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Current injection phase thermography for low-velocity impact damage identification in composite laminates

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A B S T R A C T

An innovative non-destructive evaluation (NDE) technique is presented based on current stimulated thermography. Modulated electric current is injected to Carbon Fibre Reinforced Plastics (CFRP) laminates as an external source of thermal excitation. Pulsed Phase Thermography (PPT) is concurrently employed to identify low velocity impact induced (LVI) damage. The efficiency of the proposed method is demonstrated for both plain and with Carbon Nanotubes (CNTs) modified laminates, which are subjected to low-velocity impact damaged composite laminates at different energy levels. The presence of the nano reinforcing phase is important in achieving a uniform current flow along the laminate, as it improves the through thickness conductivity. The acquired thermographs are compared with optical PPT, C-scan images and Computer Tomography (CT) representations. The typical energy input for successful damage identification with current injection is three to four orders of magnitude less compared to the energy required for optical PPT.

1. Introduction

Carbon/epoxy laminated composites are widely employed for structural elements in the aerospace industry due to their enhanced specific properties. Fibre reinforced laminates are suitable for complex geometrical applications, tailored mechanical behaviour and durability depending on the orientation of the layers of the laminate and the employed matrix. However, the anisotropy of advanced composite laminates leads to the initiation and propagation of different "damage entities", often acting/interacting at distinct scales [1,2]. The assessment of their structural integrity, particularly in the presence of aggravating circumstances is of primary importance in order to secure airborne safety and cost efficiency.

The structural integrity of aircraft structures is primarily compromised by in-service fatigue [3]. Additional damage induced by incidental loads may become critical when interacting with cyclic loading. LVI is identified as an extremely hazardous cause of damage as it often induces damage invisible to the naked and may prove critical under certain circumstances [4]. LVI incidents may take place even during a scheduled maintenance service. When a LVI incident occurs, the induced damage tends to expand radially at the interlaminar faces, depending on the local strain energy release rate, which in its turn is governed by the relative change of the elastic properties as the laminae change orientation in the laminate [5].

LVI damage provides a challenging field for the application of a variety of non-destructive evaluation methods [5–8]. Of the many non-destructive techniques, Infrared Thermography (IrT) has proved its efficiency in defect identification and material characterisation processes. IrT is a non-contact technique that provides full-field imaging which is fast and hence, cost effective [7]. With the appropriate stimulation energy, IrT provides thermal imprints of defects beneath the surface of materials giving a visual representation of the internal condition. A major technical difficulty for efficient damage identification with IrT is the uniform thermal excitation of the investigated structure in order to effectually pinpoint any present flaws [9–13].

Within the scope of this work, a novel thermal stimulation technique is developed. For this purpose, rectangular CFRP quasi isotropic plates were subjected to LVI. Two different energy levels were employed for LVI in order to assess the ability of the method to identify various defect sizes. Modulated electrical current was injected through the composite specimens in order to impose the necessary thermal gradient around the damaged area which was monitored using PPT. The anisotropic electrical conductivity and thermal diffusivity of the composite laminate makes the damage identification and quantification with PPT a challenging and demanding task. In this work, LVI induced damage was successfully identified for two impact energy levels and compared with typical optical IR stimulated PPT imaging ultrasonic imaging

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(C-scan), and CT representations of the cross sectional area of the impacted laminates.

2. Background

2.1. Infrared thermography

IrT is a thermal stimulation technique that identifies thermal variations on the surface of structures. Early research works [14,15] identify the potential of these variations to reflect the structural state beneath the surface such as manufacturing flaws, delaminations, or cracks. IrT methods are categorised in active and passive depending on the introduction of thermal stimulation. In the passive configuration, the structure is physically in higher temperature than the ambient and hence no external thermal excitation is needed. In the active approach, external thermal stimulation is employed to thermally excite the material surface, ideally in a uniform way. The presence of thermal gradients on the surface during (uniform) heating or cooling phase are potentially due to underlying damage or discontinuities and are manifested with local temperature extrema on a 2D representation, such as a thermal snapshot captured by the infrared camera [9]. Depending on the source and modulation of the thermal stimulation, a wide variety of different thermographic techniques may be employed. Step Heating Thermography (SHT), Vibration Thermography (VT), Pulsed Phase Thermography (PPT), Lock-in Thermography (LT) and Pulsed Thermography (PT) are typical examples of well-known thermographic techniques [9].

