Numerical Investigation of Compression-After-Lightning Strike Characteristics of Carbon/Epoxy Laminates

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Abstract: The increasing use of composite materials in aircraft structures has emphasised proper investigation into the effects of lightning strike damage and the damage tolerance required to withstand such strikes. Testing laboratory-scale artificial lightning strikes to design lightning-resistant materials/structures is a costly endeavour, but this cost can be reduced with the use of finite element analysis available to the industry. The aim of this paper is to generate a model to predict the compressive failure of aerospace-grade carbon/epoxy laminates after a lightning strike. This is done using two user-defined material subroutines in ABAQUS to estimate the lightning strike damage and check for residual compressive strength. The main criterion used to determine lightning damage is the temperature levels after the lightning strike. The modelled laminate is compressed after being hit with 100kA peak current Waveform D.

Keywords: Laminate; Strength; Compression-After-Impact; Lightning Damage

1. Introduction

The usage of composites in the aerospace industry has been growing significantly, with improvements in manufacturing techniques increasing the percentage of aircraft composite structures. Such an increase in composite usage would place emphasis on proper testing of lightning strikes on composite materials. International Air Transport Association (IATA) statistics has shown that an aircraft is struck by lightning every 1000 hours, equivalent to one strike per aircraft ever year (1). This means that it is only a matter of time for an aircraft to be struck by lightning. Therefore, investigation of damage tolerance of composite materials to lightning strikes is a matter of great concern due to the different behaviour of composites when struck by lightning as compared to metals.

A previous model has been created in ABAQUS to model the lightning effects on an AS4/3506 carbon/epoxy laminate (2). The paper characterized direct lightning effects by primarily focusing on the thermal effects of a 40 kA current lightning strike on carbon/epoxy laminates. While the paper (2) is comprehensive on establishing the physical effects of lightning strikes, it did not evaluate the residual strength of a lightning-struck laminate. It was addressed in the paper (3) in which a maximum current of 93.7 kA strike was used in accordance with the standardized Society of Automotive engineers (SAE) Aerospace lightning Waveform D (4). The paper (3) did not note the through thickness damage of the lightning strike, but only damage to the top layer and utilized a much thinner composite laminate. It also did not consider the temperature degradation in between the matrix damage, but only applying a single reduction factor to the element properties within the temperature boundaries. Regardless of if the element is at 301°C or 499°C, the amount of damage is set to be the same. Wang et al. (3) have also done the compression-after-lightning test with a specimen size of 500 mm x 250 mm x 2 mm, but they had undesirable failure modes such as compressive failure away from the lightning damage. In this paper, a compression-after-lightning test has been modelled to evaluate the laminate's residual compressive strength. This paper mainly focuses on the lightning damage after a peak current strike of 100 kA and the subsequent compressive modelling using an ASTM standard compression-after-impact specimen (5).

2. Methodology

2.1 Dimensions, mesh size and properties

A composite laminate is modelled to meet the ASTM standard test method D1737/D1737M (5) for compressive residual strength of polymer matrix composite plates. The laminate is a flat rectangular plate with the dimensions of 150 mm x 100 mm x 4 mm. The finite element models are developed in two sequential steps: (a) the lightning strike model, after which the temperature field is transferred for (b) the compressive model. The composite laminate was discretized with 8-node linear brick coupled thermal-electrical elements (DC3D8E) in the lightning strike model, then converted 8-node linear brick stress/displacement elements (C3D8) in the subsequent compressive model. It is meshed using three-dimensional brick elements of 1.6 mm x 1.6 mm in-plane dimensions. A coarser mesh (2.5 mm x 2.5 mm) is also used in a mesh size study. The predicted lightning damage and the consequent predicted compressive strength were found to be not sensitive to the mesh size, and the results with the 1.6 mm element size are used for the rest of the paper.

