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Characterising the behaviour of composite single lap bonded joints using digital image correlation

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ABSTRACT

Three-dimensional and two-dimensional Digital Image Correlation (DIC) have been used to evaluate the evolution of deformation and strain in composite single lap bonded joints prior to failure. In general, composite components are increasingly being joined using structural adhesives for aerospace and other safety critical applications. Reliable design requires that the mechanical behaviour of composite bonded joints is well understood. In this respect, experimental tests are crucial to (a) characterise the deformation and strains induced under load and (b) develop and validate realistic numerical models. Although modern numerical models contain many degrees of freedom, only a few degrees of freedom are typically measured using conventional instrumentation such as strain gauges and extensometers. However, 3D DIC provides an opportunity to measure full-field deformations and surface strains. In the current study, 3D DIC was successfully used to measure full-field in-plane surface strains and out-of-plane surface deformations for composite single lap bonded joints (adherends manufactured from both fibre preimpregnated resin (pre-preg) and resin infused non-crimp-fabric (NCF)). Moreover, strategically located strain gauges were used to validate the strains measured by 3D DIC. Finally, 3D DIC measurements may be useful in detecting subcritical damage as shown in the case of the pre-preg joint. The specific location and magnitude of the maximum principal strain in the adhesive fillet region were determined using high magnification 2D DIC.

1. Introduction

Pre-preg composites consisting of carbon fibres pre-impregnated with resin are traditionally used in applications where performance, material qualification and consistency are of paramount importance such as in the aerospace industry [1]. However, the high cost of pre-preg material and associated manufacturing process has seen an increase in the usage of resin infused non-crimp-fabric composites in aerospace structures [2,3]. Adhesively bonded non-crimp-fabric composites have significant potential for use in primary as well as secondary structural aerospace applications. With regard to joint configuration, the single lap joint is widely used to evaluate the bond quality in aerospace structures [4]. This joint configuration causes secondary bending to occur under tensile loading due to the eccentric load path inherent in the joint geometry. It is important to characterise the surface strains and out-of-plane deformation occurring in these joints to develop accurate numerical models for structural design and analysis purposes.

In the past, strain gauges [5–7], Moiré interferometry [5] and photoelasticity [8] have been successfully used to characterise single lap joints. However, a number of issues may compromise strain gauge measurements, including (1) surface contact requirement, (2) bonding of strain-gauges (e.g. surface preparation, and misalignment), (3) single point information, and (4) transverse sensitivity of resistive strain gauges. The principal advantage of the 3D DIC system over conventional instrumentation is that it provides full-field strain and out-of-plane displacement information for hundreds of points for one test specimen [9]. For uniform strain fields, the results may be further averaged to provide a statistical mean.

In general, DIC is an advanced, image based, noncontact, full-field deformation measurement method capable of analysing materials under-going thermal, mechanical or variable environmental loading [10]. The method has been applied in many fields such as civil engineering [11,12], mechanical engineering [13], material science [14–16] and biomedical engineering [17,18]. In relation to materials testing, the technique involves tracking the movement of a naturally occurring or an applied surface pattern as load is applied to a specimen during a mechanical test. Full 3D surface measurements can be achieved with stereoscopic multi-camera arrangements. The DIC technique has been described by several authors—see Pan et al. [19]; for example, a synopsis of the

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procedure is sufficient here. First, a series of digital images are acquired during specimen loading. The first 'reference' image is normally captured at zero load and corresponding zero strain. Post-acquisition, the area of interest is divided into discrete pixel blocks containing a minimum number of distinct surface features. Each subset should have a unique signature pattern. A correlation function based on the sum of the squared differences of the pixel grey values is minimised to determine the distortion of the signature patterns from image to image. Strain values are subsequently derived from the deformations often using a central difference scheme.

Similar to conventional strain measurement techniques, experimental challenges are associated with the DIC technique. Haddadi and Belhabib [20] identified key sources of errors inherent in the DIC technique which include lighting, speckle pattern, subset size, grid pitch, data filtering and out-of-plane displacement (2D DIC). Speckle size in conjunction with the subset size was also found to influence the accuracy of measured displacements [21]. Lava et al. [22] stated that major attention should be given to the perpendicular alignment of the camera to the specimen surface (2D DIC). However, 3D stereo systems can largely compensate for oblique angle observation [22] and significant out-of-plane displacement [23]. Unfortunately, the accuracy and precision of 3D systems are typically not as good as those of a perpendicular 2D set-up [22], and the calibration procedure tends to be complicated. Tung and Shih [24] recently proposed a simplified 3D DIC system (using only one image capture device) to improve measurement precision. Distortion correction was cited as a key factor in improving measurement precision.

