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Edge-illumination X-ray dark-field imaging for visualising defects in composite structures

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ABSTRACT

Low velocity impact can lead to barely visible and difficult to detect damage such as fibre and matrix breakage or delaminations in composite structures. Drop-weight impact damage in a cross-ply carbon fibre laminate plate was characterised using ultrasonic C-scan measurements. This was compared to the results provided by a novel X-ray imaging technique based on the detection of phase effects, which can be implemented with conventional equipment. Three representations of the sample are provided: absorption, differential phase and dark-field. The latter is of particular interest to detect cracks and voids of dimensions that are smaller than the spatial resolution of the imaging system. The ultrasonic C-scan showed a large delamination and additional damage along the fibre directions. The damage along the fibre directions and other small scale defects were detected from the X-ray imaging. As the system is sensitive to phase effects along one direction at a time, the acquisition of an additional scan, rotating the sample 90° around the beam axis, provides information in both fibre directions. These two techniques enable access to a set of complementary information, across different length scales, which can be useful in the characterisation of the defects occurring in composite structures.

1. Introduction

Composites are widely used in aerospace and wind energy applications as they offer significant advantages such as high strength to weight capacity. However, one major concern related to composite structural integrity is the susceptibility to low-velocity impact damage. Such impacts can result in various forms of barely visible damage modes that can lead to a severe reduction in strength and integrity of composite structures [1]. The severity of the different damage modes depends on a variety of parameters such as the velocity and mass of the impactor and the material orientation of the composite structure [2,3]. The failure process caused by low-velocity impact in composites is a complex phenomenon: matrix cracking, delamination, fibre debonding and breakage are examples of various failure modes [4]. The mechanism of damage initiation and propagation has been investigated [5] and evidence of extensive delamination in the region adjacent to the failure zone has been reported [6].

Therefore, it is important to efficiently monitor the composite structure during its service life to detect different damage types and to ensure the safe operation of the structure [1]. A variety of non-destructive testing methods are utilised for post-fabrication and in-service inspection [7–9]. Ultrasonic C-scans have been found to provide very sensitive measurements of the location and size of damage, especially for delaminations [10–12]. Ultrasound has been demonstrated to detect and map out-of-plane ply wrinkling, in-plane fibre orientation and porosity in composites [13]. X-ray systems are especially suited for the detection of internal defects that cannot be detected by visual inspection [1]. Dye penetrant has been widely used to overcome the limited X-ray contrast in carbon fibre composites [7,14]. Micro CT scans enabled the 3D visualisation and characterisation of different damage types in composites, including voids and micro cracking [10,15]. Detailed 3D models of composite structures with defects have been developed based on C-scan and CT scan data [13,16].

X-ray phase-contrast imaging (XPCI) extends the application of conventional radiography to those area where low-contrast details have to be observed non-destructively. This is obtained through the sensitivity of the modifications of the phase of the X-ray beam caused by the sample [17]. XPCI finds application in a wide range of fields, encompassing medicine and biology, security and materials science. Several approaches exist for obtaining phase-contrast images in the X-ray regime, using large-scale synchrotron facilities and more compact X-ray-tube-based equipment [18–27]. Details

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on the imaging methods, developments and their applications are covered in recent reviews on the subject [28–30].

Here we focus on edge-illumination (EI) [25], and its area-imaging implementation sometimes referred to as "coded-aperture" [31], which are XPCI techniques enabling quantitative amplitude and phase retrieval [32]. EI can be adapted for use with several types of radiation sources, including synchrotron radiation [25], rotating anode [31,32] and microfocal [33] X-ray tubes; notably, its compatibility with compact, laboratory-scale equipment makes it particularly attractive. EI hard X-ray dark-field imaging was also recently developed [34], that provides a third representation of the sample which is linked to sub-pixel length scale density fluctuations.

We present the application of EI dark-field imaging to the visualisation of defects occurring in a cross-ply composite plate after impact damage. The sample, the ultrasonic C-scan setup and the X-ray dark-field imaging system are described. The images obtained by means of such systems are presented and compared to conventional radiography. Details that are not detectable in the standard absorption radiography are highlighted with the XPCI system, and a comparison with the ultrasonic C-scan shows the complementarity of these techniques.

2. Materials and methods

2.1. Cross-ply specimen

The specimen was supplied by the Composite Systems Innovation Centre, University of Sheffield, and had been investigated in a separate study [35]. The composite plate (990 mm × 110 mm × 2 mm) was fabricated with unidirectional prepregs by autoclave cure using Cytec 977-2/ Tenax HTS cross-ply laminates. The plate consists of 8 prepreg layers with a symmetric layup sequence of [0/90]2s. Additionally, the plate contains a 25 μm thick polyimide film and an 18 μm thick layer of flexible printed circuit boards for electrical resistance measurements [35]. The specimen was subjected to a 7.4 J impact damage using a hemispherical 15 mm impactor head following standard drop weight impact procedures. A small degree of fibre fracture and indentation was visible on the surface of the plate.

