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Research article

# DELAMINATION BUCKLING IN FOUR-POINT BENDING TESTS – AN EXPERIMENTAL INVESTIGATION

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**ABSTRACT**

A set of carbon-fibre laminated specimens have been subjected to (static) four-point bending tests to assess the conditions for delamination induced by local buckling events of the compressed lamina. Testing conditions prescribed by the ASTM D7264/D7264M-1 standard, valid for monolithic samples, have been followed. It is worth noticing that the delaminated area, which is loaded in compression, at a certain point reaches a critical value and snaps upwards. During the experimental campaign, the applied load and the corresponding displacements have been recorded, as well as the length of the crack and the deformation of the delaminated area by using a Digital Image Correlation (DIC) technique.

**KEYWORDS**: carbon fibre, four-point bending test, buckling, snapping, delamination, digital image correlation

## 1. Introduction

The detachment of a thin superficial layer from an underlying substrate due to the combined action of local buckling and fracture propagation is a damage mode common to many technological applications and natural objects from the nano scale of thin superficial layers to the macro scale of civil engineering constructions.

Among layered structures and materials, fibre reinforced composite laminates – made up of several fibre reinforced laminae stacked on top of each other – play a central role in contemporary engineering. Thanks to their high strength and stiffness to weight ratios, composites are used for high performance structural applications in both civil and industrial engineering [1]. Conversely, composites are prone to a number of damage phenomena [2]. Delamination is one of the most critical issues for the integrity and the mechanical performance of fibre-reinforced composite laminates. Delamination cracks in composite laminates may originate from manufacturing defects, low-energy impacts, and many other causes [3, 4].

Once present, a delamination crack can propagate because of high interlaminar stresses. These can be produced by different loading conditions. A particularly dangerous case is when a superficial layer is loaded under compression (due to applied loads, thermal and/or residual stresses). The regions where bonding is weak or missing may undergo local buckling. Therefore, high stresses arise at the crack front, thus promoting the further expansion of the debonded region [5]. To investigate experimentally buckling-driven delamination in composites, many Authors have suggested to carry out four-point bending tests on laminated specimens with mid-span, through-the-width delamination cracks [6-11].

Here, the results of a new experimental campaign are summarised, where an accurate method to measure the opening displacement of the lamina during delamination is proposed based on a backward application of the Digital Image Correlation technique from the final deformed state to the initial undeformed configuration. For further information about the experimental activities, as well as for the description of an analytical model of the tests, the reader is referred to the first Author's PhD dissertation [12].

## 2. Four-point bending tests

### 2.1. Specimens manufacture

Specimens were produced by Microtex Composites S.r.l. according to the design of Fig. 1: a 300 mm × 400 mm laminated plate was manufactured using quasi-unidirectional carbon-fibre fabric GV325P 12KZH GL (SYT49 EC968) with an epoxy resin content of 36%. The laminate was subjected to a cure cycle for 90 minutes at a temperature of 135 °C, at 6 bar pressure. The curing temperature was reached with a dry ramp rate of 2 °C/min. The laminate was cooled with a 3 °C/min. The slow heating rate enabled the epoxy resin to penetrate into the carbon fabric. The curing cycle however influenced the final thickness of the laminate, which resulted thicker than the design value of 4.8 mm.

The plate had a total of 16 plies. An artificial delamination was created between the 2nd and 3rd plies by the introduction of a polytetrafluoroethylene (PTFE) insert. Ten 220 mm × 13 mm specimens with a 40 mm long central delamination were cut from the plate (Fig. 2) by water jet to avoid edge effects. The measured geometric properties of specimens are reported in Table 1.