The primary objective of this study was to investigate the use of the 3D Digital Image Correlation (DIC) technique to evaluate the in-plane strain and out-of-plane deformation of single lap joints under quasi-static loading conditions. In general, composite laminates exhibit relatively low strains ($<5\%$) at failure and consequently the application of DIC is challenging in terms of achieving good strain precision. The second objective was to evaluate the surface strains in the adhesive fillet region of a single lap joint and locate the maximum principal strain prior to failure of the bonded joints. As the thickness of adhesive bondlines is typically in the range of 100–1000 μm, experimental strain analysis of the adhesive bondline by means of conventional strain gauging was not possible. The use of high magnification 2D DIC for measuring bondline strains has not been extensively studied [25,26].

The current study focuses on the application of both 3D and 2D DIC to characterise composite single lap bonded joints manufactured from pre-preg and non-crimp-fabric laminates. Section 2 summarises the manufacture and testing of the composite single lap bonded joints. The experimental set-up, test procedure and the precision associated with the 3D DIC method is described in Section 3. Finally, the 3D DIC and 2D DIC high magnification results are presented and discussed in Section 4.

2. Materials and methods

The manufacture, testing and static failure behaviour of the single lap joints presented in this section have been described by the authors in detail elsewhere [27]. The most important aspects are summarised in this section. The pre-preg (Hexcel HTA/6376) and NCF (Bi-directional (0°/90°) carbon fibre NCF, from Saertex) composite panels were bonded using a two-part research grade epoxy paste adhesive in a hot drape former (HDF2 from Laminating Technology) and cured at 80 °C for 4 h under 1 bar vacuum pressure. Single lap joints were then cut from the bonded panels using a wet diamond edged cutting wheel.

Fig. 1 shows the final specimen dimensions which were in accordance with ASTM D 5868-01 [28].

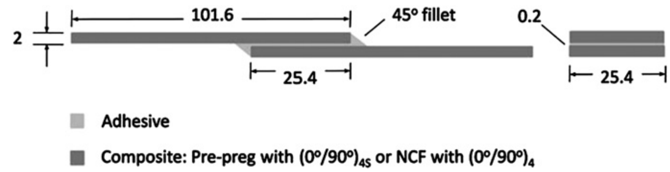

Fig. 1. Composite single lap bonded joint with nominal dimensions in millimetre.

Table 1
Details of quasi-static tensile tests on single lap bonded joints.

Composite	Laminate[a]	Number of tests	Failure load (kN)	Standard deviation
Pre-preg	$(0°/90°)_{4S}$	5	12.4	1.6
NCF	$(0°/90°)_4$	5	13.2	1.0

[a] Surfaces were treated with O_2 vacuum plasma.

X-ray microtomography (XMT) using a Phoenix X-ray nanotom (GE Sensing and Inspection Technologies) was employed to evaluate the void content in the adhesive bondline. A representative test specimen of each single lap bonded joint was scanned. The void content in the bondline of the pre-preg and NCF joints was 9.2% and 11.6% respectively at a voxel size of 16 μm.

Quasi-static tensile tests were conducted on the pre-preg and NCF composite joints to determine the static strength at room temperature. The tests were performed at 0.01 mm/s cross-head displacement rate using a Dartec servo-hydraulic testing machine fitted with a 100 kN capacity load cell. Joint details and test results are given in Table 1.

3. Equipment and methodology: 2D and 3D DIC

The experimental arrangement and methodology for the 3D and 2D DIC tests are detailed in this section. Representative pre-preg and NCF composite single lap joint were selected from each batch (Table 1) for testing with 3D DIC. A representative NCF composite single lap joint was chosen for testing with high magnification 2D DIC.

3.1. Experimental arrangement: 3D DIC

The 3D DIC apparatus consisted of (a) two Imager E-lite 2M cameras fitted with 50 mm lenses, (b) two gated white light sources and (c) a computer complete with Davis Strainmaster® software (La Vision, GmbH). The 3D DIC experimental arrangement is shown in Fig. 2.

It was possible to offset the hydraulic grips to accommodate the asymmetric nature of the single lap joint and to obviate the need to bond end tabs to the specimen. The charge coupled device (CCD) chips were 12 bit and had a spatial resolution of 1626×1236 pixels and a pixel size of $1.4\ \mu m \times 1.4\ \mu m$. Each light source contained $12 \times$ LEDs in a linear configuration. The working distance of each camera from the specimen and the included angle between the cameras was approximately 500 mm and 80°, respectively.

Fig. 3 shows the composite single lap bonded joint in the tensile testing machine. The speckle required for the 3D DIC strain measurement is evident in the overlap region. Extensometers (Epsilon 3542) with a gauge length of 50 mm were employed to measure the local stiffness of the joint across the overlap. The global stiffness of the joint was determined using the cross-head displacement. Furthermore, the specimen was instrumented