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Probabilistic failure assessment of Fibreglass composites

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ABSTRACT

In this paper, the Generalised Probabilistic Approach (GPA) recently proposed by some of the present authors is applied in order to analyse the short fibre-reinforced materials behaviour at failure. Firstly, an experimental campaign consisting of tension tests, three- and four-point bending tests is carried out on a commercial Fibreglass composite. Then, the Primary Cumulative Distribution Function of Failure (PCDFF) is determined by employing both experimental and numerical results. In particular, the PCDFF is derived in two cases: (a) by considering the specimens subjected to the above three loading conditions separately (GPA single application); (b) by collecting both the specimens subjected to tension and those subjected to three-point bending in order to constitute a unique set (GPA joint application). Finally, a comparison between experimental failure probability values and PCDFF, being the latter obtained from both single and joint application of GPA, is provided for each loading condition.

1. Introduction

Nowadays composite materials are widely employed in many engineering applications, such as aerospace, marine and automotive fields, due to their excellent mechanical properties in terms of strength-to-weight ratio, stiffness-to-weight ratio, structural tailoring capability and damage tolerance [1]. During their service life, such materials are subjected to complex loadings that may lead to failure.

In comparison with traditional isotropic materials, a reliable failure prediction of composites is difficult due to several uncertainties related to both micro-structural geometry and mechanical behaviour [2–4]. The load-bearing capability of composites is characterised by a large randomness, mainly due to the complexity and interaction of failure modes, the material anisotropy and heterogeneity and the defects induced during the manufacturing process [5,6].

A large number of approaches based on deterministic analysis of composite failure is available in the literature [7–13]. Such approaches assume the univocal determination of the structural and mechanical quantities, whereas the systematic uncertainties caused by the random nature of the examined material are neglected.

In designing structures made of fibre-reinforced materials, such approaches based on characteristic values of the mechanical properties may lead to serious misinterpretations concerning the failure onset. Furthermore, such methods are not able to quantify the failure probability of structural components neither locally nor globally and, consequently, they provide insufficient information about safety, making difficult to take decisions concerning redesign and maintenance.

In order to overcome the drawbacks related to the deterministic methods, several approaches based on the probabilistic theory have been proposed in the last decades (see the review in Ref. [14]). In particular, Fukuda and Chou [15] have used the probabilistic theory to estimate the strength of unidirectional short fibre composites, whereas Cassenti [16] has investigated the failure probability and the probabilistic location of failure of composite beams by applying the weakest link principle. Other studies have been conducted to evaluate the reliability of laminated plates subjected to various loading conditions [5,17–19]. Moreover, Kam et al. [20] have developed a probabilistic non-linear finite element method for composite structures, whereas Nakayasu and Maekawa [21] have proposed failure envelope diagrams to evaluate the mechanical behaviour of composite laminates. Further, Monte Carlo simulations together with the Tsai-Hill or Tsai-Wu criterion have been applied to evaluate the failure behaviour of fibre-reinforced plates under transverse random loading [22,23].

In the framework of the probabilistic approach, both the design and the lifetime evaluation of structural components made of

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Nomenclature

E	elastic modulus
GP	Generalised Parameter
GP_{eq}	equivalent Generalised Parameter
i	i-th specimen
j	j-th finite element
k_i	rank index
N	total number of tested specimens
N_e	total number of finite elements
P	load at failure
P_{fail}	global cumulative failure probability
$p_{fail,ij}$	local cumulative failure probability
S_{ref}	reference size
S_{eq}	equivalent size
β	Weibull shape parameter
δ	Weibull scale parameter
ΔS_j	size of j-th finite element
ε_f	flexural strain
ε_{ut}	ultimate tensile strain
λ	Weibull location parameter
σ_f	flexural stress
σ_{ut}	ultimate tensile stress

Acronyms

CDFF	Cumulative Distribution Function of Failure
ECDFF	Experimental Cumulative Distribution Function of Failure
GPA	Generalised Probabilistic Approach
PCDFF	Primary Cumulative Distribution Function of Failure

fibre-reinforced materials require the assessment of the Global Probability of Failure (GPF) of the above components. Such a GPF estimation is related to stress and/or strain distributions inside the component, which may be computed from a finite element analysis of the whole component. The GPF estimation implies the simultaneous consideration of the local probabilities of failure of each finite element of the discretisation in order to estimate the global failure critical condition. The assessment of the GPF is based on the weakest link principle.

