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# An experimental study of the behaviour of delaminations in composite panels subjected to bending

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ABSTRACT

Delamination is one of the most common forms of damage suffered by laminated composites and often occurs as a consequence of manufacturing defects or an impact. This paper reports an investigation of the buckling behaviour and resultant damage modes in delaminated composites subjected to four-point bending. The stereoscopic Digital Image Correlation (DIC) method was used to measure full-field deformations and to evaluate maps of surface principal strains in Carbon Fibre-Reinforced Plastic (CFRP) laminates with artificial delaminations. The effect of delamination size and shape on buckling behaviour was investigated using circular and elliptical delaminations in thin beams under four-point bending. For circular delaminations, initially the delamination grew along the transverse direction and then changed to the longitudinal direction. For elliptical delaminations, the delamination grew only along the longitudinal direction. Furthermore, the orientation of the delamination had a small influence (10–15%) on the critical delamination-buckling load, which decreased with increasing ratio of minor to major axis length of the delamination.



## 1. Introduction

The versatile properties and their potential for saving weight have caused Carbon Fibre-Reinforced Plastics (CFRP) to attract much attention from the aerospace industry. In laminated composites, delamination is the most common form of damage and can result from manufacturing defects or the effect of events during the service life, such as impacts or slamming. When a composite plate with a delamination is subjected to in-plane compression or a bending load, initial localised buckling occurs in the delamination due to its reduced flexural stiffness, which increases with increasing load [1]. However, other failure features such as cracks in the matrix, fibre breakage and fibre/matrix debond can also appear. The ultimate failure of a composite plate with a delamination is usually associated with these damage mechanisms. A deep understanding of the interaction of these damage mechanisms and failure processes is important for engineering applications and was the focus of this study.

The topics of buckling behaviour and delamination growth have been studied widely in last two decades. Extensive research work has been undertaken to investigate delamination-driven buckling under compression loading. The "thin film" model developed by Chai et al. [2] was the earliest analytical model proposed to predict the local buckling load in composite panels, and considered a single through-width delamination only. Further models, such as a delaminated sub-laminate on an elastic foundation [3], have been used to investigate the delamination buckling behaviour of composite laminates. Subsequently, the effect of transverse shear [4,5] was also considered. The finite element method has been used to study buckling and post-buckling behaviour of composite structures containing arbitrary shaped or multiple delaminations and subjected to compressive loading [6–8]. Experimental studies designed to validate analytical and numerical models have also been reported [9,10].

However, bending-induced compression of structures in real load scenarios is more common than pure compression [11]. Kardomateas [12] employed an analytical model based on the "sub-laminate" model to predict buckling loads for delaminated composites under pure bending and compared them with experimental results. Murphy and Nichols [13] developed a low-dimensional model of a delamination in a laminated beam and used experiments to validate the analytical results. Kinawy et al. [14] developed a mathematical model based on the Rayleigh–Ritz approach to analyse the buckling and post-buckling behaviour of a delaminated composite structure in bending. Most experimental studies including those cited above are confined to single

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through-the-width delaminations [11,15], i.e. delaminations that extend across the entire cross-section of the test specimen and are usually perpendicular to the applied loading, almost none consider laminated composites with partial delaminations, i.e. ones that do not extend across the full cross-section. In addition, these experiments tend to follow a traditional approach to obtaining experimental data based on strain gauges and hence lack comprehensive information about damage development such as delamination shape and location. Hence, it is apparent that the buckling behaviour and growth of delaminations is still an open field for exploration by experiment.

On a parallel path, damage initiation and progression in laminated composites due to matrix and fibre cracking have been studied extensively, including experimental studies aimed at investigating the initiation and growth of damage [16–19]. From an experimental point of view, the process of damage in composite plates involves a number of damage modes, including cracking along fibres, which is the first damage observed in most cases. Wang [20] investigated analytically the various cracking events in unidirectional composite plates subjected to uniaxial tension. Transverse cracks occurred first and these cracks continued to form in increasing numbers with increasing applied load. Subsequently several other matrix-dominant cracking modes emerged. Rebiere and Gamby [21] employed a variational approach to investigate the damage mechanisms in unidirectional composite laminates. An energetic criterion based on the strain energy release rate was used to predict the damage initiation and growth. However, none of these cited studies consider the interactions between delamination and matrix/fibre cracking under generalised load conditions. Riccio [22] investigated the effect of fibre–matrix failure on the buckling behaviour of a delaminated composite panel subjected to compression load, based on a geometrically nonlinear finite element approach.