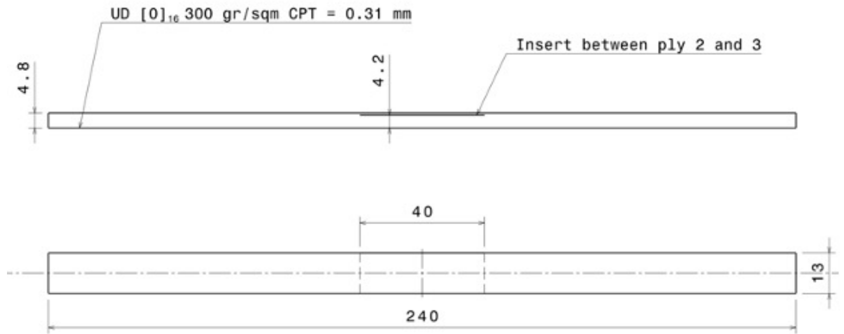


**Figure 1.** Specimens design


**Figure 2.** Four-point bending test specimens

**Table 1.** Geometric property of specimens

| Specimen # | length [mm] | thickness [mm] | Width [mm] |
|---|---|---|---|
| 0 | 238.00 | 5.20 | 13.00 |
| 1 | 238.00 | 5.20 | 12.93 |
| 2 | 238.00 | 5.27 | 12.87 |
| 3 | 238.00 | 5.22 | 12.92 |
| 4 | 238.00 | 5.35 | 12.78 |
| 5 | 238.00 | 5.20 | 12.93 |
| 6 | 238.00 | 5.27 | 12.88 |
| 7 | 238.00 | 5.30 | 12.88 |
| 8 | 238.00 | 5.28 | 12.90 |
| 9 | 238.00 | 5.30 | 12.90 |
| 10 | 238.00 | 5.38 | 12.77 |
| mean | 238.00 | 5.26 | 12.89 |
| Dev St % | 0 | 5.02 | 6.62 |

## 2.2. Load test

The delaminated specimens were subjected to four-point bending tests by using the Zwick-Roell Z010TH universal testing machine available in the MUSAM-Lab of the IMT School for Advanced Studies Lucca, equipped with a 10 kN load cell. As far as possible, the ASTM standard [13], valid for monolithic samples, was followed to perform the tests.

The tests were performed under displacement control with a rate of 0.5 mm/min. The spacing between the upper knives was set at 100 mm, and the spacing of the lower knives was set at 200 mm. The centre of the debonded region was placed symmetrical to the middle span cross-section (Fig. 3). Specimens 1, 2 and 3 were tested without imperfection; specimens 4, 5, 7, 8, 9 and 10 were tested with a 0.63 mm needle imperfection placed between the delaminated plies at the middle span; specimen 6 was tested with a small piece of paper imperfection placed at the middle span.

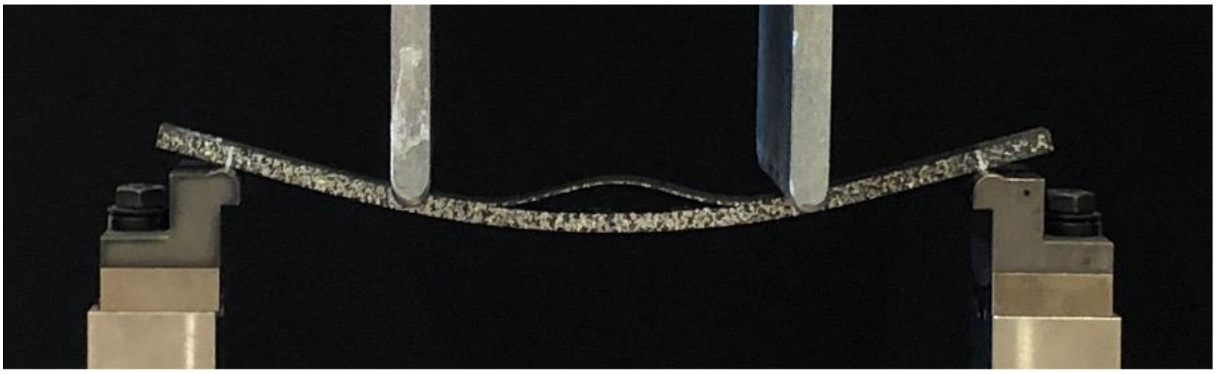

**Figure 3.** Load tests

## 2.3. Digital image correlation

The Digital Image Correlation (DIC) is a non-contact optical technique for measuring strain and displacement fields. The application of DIC to mechanics began during the first years of ’80 [14–16]. Nowadays it is widely used and a recent review on this topic is reported in [17]. The basic idea of DIC is to compare a sequence of photos of a specimen during the progressive application of a load. The specimens are previously prepared by a random paint film, which allows the software to follow the position of pixels during a deformation stage. The images can be captured by a suitable digital camera.

In this study, a 2D Digital Image Correlation analysis was carried out to measure the full field displacement (Fig. 4). We use the VIC Correlated Solution instrument to acquire images with a resolution of 2 Mpixel at a rate of 1 photo/second.

The photos were processed by the software GOM Gmbh able to identify areas of a measurement image that contain enough information. In this way, the software can identify the same areas in other measurement images as well. The software can identify the locations of distinct transitions of grey values from black to white based on the gradient. In each distinct grey value transition, the software fits an ellipse. The centre point of the ellipse is the measuring point.