The laminate is modelled as a ply-by-ply quasi-isotropic laminate with the layup of $[+45/0/-45/90]_{4s}$, totalling 16 layers on the top half of the laminate, with each layer simulated as a single orthotropic element with a thickness of 0.125 mm. The remaining 2 mm thickness on the bottom half of the laminate is modelled as a single homogenised quasi-isotropic element to reduce computational costs. The previous tests indicating that the lightning damage does not penetrate to the bottom half (6). The equivalent properties are calculated from orthotropic layer data.

Tables 1, 2 and 3 show the properties of the AS4/3506 carbon/epoxy laminate used in the lightning simulation. The values from the bottom half are the homogenised values.

Table 1: Composite thermal properties (7)

Temp	Density	Specific Heat	Thermal Conductivity$(W/mm*K)$		
(°C)	(kg/mm^3)	$(J/kg*K)$	Long	Trans	Thick
25	1.52E-06	1065	4.66E-02	6.83E-04	6.83E-04
350	1.52E-06	2100	2.47E-02	3.73E-04	3.73E-04
510	1.08E-06	2100	1.46E-02	1.79E-04	1.79E-04
1000	1.08E-06	5750	1.17E-02	1.32E-04	1.32E-04
3316	1.08E-06	5875	1.00E-04	1.00E-04	1.00E-04

Table 2: Composite electrical properties (7)

Temp (°C)	Electrical Conductivity(S/mm)		
	Long	Trans	Thick
25	35.97	1.15E-03	3.9E-06
350	35.97	1.15E-03	3.9E-06
510	35.97	2	2
1000	35.97	2	2
3316	35.97	2	2

Table 3 shows the elastic properties of AS4/3506 laminate at room temperature of 27°C.

Table 3: Composite elastic properties (7)

Top Half (Ply-by-ply)			Bottom Half (Homogenized)		
Engineering Constant	Unit	Values	Engineering Constant	Unit	Values
E1	[GPa]	130	E1=E2	[GPa]	49.8
E2=E3	[GPa]	7.7	E3	[GPa]	7. 7
G12=G13	[GPa]	4.8	G12	[GPa]	19.1
G23	[GPa]	3.8	G23=G13	[GPa]	3.8
v12=v13	-	0.3	v12	-	0.3
v23	-	0.35	v23	-	0.35

2.2 Lightning Simulation

The lightning simulation was conducted first in ABAQUS/Standard in two steps, a coupled thermal-electric step, where the lightning current is applied and a heat transfer step, where the initial lightning strike temperatures is allowed to propagate. The lightning damage is generated from a model previously developed by Lee (2). His model utilized subroutines to control the lightning current strike and flagged element failure based on their peak temperature. The lightning current has been increased to match standard SAE Waveform D at its peak current of 100 kA (4). All other boundary conditions and methods of calculating lightning damage has been kept the same as what was laid out in (2). The damage from the lightning strike is simulated by usage of a pre-defined temperature field. As laid out in (2), the damage boundary is between 300°C where the composite starts to degrade and 500°C where the composite is fully degraded. A solution dependent variable (SDV1) is monitored to estimate the degree of thermal damage in composite, with a zero value increasing from 300°C noting the start of damage to one value noting 500°C or above where the element is considered to be fully damaged.

2.3 Compression After Lightning Simulation

The compression after lightning simulation is sequentially performed in ABAQUS/Standard. Using the results from the lightning simulation, the elements' elastic moduli were softened linearly from 300°C to 500°C where at 500°C, the properties of the composite are set to close to zero. The boundary conditions are set as per the ASTM compression-after-impact (CAI) test rig as seen in Figure 1. The base of the model has no Degree of Freedom (DoF) in the X, Y and Z directions to simulate the base being fixed in the test rig. The sides of the model have no DoF in the Y and Z directions but is allowed to translate in the X direction in the compression direction. The top of the model has no DoF allowed in the Y and Z direction and has a displacement linearly increased over a duration of 5 seconds up to 2 mm to simulate the applied compression. This displacement was chosen to apply a failure strain of 1.3%. Figure 2 shows the model with the boundary conditions applied, with the sides labelled.

