Composites: Part A 65 (2014) 148–160

Contents lists available at ScienceDirect

Composites: Part A

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

Fibre break processes in unidirectional composites

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ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 12 June 2014
Accepted 13 June 2014
Available online 26 June 2014

Keywords:
A. Fibres
A. Laminates
C. Micro-mechanics
C. Numerical analysis

ABSTRACT

A model to predict the effects of the accumulation of fibre breakages in unidirectional carbon fibre composites has been developed that takes into account several physical phenomena controlling fibre failure, including the stochastic nature of fibre strength, stress transfer between fibres due to the shear of the matrix, interfacial debonding and viscosity of the matrix. The damage processes leading up to failure are discussed and quantified, first in terms of fibre breaks for the case of monotonically increasing tensile loading, then for sustained loading and finally the implications for more complex loads and structures are discussed. It is clearly shown that the failure of a unidirectional composite structure results from the formation of random fibre breaks, which at high loads coalesce into clusters of broken fibres. Failure occurs suddenly with little warning in a sudden-death manner. The kinetics of fibre failure are different under steady loading, however, failure of the structure is still controlled by the viscoelastic nature of the matrix leading to the development of clusters of fibre breaks.

1. Introduction

Composite structures, in which unidirectional plies control their mechanical properties and ultimate failure, present a particular challenge when attempts are made to determine their long term behaviour and reliability. Structures, such as pressure vessels made of carbon fibre/epoxy for the storage of hydrogen or other gases at high pressures, typically hundreds of atmospheres, require a greater understanding of failure processes [1,2] in the composite reinforcement so as to provide meaningful tests of long term reliability. Whilst failure of these structures can occur in any of the component parts it is the composite shell, overwrapping the liner which ensures gas tightness, which determines the burst strength. The critical degradation process in the composite plies is fibre failure.

Previous studies [3–9] have addressed the modelling of fibre failure at the microscopic scale (modelling fibres, matrix and their interface explicitly). The difficulties of experimentally observing the accumulation of damage at the level of individual fibres are considerable and require means that are not readily available. For this reason, the logical process adopted in this paper is to use simulations to refine the understanding of the fibre break phenomenon based on relevant modelling which have been confirmed by high resolution computed tomography observations [10–14]. Compared to the initial formulation of the modelling [3], a new process for the analysis has been added: the quantification of groups of broken fibres during the lifetime of the considered structure and the calculation of the average minimum distance to the nearest neighbour of fibre breaks [15,16]. These important additions complement the original model and give a more precise description of the fibre break phenomenon. It will be seen that it provides a tool which allows the random nature of fibre failures to be further interpreted so as to quantify the clustering effect of broken fibres. The paper therefore qualifies and quantifies, with great precision, the damage accumulation in unidirectional composites subjected to rapid monotonic tensile loading in the direction of the fibres. Under these conditions the viscoelastic properties of the matrix can be ignored. However loadings maintained for longer times, as well as complex loadings, the viscoelastic nature of the matrix must imperatively be taken into account. The precision of the description of the failure process as well as the complexity of the loadings considered are the points which constitute the originality of the this study.

The present paper can be seen to be organised in three distinct parts each containing original results which have led to subsequent results discussed later in the paper. Section 3 considers the failure of unidirectional carbon fibre composites loaded in the fibre direction and tested in monotonically increasing tension leading to failure within a few minutes (denoted as ML-H conditions). It is assumed in this section that the viscoelastic nature of the matrix can be ignored. Section 4 also describes the failure of unidirectional

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http://dx.doi.org/10.1016/j.compositesa.2014.06.009
1359-835X/

composites, however monotonically increasing then sustained tensile loading (SL conditions) is considered which allow the effects of the viscoelastic character of the matrix to be studied. In Section 5, the effects of complex loading conditions on a unidirectional composite specimen have been analysed: monotonic tensile loading with different rates of loading, from mean to low (ML-M conditions, ML-L conditions), preloading followed by monotonic loading to failure or sustained loading. Section 6 examines the possibility of extending the studies on unidirectional composites to laminated structures.

2. Summary of the modelling

2.1. A model solidly based on earlier studies

The present work is solidly based on earlier studies and owes much to earlier researchers who have described the physically based processes governing composite behaviour beginning with analytical techniques. These earlier studies, based as they were on a logical examination of mechanical processes at the level of reinforcements, have allowed a general understanding of the phenomena governing composite behaviour and ultimately failure. The following, non exclusive studies, should be cited: Rosen [17], Cox [18], Zweben [19], Hedgepeth [20], Ochiai et al. [21], Curtin [22, 23], Curtin and Ibnabdeljalil [24], Goree and Gross [25], Harlow and Phoenix [26,27], Scop and Argon [28,29], Kong [30], Batdorf [31,32], Nedele and Wisnom [33,34], Hedgepeth and Van Dyke [35], Baxevanakis [36], Landis et al. [37,38], Phoenix et al. [39–42], Wisnom [43], VanDenHeuvel et al. [44,45], Lipschitz and Rotem [46], Lagoudas et al. [47], Beyerlein et al. [48], Pitkethly and Bader [49].