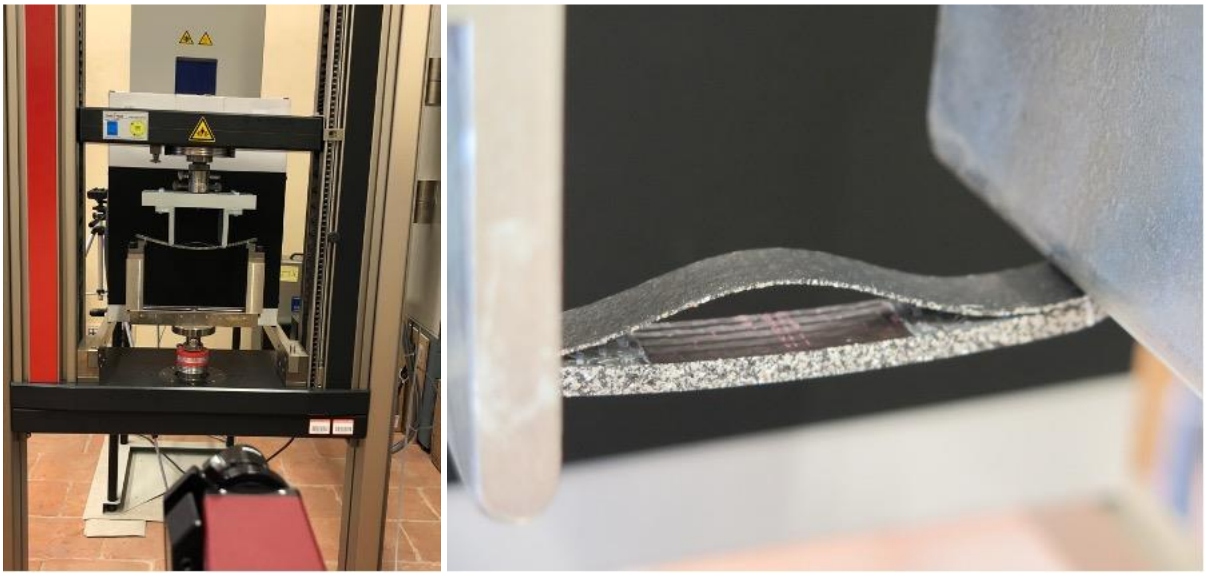

**Figure 4.** Setup for testing and for digital image correlation

## 2.4. Crack opening

To measure the crack opening displacement during the test, the DIC was used. The acquired photos were processed with the software GOM-correlate. The area of interest was focussed on the entire specimen. As a first step, we performed a classical DIC, but the displacement field of our specimen was very large. In fact, by looking at the deformed specimen in Fig. 5, it can be observed that the displacement is of the same order of the thickness. The area of interest of the upper sub-laminate was very thin, so at a certain point, during the classical forward DIC, the software lost the area of interest of the upper sub-laminate. For this reason, we then switched to a backward analysis, where the area of interest was set in the deformed configuration. Thanks to this, we were able to measure the relative displacements between the upper and lower sub-laminates.

The frame-rate was 1 photo/second, whereas the sampling-rate of the universal testing machine was 10 measures per second. For the above-mentioned reason, we synchronised the displacement field and the load field by eliminating 9 measures for each second from the load acquisition.

In Fig. 6, the applied bending moment versus crack opening, $\Delta V$, measured in the middle-span, is displayed. The distance between the upper and lower sub-laminates at the middle span is close to zero (or slightly more than zero due to the insertion of the needle) until the load reaches the value of about 500 Nmm/mm. That value corresponds to the snapping bending moment. After snapping, we can observe a non-linear behaviour of the specimens until crack propagation, when $\Delta V$ is around 2 mm. The test results of specimens 1, 2, 3 and 6 are not reported here because specimen 1 was used to set-up the test, while in specimens 2 and 6 snap-buckling occurred together with unstable delamination, and specimen 3 broke before snap-buckling occurred.

The values of the applied bending moment, at which buckling and crack propagation occurred, are summarised in Table 2.