This study explores the experimental methodology required to evaluate the buckling and post-buckling behaviour of CFRPs laminates containing a near-surface embedded delamination subject to four-point bending. Full-field maps of displacement and strains have been obtained using Digital Image Correlation to explore the failure phenomena and damage mechanisms of CFRP laminates with an embedded delamination. In this study, we have also investigated the influence of the shape, orientation and the size of the delamination area, in order to enhance our understanding of the interaction between the buckling behaviour and the delamination growth as well as providing data on the post-buckling load capacity of the laminate.

## 2. Experimental procedure

### 2.1. Specimen preparation

Laminate specimens nominally 260 × 25 mm were manufactured from MTM 57/T700 (Umeco, Heanor, UK) pre-preg CFRP layers with a resin content of 38% by weight. For most delaminations caused by impact damage, Melin and Schön [23] found that delaminations were substantially larger adjacent to the opposite face to the impact and buckling behaviour induced by the delaminations near the surface of the opposite face was larger in extent and magnitude than near the impacted surface. Furthermore, Butler et al. [10] found that the delaminations from which propagation will occur were at depths of less than 25% of the total thickness. Hence, based on the above evidence, artificial delaminations were introduced between an outer laminate and the adjacent inner one. The stacking sequence of the laminate was [0//90/0/90/0/90/0/90/0/90/0], where "//" was the through-the-thickness location of the delamination. The fibre orientation of 0 degrees was aligned with the longitudinal axis of the laminate. During layup, a PTFE film of 0.08 mm thickness was placed in the centre of the specimen between the first or upper and the second layers to prevent adhesion and create an artificial delamination. Circular and elliptical pieces of PTFE film were used with diameters of the order of 10 mm. In order to fabricate the laminate, the specimen was cured by using a temperature cycle in a hot press (Meyer, USA) at pressure of 3 bar. During the cure cycle the temperature of the laminate was raised at a rate 3 °C/min up to 120 °C and held for 1 h. The relatively slow heating rate allowed the epoxy matrix to fully infuse the carbon fibre. Subsequently, the laminate was cooled down naturally to the room temperature at the same pressure. The curing process influences the final thickness of the laminate and the process described above produced a laminate of nominal thickness 2.60 mm. The laminate produced in the manufacturing was made oversize to avoid introducing edge effects into the specimen which was produced by trimming the manufactured laminate to 260 mm long by 25 mm width using a wet diamond saw (Vitrex 103450, UK).

The displacements of the specimens was measured using Digital Image Correlation, so prior to performing any experiments, the upper face of the specimen was spray-painted with a uniform thin coat of white paint (Pro Paint Matt White, CRC, UK) and then a black speckle pattern (Super Multipurpose Spray Paint Matt Black, Plasti-Kote, USA) was sprayed on the top of the white paint to provide an adequate contrast following the guidelines provided by Sutton et al. [24] such that the typical diameter of the speckle was 0.1 mm (see in Fig. 1). This was a compromise because a small speckle size increases the accuracy of measurements but reduces the probability of correlation with large deformation. The coating thickness was as thin as possible to ensure it was a reliable witness for the deformations on the surface of the specimen and to avoid it peeling under large deformations. Since the delamination was located nominally in the centre of the specimen, the region of interest (ROI) was centred on the axes of symmetry of the specimen and was 50 mm long by 25 mm width, i.e. the same width as the specimen.

### 2.2. Ultrasonic imaging

An automated ultrasonic inspection system (Midas NDT, UK) was employed to examine each specimen. The system consisted

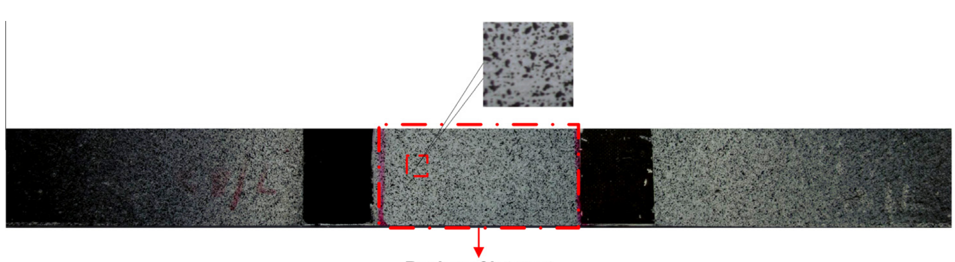


**Fig. 1.** Photograph of a typical CFRP composite specimen (260 × 25 mm) showing the region of interest (chain box) for which displacement data was acquired using Digital Image Correlation based on the painted speckle pattern shown inset.