown in Fig. 2(b).

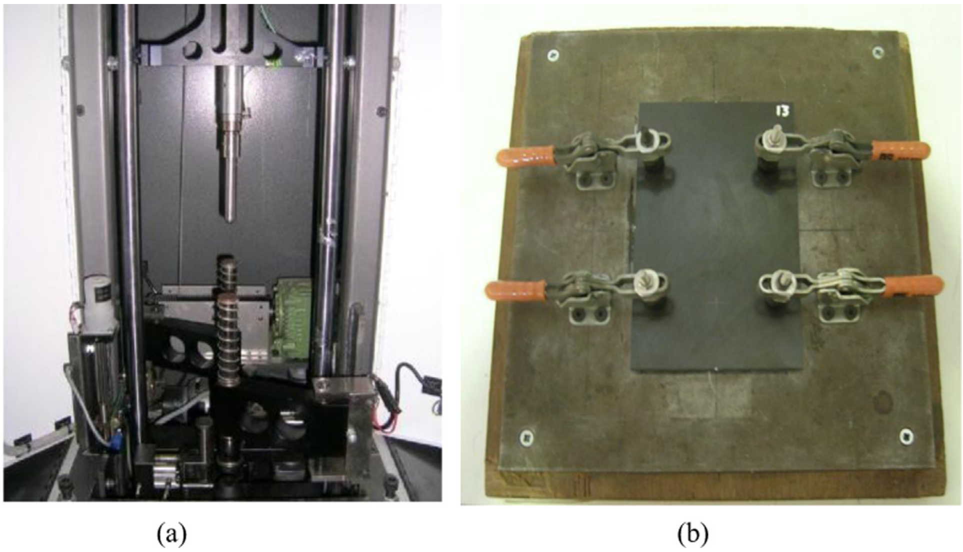

Fig. 1. (a) The weight-drop machine used for impact generation and (b) specimen support fixture.