Structural Response of CFRP Materials Subjected to Simulated Lightning Strikes

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Abstract

The buckling response of Carbon Fibre Reinforced Polymer (CFRP) panels damaged by simulated lightning strikes is evaluated. Five panels constructed with carbon/epoxy material were subjected to an electrical current with 10/350μs waveform that simulates an idealized lightning strike. The buckling experiments were conducted in a newly designed modified buckling test, herein referred to as Compression After Lightning Strike (CALS), which is able to accommodate large composite panels and allows the full extent of the lightning damage to be included in the compression test. Stereo Digital Image Correlation (DIC) was used on both sides of the plate to obtain the strain and displacements that occur during the CALS test and hence determine how the lightning strike affects the mechanical performance of the structure. The experimental results were benchmarked and compared against a shell post-buckling finite element model (FEM). The results reported show good agreement between the experiment and the model predictions.

Introduction

Assessing the effectiveness of lightning protection is an integral part of the testing/qualification of wind turbine (WT) blade and aircraft designs. The introduction of conductive CFRP composites has made lightning protection more challenging for these structures [1]. CFRP materials, which are used due to their high specific stiffness and strength properties, are also semi-conductors with strongly anisotropic electrical and thermal properties. Thus, CFRP materials exhibit properties different from conductive materials like metal alloys, making CFRPs more susceptible to lightning damage. In WT blades direct strikes occur when lightning attaches to the CFRP normal to the blade surface. This causes large current densities, which result in large temperature rises and damage near and surrounding the attachment point. The present study examines the effect of lightning strike damage on the structural response of CFRP WT blade structures. The compressive behaviour of CFRP sparcaps in WT blades is a crucial design driver, and the research presented here, for the first time, investigates the buckling response of CFRP panels damaged by lightning.

Methodology

Five CFRP unidirectional eight-ply laminate specimens were manufactured using a carbon/epoxy material system. The eight laminates were manufactured using vacuum liquid resin infusion to give panel dimensions of 550mm long x 500mm wide x 7mm thick and post cured at 70°C for 6 hours. The top edge was chamfered to expose the fibres for electrical grounding. An example of the laminates are shown in Fig. 1. One of the samples was used as a control specimen, and the remaining were subjected to direct lightning strike tests.

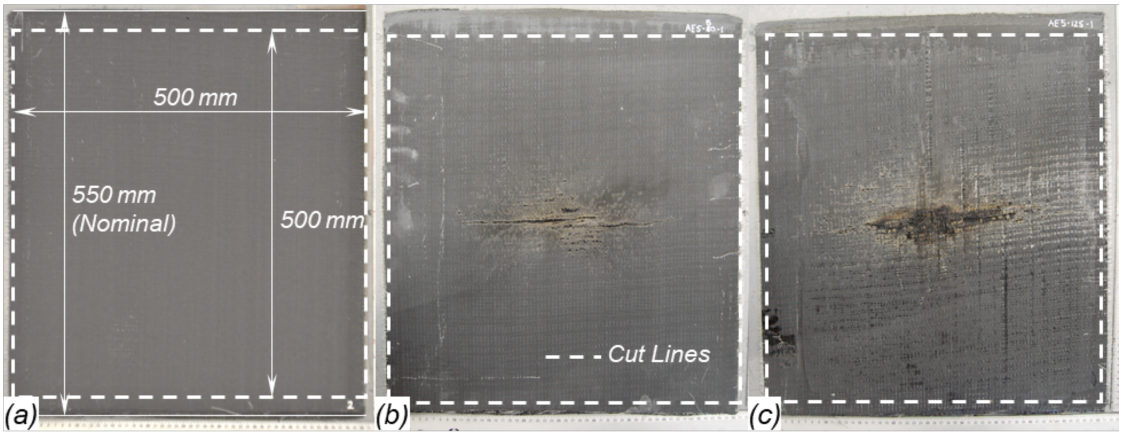

Fig. 1: CFRP experimental specimens: (a) Control, (b) 50kA damaged and (c) 125kA damaged

The CFRP panel specimens were subjected to electrical current with a unipolar 10/350μs waveform simulating the first return stroke during a direct strike in accordance with IEC 61400-24-Ed1.0 [4]. A large current generator was used to inject the current via an electrode with a 20mm gap. The peak currents subjected to the samples were 50, 75, 100, and 125kA. Two of the damage samples are shown in Fig. 1(b)(c). The lightning strike simulation setup is shown in Fig. 2(a). After the lightning strike, the damaged and the control specimens were cut using a waterjet cutter to a final plate dimension of 500mm square as shown in Fig. 1.