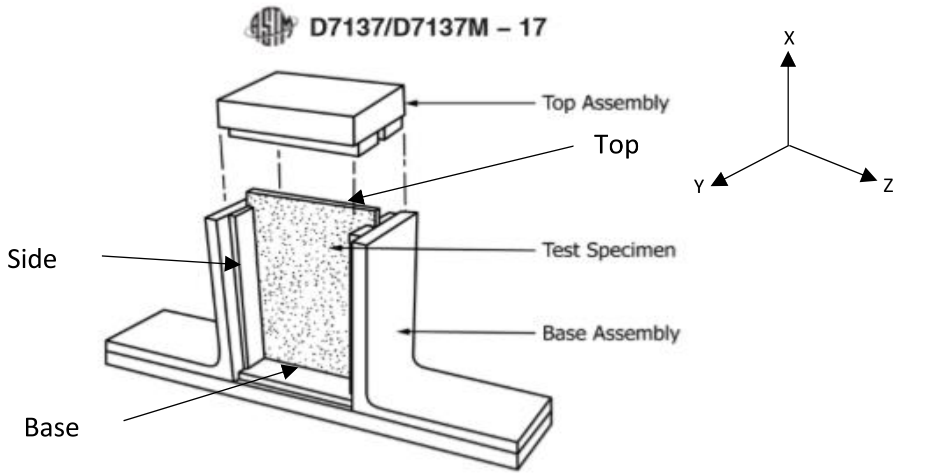

Figure 1 ASTM test rig with a plate in place

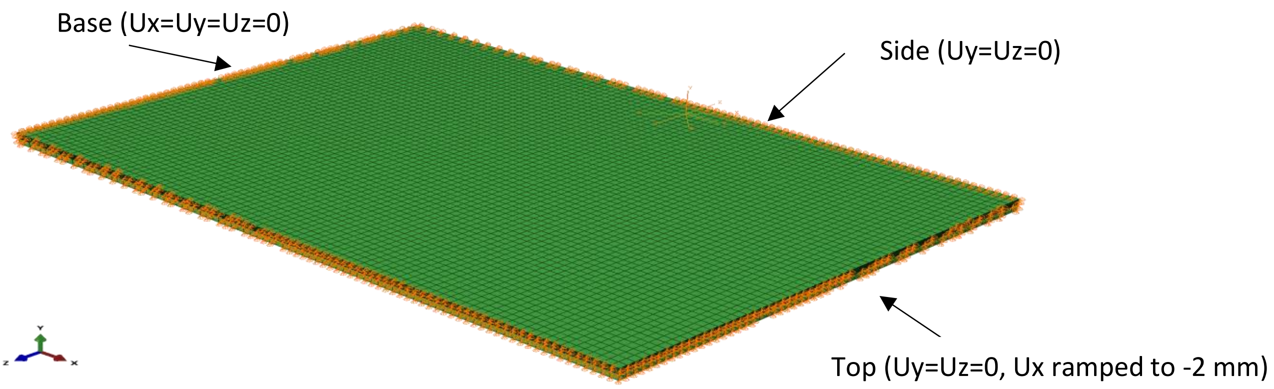

Figure 2 The FE model with the boundary conditions labelled

The residual strength of the composite is determined by the sum of the reaction force in the nodes at the bottom of the composite plate opposing the compressive force.