The increasing computational power of computers has allowed the present authors to develop models based on the understanding of the phenomena. It is now possible, within a reasonable computational time (less than one day) and by using a multi-scale approach, for a detailed simulation of those physical phenomena involved in composite behaviour to be made. This approach has already been favourably compared with experimental tests made on specimens using acoustic emission [3,50] and high resolution tomography to monitor damage [10]. It has also been favourably compared to slow burst tests made on pressure vessels [51]. The model which is the basis of the approach has been described in detail elsewhere [8]. In this paper the most important guidelines of the model are summarised.

2.2. The microscopic scale: description of the Representative Volume Element

At the microscopic scale the composite is seen to be composed of fibres, matrix and fibre/matrix interfaces. The size of the Representative Volume Element for a fibre volume fraction $V_f = 0.64$ (Fig. 1) has been deduced from the 2-dimensional (2D) work of Baxevanakis [36] who used multi-fragmentation tests on single fibre embedded in a matrix to determine the length of the weakest link of a fibre (≈ 0.5 mm). By varying the number and lengths of fibres in a bundle of fibres, Baxevanakis found, numerically, that beyond a certain number of fibres (6) and a certain length ($L = 4$ mm) the strength of the composite material converged. This allowed the size of the 2D-RVE to be defined. The numerical study showed also that the failure stress was reached for a critical state of damage defined as follows: each fibre fails only once in the 2D-RVE ($L = 4$ mm) and all the fibre breaks were concentrated in the same plane. This implies that although the load transfer length, as defined by Cox [18], depends on the shear modulus of the matrix and the Young's modulus of a single fibre, together with the interfacial bond, the

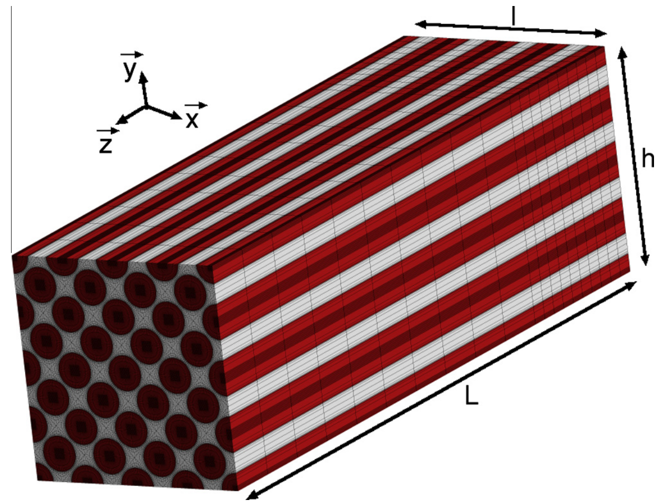

Fig. 1. Size of the cell representative of the RVE (for $V_f = 0.64$): $L = 4$ mm, $l = h = 0.05$ mm).

failure of the 2D-RVE, containing several fibres, is a more complex process leading to a deterministic value of strength not directly related to the behaviour of a single fibre embedded in a block of matrix. This study allowed Blassiau [3] to extend the 2D-RVE to a 3-dimensional (3D) RVE consisting of approximately ($6 \times 6 = 36$) fibres. Geometrical constraints determined this number to be 32 fibres arranged regularly in a hexagonal array.

Representative cells of the virgin material and of the six material damage states define *i*-plets [31,32] ($i = 0, 1, 2, 4, 8, 16, 32$) (Fig. 2). An *i*-plet corresponds here to a group of *i* broken fibres perfectly (periodically) dispersed in a cell. Experimentally, an *i*-plet consists of *i* number of closely related fibres breaks, which occur within a cube of sides of 70 μm [52]. It is observed that one fibre fails only once within this cube. Within the defined damage states small order *i*-plets (1/2/4-plets), medium (or intermediate) order *i*-plets (8/16-plets) and high order *i*-plets (32-plets) can develop. According to the definition of the length *L* of the cell, a single fibre cannot break at two points within a cell. The fibre breaks within the cell are assumed to be co-planar (this is the most detrimental configuration but also, as already mentioned, the configuration which provokes the break of the 2D-RVE). Five states of fibre failure are considered in the model taking the CS32 cell, which contains thirty-two intact fibres, to the C1 cell in which all fibres are broken (to save computation time, the cell C32 is omitted. It has been verified that this does not change significantly the simulation results). The first damaging step is from the CS32 cell to the C16 cell in which two fibres are simultaneously broken. The second is from the C16 cell to the C8 cell: 2 fibres are again simultaneously broken. The third step is from C8 cell to C4 cell: 4 fibres are simultaneously broken. The fourth step of the break is from C4 cell to C2 cell: 8 fibres are simultaneously broken. The fifth step is from C2 cell to C1 cell: 16 fibres are simultaneously broken. Two independent clusters of 32 broken fibres (32-plets) can interact in all directions thus forming larger clusters (groups of 32-plets). It should be underlined that the clusters identified in the calculations are defined differently from those in the experiments [52]. In the modelling, a 16-break cluster has 16 fibre-breaks dispersed in a 32-fibre element, while in the experiments a 16-break cluster has a bundle of 16 fibres completely broken. This is likely to affect stress concentrations and the propagation of damage.

2.3. The microscopic analysis: overstressing on fibres

The microscopic analysis is based on calculations that have been made using the Finite Element method for a given cell *C* with