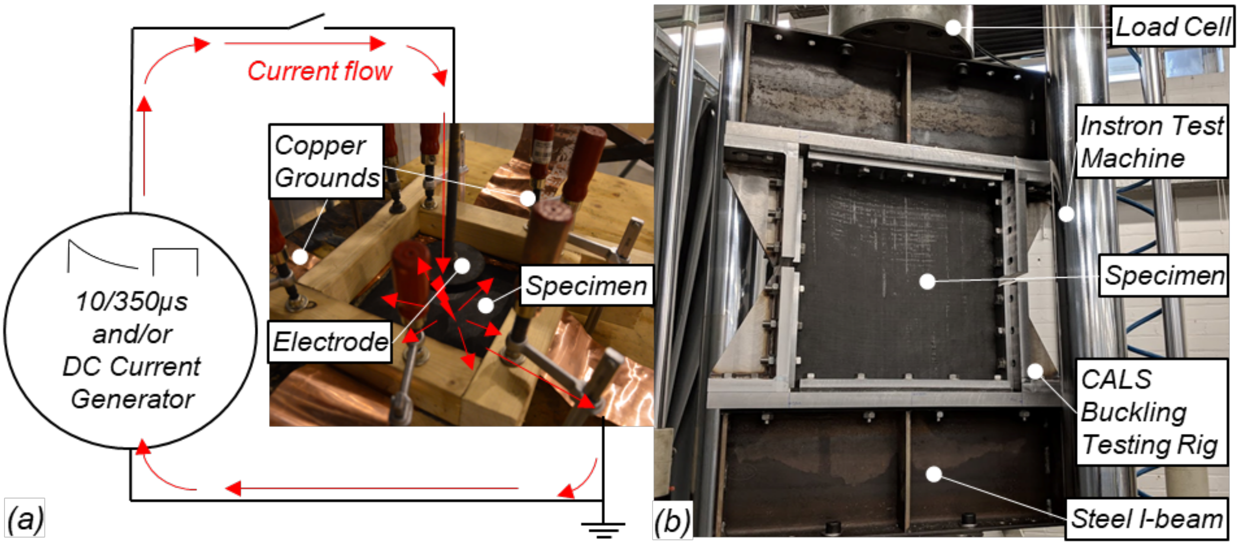

Fig. 2: Experimental setup for complete test: (a) lightning strike damage setup and circuit diagram; (b) structural test showing CALS rig

A new rig was designed and manufactured to capture the effects of lightning strike induced damage on the structural scale. The new CALS test configuration and rig is shown in Fig. 2(b). The upscaling was done to fit a variety of plate widths and lengths (larger than 450mm), to closely resemble WT blade sparcap structures close to the blade tip where the propensity for direct lightning strike is the most severe. The rig was designed with interchangeable supports, and configured to a simply supported plate system for the present study. The CFRP plates were loaded in the fibre direction with a 0.5mm/min loading rate in compression. The tests were conducted, so that the buckling and post-buckling responses could be studied using DIC on both sides of the plate. The test setup parameters are shown in Table 1.

Table 1: DIC Test Setup Parameters and Correlation Parameters

DIC Test Setup	
Technique Used	2 x Stereo 3D Image Correlation (2 cameras measuring top surface and 2 cameras measuring bottom surface)
Camera	4 x MANTA G504B (gigabit Ethernet)
Sensor	12 bit, 2452 x 2056 pixels
Lens	2 x AF NIKKOR 28mm F/8D 2x AF NIKKOR 50mm F/8D
Lightning	4 x NILA ZAILA LED Lights
Imaging distance	~2 m from bottom surface ~4m from top surface
Field of View	400 mm x 400 mm x 100 mm
Pixel resolution	~ 1px = 0.27 mm
Correlation Setup	
DIC Software	MatchID 2018.2.2
Correlation Procedure	Zero Normalized Sum of Differences Squared
Subset Size	33 px
Step Size	16 px
Sub-pixel interpolation	Bicubic Spline
Shape Function	Quadratic
Stereo Transformation	Quadratic
Strain Calculation	Logarithmic Euler-Almansi strain tensor
Smoothing	None
Displacement Noise Floor (u, v, w)	(0.026227, 0.0089122, 0.13067) mm
Strain Noise Floor $(\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy})$	(150, 95, 120) μm/m

The experimental results were benchmarked and compared against a post-buckling FEM run in Abaqus 6.14. The model was constructed using shell elements that represented the specimens. The damage induced was taken into account by altering the material properties to have essentially no stiffness ($E = 1MPa$). The damage regions were modelled by assuming an elliptical shape with equal area to the damage seen on the surface. The extent (area and depth) of the damaged zones was estimated based on visual inspection and X-ray CT scanning of the damaged plate samples.

