Engineering Failure Analysis 94 (2018) 364–378

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Modelling of mechanical failure due to constrained thermal expansion at the lightning arc attachment point in carbon fibre epoxy composite material

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ARTICLE INFO

Keywords:
Lightning strike
Constrained thermal expansion
Composite material
Strain rate effects
Finite element modelling

ABSTRACT

Examination of artificial lightning strike test damage suggests that mechanical loading contributes to some aspects of composite material degradation and failure. So far numerical work has focused on modelling resistive heating from the electrical load and a very limited number of studies have considered the thermal induced mechanical effects. Also preceding work which has modelled the effect of acoustic pressure loading has predicted the influence on specimen damage to be negligible. Thus the objective of this paper is to quantify the potential magnitude of the internal specimen mechanical loading resulting from electrical load induced thermal expansion. This is achieved through a simulation study and the definition of a bespoke modelling procedure to map specimen time dependent temperature from a thermal-electric analysis into a mechanical thermal-expansion analysis. The study compares predicted behaviour with measured test specimen damage. The results for the first time quantify the potential scale of loading resulting from constrained thermal expansion, the dimensions of induced damage and the strain rate magnitudes required for accurate material representation.

1. Introduction

From measurements taken on test aircraft flown purposely into active lightning storms [1–3] standardised lightning intensity and current waveforms have been established for laboratory certification testing [4, 5]. Examination of composite specimens under these standardised test conditions suggests that mechanical loading contributes to some aspects of lightning strike damage [6–8]. Experimental results on composite specimens typically exhibit three damage modes; material ablation and decomposition, fractured fibres and cracked matrix material, and delamination of the laminate [8–18].

However, there is still limited understanding of the mechanisms during a lightning strike which lead to damage, partly due to the complex thermal, electrical, electromagnetic and mechanical components of the event [19–21], and partly due to the limited number of artificial lightning strike tests which have been published. The major challenge with testing is the speed and intensity of a lightning strike which makes it very difficult to directly acquire high resolution physical measurements during a test [13]. Post-test inspection of the damage is also complicated given the different damage modes, their interconnections and the damage concentration at the lightning arc attachment point.

Numerical simulations have the potential to generate further understanding of the behaviour during experiments and reduce the volume of testing typically required for new design certification. To date numerical studies have mostly focused on modelling

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https://doi.org/10.1016/j.engfailanal.2018.08.003
Received 22 March 2018; Received in revised form 9 August 2018; Accepted 12 August 2018
Available online 13 August 2018
1350-6307/

resistive heating from the electrical load [22–24] but other loading mechanics have also been studied (electromagnetic and acoustic pressure, internal explosive loads [6, 7, 18]) but with significantly less attention. Thus the objective of this paper is to investigate the potential contribution of the internal specimen mechanical forces due to thermal expansion. This will be achieved through a simulation study using an established modelling approach for thermal-electric resistive heating, and adding a mechanical simulation phase which represents specimen internal thermal expansion. A bespoke modelling procedure to appropriately map the specimen time dependent temperature from the thermal-electric simulation into an appropriate mechanical thermal-expansion model will be defined and demonstrated.

First focusing on experimental studies [8–18] these have identified the previously noted damage modes occurring in composite specimens. However a significant range in the form and scale of each type of damage is found generally in the literature. This inconsistency is due to the variation in the individual specimen designs (materials, material stacking sequence, lightning protection system), differing intensity and current waveforms, and test setup (varying distance between the specimen and the discharge probe, varying specimen fixturing and boundary conditions). In general the damage can be divided into three zones [7, 25]:

- Severe damage zone – identified as an area dark in appearance with char residue at the centre of the damage and with the greatest depth of damage. This zone is characterised by an absence and/or broken fibres, with the majority of surface resin absent. Signs of thermal and mechanical loads are present, evidenced by areas with ash and charring (thermal) and sharp resin morphology and fractured fibres (mechanical).
- Moderate damage zone – identified as a surface damage area surrounding the severe damage zone. This zone is characterised by damaged and absence surface resin and may include limited zones with fractured fibres (in the form of tufts of fibres protruding from the resin). Electron microscopy scanning of the surface indicates that fibres are well covered with resin and the resin fracture surface has relatively sharp and rugged morphology, consistent with mechanical damage.
- Sub-surface damage zone – identified as damage within the laminate. This may include intralaminar and interlaminar matrix cracking, and thus again suggests some form of mechanical loading.