PPT is an active thermographic technique which offers phase and amplitude images of the inspected material. PPT is an inclusive combination of both Pulsed and Lock-in thermography [16]. It is a signal processing technique well developed by Maldague et al. [17]. In this set-up, the structure is heated via a heat pulse. Thermal waves with various amplitude and frequency are generated in the near surface region (Fig. 1) in the presence of flaws. The frequency content of these waves is subsequently analysed by the Fast Fourier Transformation (FFT) so as to acquire both phase and amplitude images [16,18].

The attenuation of the thermal waves is highly sensitive to hidden defects and offers the possibility of quantitatively investigating various materials and structures. In Fig. 1 the PPT concept is depicted. In this schematic representation, the stimulation source is performed optically using a flash lamp [9]. PPT exhibits characteristic advantages over other thermographic approaches, as it provides both amplitude and phase full field imaging. In this configuration, the amplitude images provide deeper probing whereas phase images are less dependent on surface features and non-uniform heating [17,19]. Within the framework of the present study, heat excitation was provided by a square electric pulse injected in the bulk of the laminate with low frequency and thermal stimulation was achieved via the Joule effect.

2.2. Low-velocity impact damage in composite laminates

As aforementioned, LVI damage may cause the premature catastrophic failure of a structural element. This is mainly due to the reduction of the effective cross section of the laminate which makes it prone to buckling failure. LVI damage depends on many different variables. The “suspicious impactor” may come from a large number of adverse elements, vehicles, devices, tools etc. The impacted area may be one of the many exposed regions to the many candidate impactors [5]. For most LVI incidents, the surface of the composite appears intact.

The laminated structure of an advanced composite is inherently responsible for LVI damage. Damage is usually manifested as blind interlaminar failure due to step changes in the elastic properties of the material in the through thickness direction [20]. In its turn, the matrix undertakes the role of sustaining interlaminar integrity or arresting further delamination [4]. Generally, there are two types of impact damage which are encountered in multi-layered laminates: the dynamic compression of the laminate cross section at the percussion front and the multiple delaminations between the particular layers of the laminate. The type of the resultant damage is always a function of the fibre volume fraction, type of fabric and resin, fibre orientation of the particular layers as well as velocity, mass and geometrical characteristics of the impactor element [21,22]. LVI initiates more pronounced delaminations at the interlaminar areas where there are major changes of the reinforcement direction [23]. In general, LVI induced composite damage is categorised into four main groups, matrix cracking, interlaminar failure (delamination), interfacial failure (fibre–matrix debonding) and fibre failure [5,24]. Contrary to LVI, at high velocity impacts, fibre splitting and penetration are frequently encountered [24]. Fig. 2 depicts intralaminar cracking and delaminations observed after a low velocity impact.

2.3. Current injection thermography

Many stimulation techniques have been developed in years with respect to active IrT. Ultrasound [25,26], cyclic loading [10,27], optical excitation (with incandescent or flash lamps) [25], or vibrations [9], are frequently employed as sources of thermal stimulation. Fundamental to a thermal stimulation protocol is

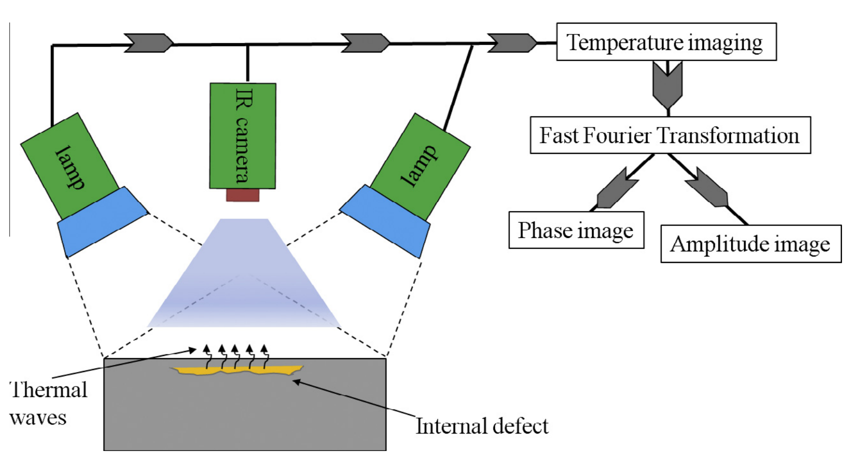

Fig. 1. Pulsed phase thermography; optical excitation mode.