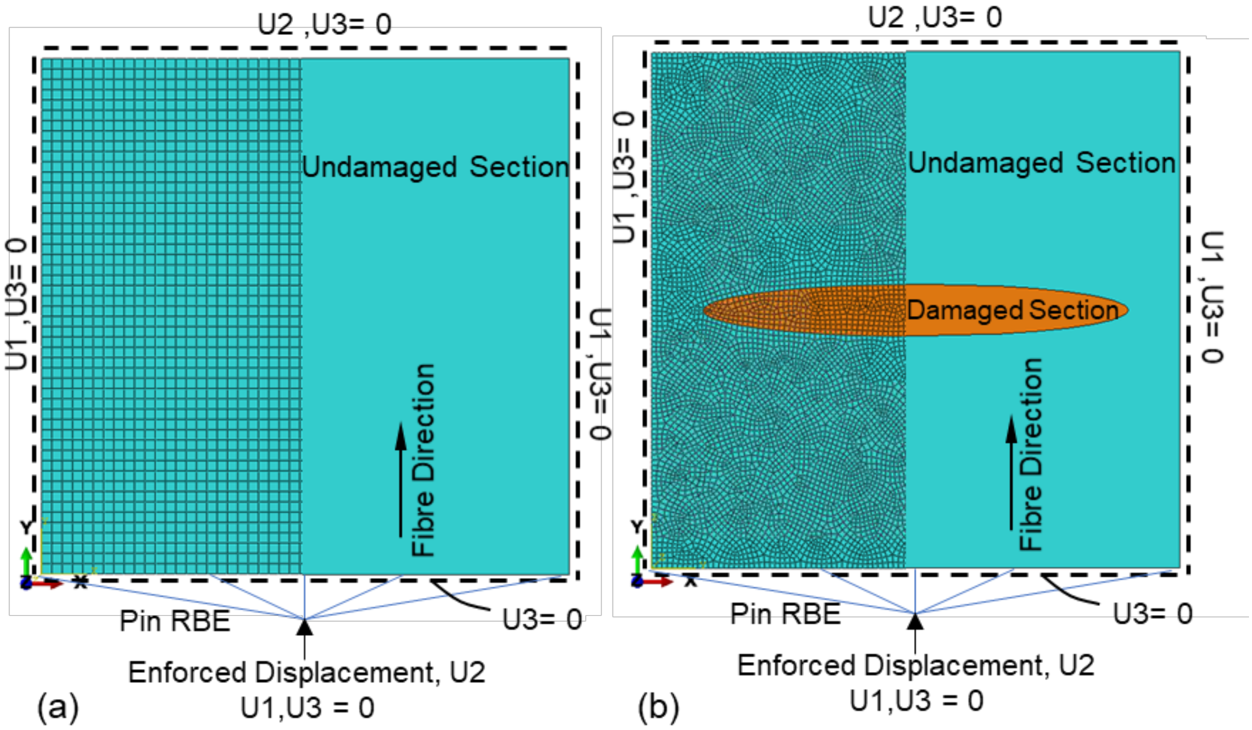

Fig. 3: Example of finite element model and boundary conditions used for (a) undamaged and (b) damaged specimens

Results and Discussion

The results from the DIC show significant differences between the control specimens and the damaged specimens. Fig. 3 shows the out-of-plane displacement for three different load levels. The out-of-plane displacements are much larger for the damaged sample specimen. The most severe case (125kA) shows a change in the location of the maximum displacement away from the damaged region. This indicates that the stiffness in the damaged regions was significantly reduced by the lightning strike events.