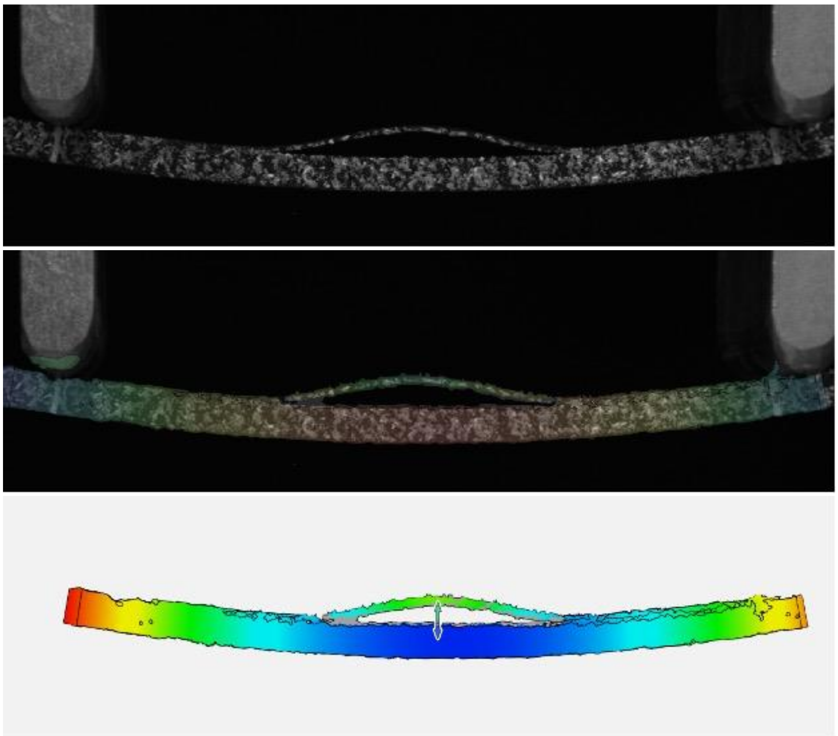

**Figure 5.** DIC output

**Table 2.** Results of experiments

| Specimen | $M_{buckling}$ [Nmm/mm] | $M_{crack}$ [Nmm/mm] |
|---|---|---|
| 4 | 553.45 | 2132.8 |
| 5 | 530.5 | 2404.2 |
| 7 | 529.0 | 2714.5 |
| 8 | 554.6 | 2403.2 |
| 9 | 540.3 | 2389.6 |
| 10 | 454.3 | 2395.5 |
| Average | 527.0 | 2406.6 |
| Dev st% | 37.3 | 184.5 |

## 3. Conclusions

The combined phenomenon of buckling and delamination has been investigated through an experimental campaign on carbon fibre-reinforced unidirectional laminates. Four-point bending tests were performed on a set specimens affected by artificial delamination cracks. A backward Digital Image Correlation technique was applied to measure the displacement field. Accordingly, the area of interest for image processing was set starting from the final deformed configuration instead of the initial reference configuration. This procedure solves the problems caused by the upward snapping of the central sub-laminate, where a classical forward DIC loses the area of interest. Thanks to this procedure, it was possible to measure the relative displacement between the upper and the lower sub-laminates with the requested accuracy. This parameter plays a crucial role for testing the predictive capabilities of analytical and/or numerical methods.

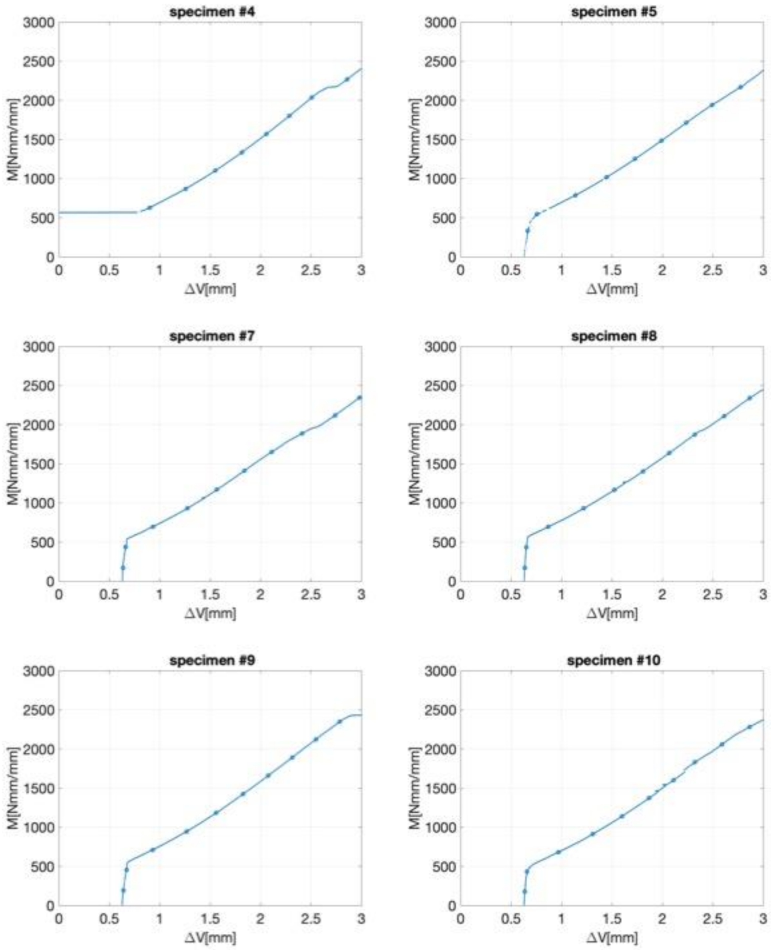


**Figure 6.** Applied bending moment vs. crack opening displacement

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