The compression-after-lightning simulation is controlled by a user subroutine created for this model. The stress and strain values are calculated over the time period (5 seconds) and upon hitting the failure point defined by the Hashin criteria (9), the element is flagged, and the elastic properties are set as close to zero. The most relevant criterion in this test is the compressive fibre failure criterion which is flagged as SDV 2. Equation 1 shows the failure criterion used when the stress in the fibre direction reaches the ultimate compressive strength of the ply ($S_{11} \leq 0$).

$$\left(\frac{\sigma_{11}}{S_{11}}\right)^2 \leq 1.0 \qquad (1)$$

Where σ_{11} is the compressive stress in the fibre-direction, S_{11} is the compressive strength which is 1690 MPa as sourced from Hexcel's datasheet for IM7/8552 material (8). The reason for using two sets of material properties is due to the availability of the high temperature electric and thermal properties for AS4/3506, the availability of compression test results of IM7/8552 which will also be used as the future baseline material.

3. Results

3.1 Lightning Damage

Figure 2 shows the extent of the damage to the underlying layers of the composite. The lightning damage in red penetrated through 11 layers of the composite. Red elements are those hit temperatures at or above 500°C. The maximum width of the fully damaged elements is 16.5 mm (red) in the top layer, and the partially damaged elements span 38.4 mm in the top layer (blue).

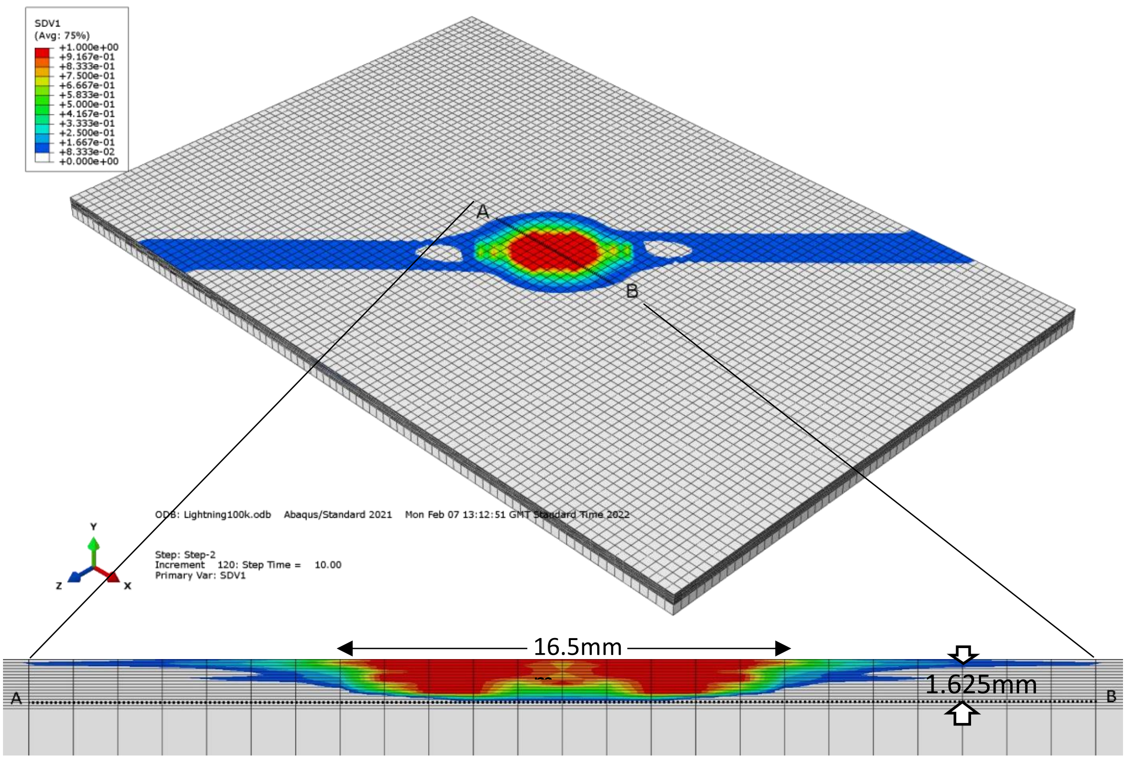

Figure 2 Lightning Damage

3.2 Compression after Lightning Response

Figure 3 shows the graph of the Compressive Stress vs Displacement of carbon/epoxy laminate subjected to 100 kA peak current. The peak compressive stress of the lightning damaged composite is 282 MPa. The load drop at a displacement of 1.908 mm mark (1.27% strain) indicates where the composite laminate is predicated to fail. The 2 mm mark is where the simulation is stopped. By close inspection of the compressive model, the lightning damage causes stress concentrations under compression. The 0° plies with the highest stress and stress concentration break first with the failed elements flagged and softened. The accumulation of the compressive damage quickly leads to the ultimate failure marked by the load drop in Figure 3.