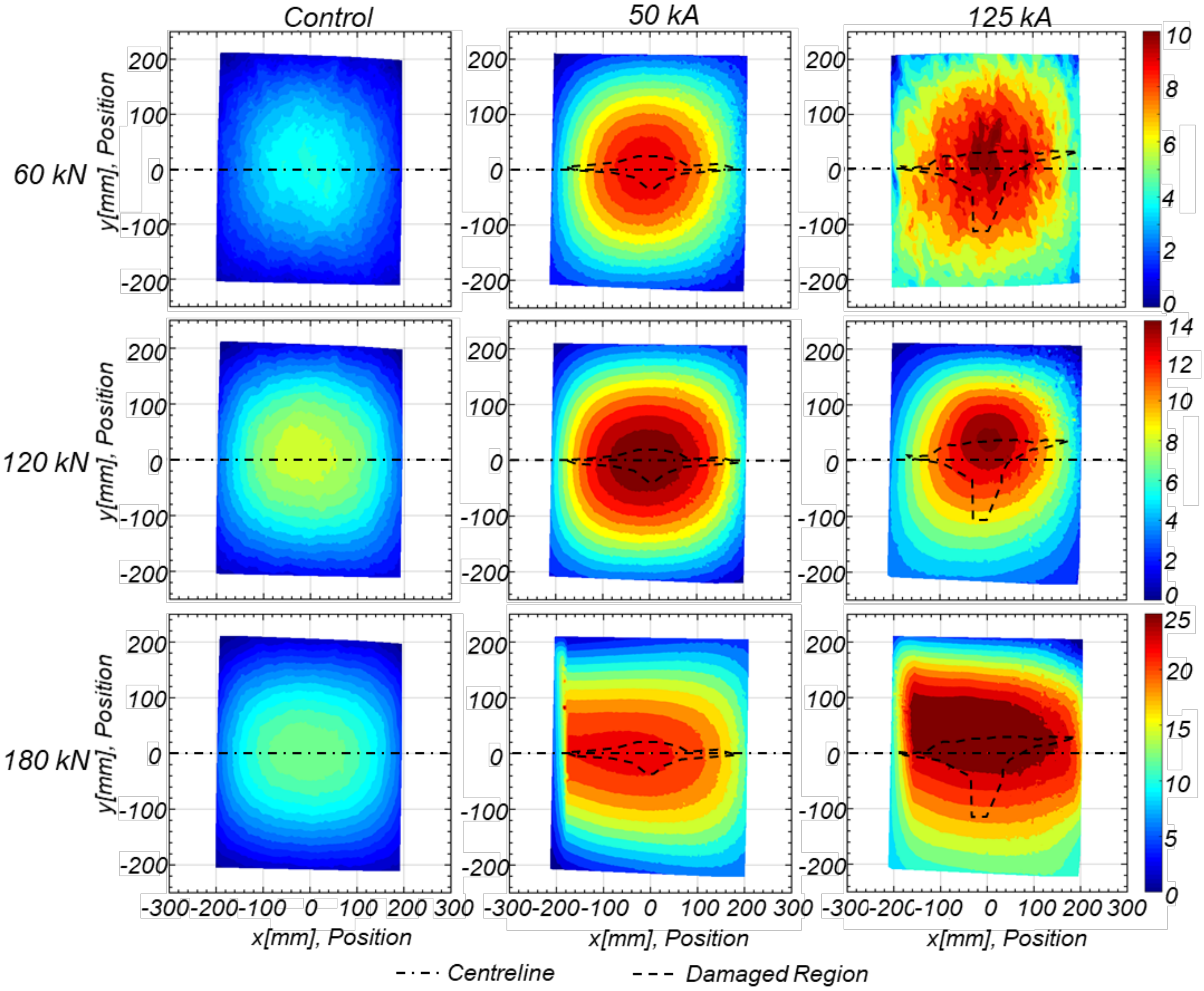

Fig. 4: Full field experimental results of out-of-plane displacement from stereo DIC at 60,120, and 180kN compressive load for the control specimen, and lightning damaged specimens struck

Considering the simplicity of this modelling approach, the predicted out-of-plane displacement field match well with the DIC results. Fig. 5 show the FEM results (compare against DIC results in Fig. 4). It is observed that the features from the DIC results are represented in the FEM predictions as well including the change/shift in displacement patterns.