In this direction, Muñiz-Calvente et al. [24,25] have recently proposed a procedure to evaluate the Global Probability of Failure of industrial components by means of the so-called Generalised Probabilistic Approach (GPA). Such an approach allows the Primary Cumulative Distribution Function of Failure (PCDFF) to be determined through an experimental campaign along with a numerical analysis, related to a certain failure type and material.

In the present work, the GPA is employed in order to analyse the failure behaviour of a commercial Fibreglass composite under different loading conditions. Firstly, the experimental campaign carried out on such a material is described. Then a brief presentation of the GPA is reported and applied to the experimental data, and finally the obtained results are discussed.

2. Experimental campaign

The failure behaviour of a short fibre-reinforced composite (commercial Fibreglass composite) is experimentally examined. The specimens tested in the experimental campaign (Fig. 1(a)) are extracted from commercial Fibreglass panels, with a fibre volume content equal to about 30%, commonly used in the construction of caravans, commercial vehicles and tanks for storage of water, food and chemical substances.

The experimental campaign consists of:

(1) tension tests (Fig. 1(b)), performed on 33 specimens;
(2) three-point bending tests (Fig. 1(c)), performed on 38 specimens;
(3) four-point bending tests (Fig. 1(d)), performed on 34 specimens.

All the tests are carried out according to the ASTM standards [26–28], by employing the universal testing machine Instron 8862, available at the "Testing Laboratory of Materials and Structures" of the University of Parma, Italy.

The specimens are obtained by using a computer numerical control milling machine, and prepared in the same direction in order to minimise, as much as possible, the errors generated during the sampling procedure.

Tests are performed under displacement control, with a head displacement rate computed according to the aforementioned ASTM standards, and measuring the load by means of a load cell.

Moreover, the Digital Image Correlation (DIC) technique is applied to extract a 2D full-filled displacement field of each tested specimen. In order to obtain a well-contrasted grey-scale speckle pattern, specimens are irregularly spray-painted before testing. The digital camera (a full-format Nikon D7200, 6000 $\times$ 4000 pixels) captures images of the specimen surface at a rate equal to 1 frame every 5 s and 15 s for tension tests and bending tests, respectively. The captured images are analysed by means of the free software Ncorr [29,30], developed in MATLAB environment. The experimental testing set-up is shown in Fig. 2.

The following sub-sections briefly summarise the above tension tests and bending tests as far as specimen geometry, test configurations and experimental results are concerned.

2.1. Tension tests

The tension tests (Fig. 1(b)) are carried out according to the ASTM D 3039/D 3039M-14 standard [27], which deals with the standard test method for evaluating tension properties of polymer matrix composite materials. The 33 specimens tested are characterised by a thickness equal to 2.7 mm, and mean values of length and width equal to 270 mm and 26.85 mm, respectively (Fig. 1(a)). The tests are performed under a head average displacement rate of 2 mm/min.

The ultimate tensile stress σ_{ut} and the elastic modulus E are computed as a function of the final load P according to Ref. [27], whereas the ultimate tensile strain ε_{ut} is evaluated by taking into account the displacement field obtained from a DIC analysis. Such values are summarised in Table 1 in terms of mean values and standard deviations determined by only considering the 26 specimens showing 'acceptable' failures (according to the ASTM D 3039/D 3039M-14 standard, failures at grips are considered as not acceptable).

2.2. Three-point bending tests

The three-point bending tests (Fig. 1(c)) are carried out according to the ASTM D 790-15e2 standard [28], which deals with the