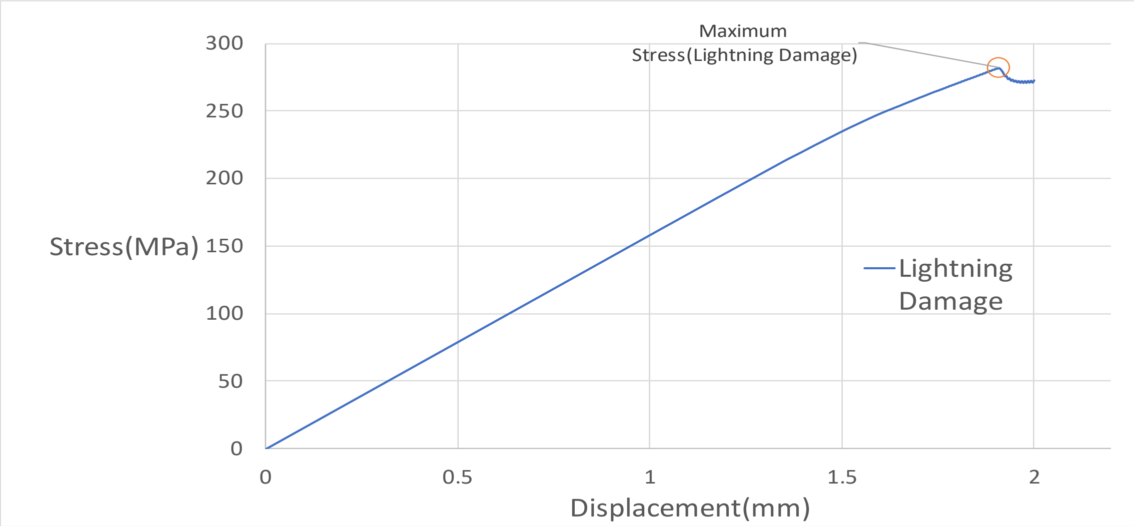

Figure 3 Stress vs. Displacement response in the compression model with lightning damage

4. Discussion

From the modelling results, the lightning damage has certainly reduced the compressive strength of the composite plate. The predicted compressive strength of 282 MPa for the lightning damaged laminate suggests that lightning damage may be equivalent to an open hole of a comparable diameter. For example, a 25.4 mm diameter hole in a 127 mm wide plate has a compressive strength of 285 MPa for the same layup and IM7/8552 carbon/epoxy material (10). These open-hole specimens were already successfully tested under compression (10) without undesirable global buckling and edge compressive failures as seen in other previous compression-after-lightning tests (3). Therefore, it is promising to conduct this compression test after 100kA maximum current lightning by cutting the lightning struck specimens down to these 150 mm by 100 mm by 4 mm standard CAI specimens.

5. Conclusion and future work

A compression-after-lightning model has been developed for the prediction of the residual strength of the lightning damaged laminate under compression. The modelling results demonstrate that the lightning damaged laminate has a similar compressive strength to the measured values from the open-hole compression tests with a comparable damage size. This implies that expensive lightning tests may be represented by quasi-static tensile tests which are carefully selected by the numerical models. Future studies should look into the actual lightning and compression tests of the IM7/8552 laminates to validate the predicted lightning damage and residual compressive strength, and finally, the similarity in behaviour between the open-hole and the lightning struck composite laminate.

6. References

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