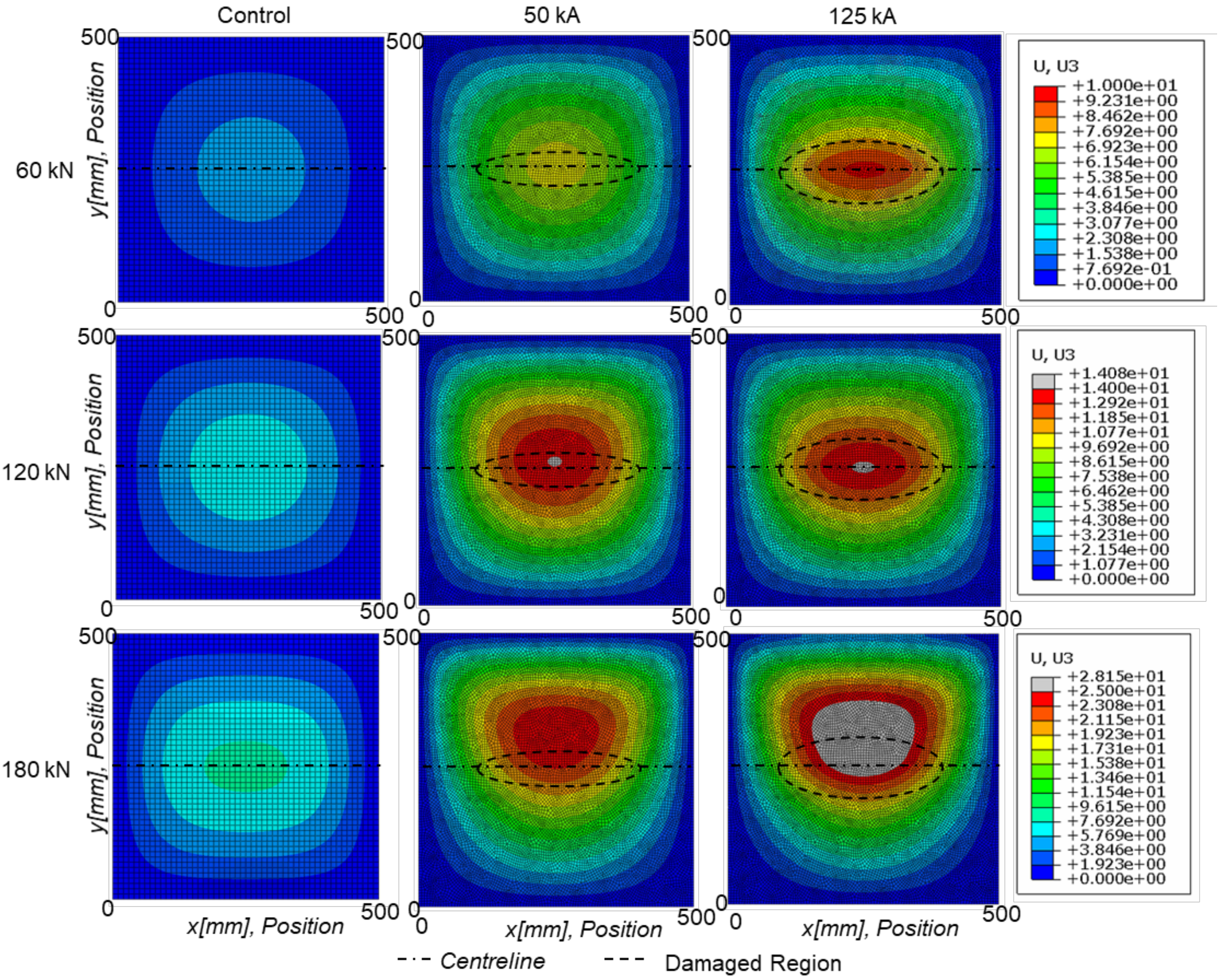

Fig. 5: FEM predictions of out-of-plane displacement at 60,120, and 180kN compressive load for the control specimen, 50kA and 125kA lightning damaged specimens

Conclusion

This paper presents the buckling behaviour of CFRP plate panels representative for wind turbine blade sparcap laminates impacted with simulated lightning strikes. A specially adapted compression loading test, the CALS, was proposed and commissioned to include important structural scale effects not included in conventional CAI coupon tests. The full field out-of-plane displacements were measured using DIC at different load levels for undamaged and lightning strike damages laminate specimens. The measured displacement fields were benchmarked against FEM predictions that include the damaged zones and a reasonable match was found.

Acknowledgment

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