Moreover experimental authors note probable or possible causes of the damage. In particular resistive heating is consistently identified to cause a significant amount of the measured damage but does not completely explain all the damage morphology which suggests some mechanical forces are present and significant. The missing resin around the fibre has been attributed by the vast majority of lightning authors to resistive heating of the composite [10, 11, 14, 15, 18, 21]. Some authors [11, 14] have also suggested that the thermal load from the arc channel may have a significant contribution while others have dismissed this load as minimal compared to the resistive heating [8]. Various authors propose that a blast force is the mechanical force responsible for fibre breakage but there remains disagreement as to the cause of the blast force. Three non-thermal loads are generally referenced in the experimental literature – pressure loads induced by acoustic and electromagnetic effects, or explosive loads resulting from rapid heating and the expansion or explosion of internal trapped gases (gas build-up due to resin decomposition). However there are only a limited number of studies which focus on these mechanical loading effects.

A number of authors [7, 8, 14, 18, 26–29] specifically discuss or investigate mechanical loading effects. Chemartin et al. [8], Gineste et al. [26] and Kawakami [14] describe the arc plasma physics which results in pressure loading and outline the use of simplifications and theoretical equations or numerical simulations, based on magneto-hydrodynamics, for the prediction of magnetic and acoustic pressures. Haigh [9], Gineste et al. [26] and Lepetit et al. [27] attempt to experimentally infer the pressure loads during testing based on a variety of test setups and specimen materials. Lepetit et al. [27] based on modelling and modified experiments concludes that of their three examined loads (Joule effect on the surface, acoustic pressure, magnetic pressure) that the acoustic and magnetic contributions are dominant, and have roughly comparable weights.

Munoz et al. [18] applied a pressure load to a composite specimen based on Chemartin's [8] proposed equation for the lightning impact shock wave. The idealised pressure wave was based on the electro-magnetic pinching, electromagnetic flux and the resulting expansion wave of the lightning channel. Both mechanical and thermal simulations were undertaken but results were considered separately. The mechanical analysis did not predict failure according to the Tsai-Wu failure criteria, however Munoz et al. [18] concluded that 'although the elements did not fail, some matrix cracking might occur through the thickness of the laminate'. Foster et al. [7] models the range of pressure loads described in the literature, including [8, 9, 14, 26], and compares the explicit Finite Element (FE) simulation predictions with measured test specimen damage. The results demonstrate that the proposed pressure loads have a negligible contribution to the overall scale of experimental damage.

Specifically for painted specimens, Lepetit et al. [28] proposes a further mechanical loading mechanism is active, confined surface explosion, which increases damage. In a similar vein Liu et al. [29], models a high explosive burn to represent a blow-out effect due to trapped gas from resin decomposition. Liu et al. [29] only offers qualitative comparison but suggests the simulation predictions compare well with damage patterns from test specimens.

Overall the preceding literature examines a small range of mechanical loading mechanisms and generally assesses, for non-painted specimens, that these are less significant in damage creation than resistive heating. The preceding literature does not consider the potential contribution of the internal specimen mechanical stresses due to the thermal expansion resulting from this resistive heating. Given the lack of literature on this mechanical loading mechanism it is appropriate to study if thermal expansion, via joule heating, is an important contributor to the measured experimental damage – in particular associated with the moderate damage zone as described above. To this end the subsequent section describes the modelling undertaken to address this hypothesis.