2.2. Ultrasonic C-scan

In order to obtain an approximation of the size, shape and depth of the impact damage in the defective composite plates, two immersion ultrasonic C-scans were performed. The plate was cut to 200 mm length, keeping the 110 mm width. The impact was located approximately at the middle of the cut-out plate. A 10 MHz unfocused ultrasonic transducer (Panametrics V312, 1/4 inch diameter) was used. For longitudinal waves travelling in the thickness direction of the composite plate at approximately 3000 m/s speed, the wavelength was estimated to be about 0.3 mm, comparable to the thickness of a pre-preg layer. The transducer was mounted perpendicular to the surface of the plate to a computer-controlled stepped motor driver. The scanned area was 80 mm × 40 mm with a step size of 1 mm in both the width and length direction. The pulse-echo signal from the pulser-receiver unit (Panametric 5601T) for each scan point was acquired using a digital storage oscilloscope (LeCroy 9304) and saved in the computer for further analysis in MATLAB with 500 time points and a sampling frequency of 100 MHz. For the first, double-through transmission scan a 12 mm thick steel plate was placed 5 mm below the composite plate in the water bath. The time-gate was set around the pulse reflected from the steel plate and the maximum amplitude for each scan point extracted. A second C-scan was performed to record the ultrasonic pulse reflected at the composite specimen (Fig. 1). Two different time gating settings were used. The first time gate was set to capture the positive maximum of reflections from the front surface. The second time gate was set to capture the negative minimum amplitude that corresponds to the reflections within the plate. Based on the total time of flight compared to the front reflection, the depth of the defect location can be estimated.

2.3. X-ray imaging

The typical experimental set-up for an EI imaging system is composed of an X-ray source, a sample mask that shapes the beam before it interacts with the sample, and an analyser which is composed of a second mask and a digital detector. A sketch of the system is shown in Fig. 2. The parameters used for this experiment are as follows. The source to detector distance was $z_{sd} = 2$ m while the sample to detector distance was $z_{od} = 40$ cm, with a geometrical magnification of 1.25. The source was a molybdenum target, rotating anode X-ray tube (Rigaku, MM007), operated at 40 kVp and 20 mA, with a source size of approximately 70 μm. The pitches of the two masks are $p_1 = 67$ and $p_2 = 83.5$ μm, and the apertures $a_1 = 12$ and $a_2 = 20$ μm, for the sample and detector mask respectively. The masks were manufactured to the authors' design by Creatv Microtech (Potomac, MD) and had a gold thickness of about 30 μm and a field of view of about 5 cm × 5 cm. The alignment of the system was performed by means of two stacks of Newport

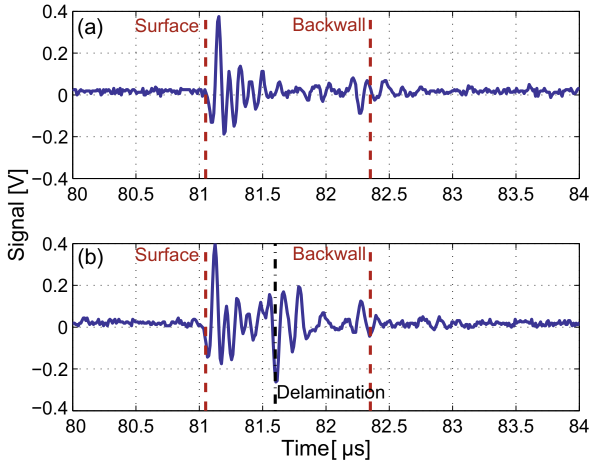

Fig. 1. Typical ultrasonic signals reflected at composite plate; pulse-echo mode; unfocused 10 MHz centre frequency immersion transducer; (a) undamaged part with front and back wall echo marked; (b) damaged part with additional delamination echo marked.

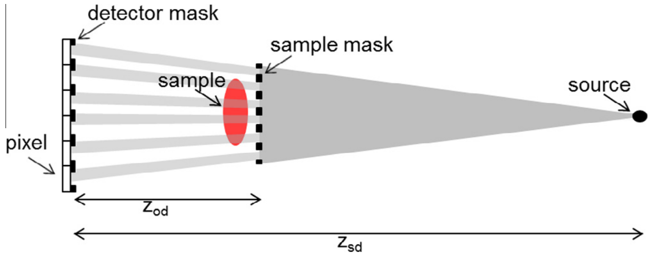

Fig. 2. Sketch of the EI imaging system used for this experiment. A rotating anode X-ray tube produces a polychromatic beam that is shaped into an array of laminar beamlets before it reaches the sample. After interacting with the sample, each beamlet is analyzed by means of the edge of a second mask, placed right in front of the detector.