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Strength degradation due to fatigue-induced matrix cracking in FRP composites: An acoustic emission predictive model

Theodore P. Philippidis *, Theoni T. Assimakopoulou

Department of Mechanical Engineering & Aeronautics, University of Patras P.O. Box 1401, GR 26504 Panepistimioupolis, Rio, Greece

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ABSTRACT

Assessment of strength degradation in unidirectional Gl/Ep $[90]_7$ composite specimens, due to fatigue-induced matrix cracking, is herein performed using acoustic emission data recorded during a static proof-loading. To address a generalized problem, coupons were subjected to constant amplitude sinusoidal loading of $R = 0.1$, $R = -1$ and $R = 10$ stress ratio. In each case, several stress level and life fraction combinations were interrogated. An engineering model, introduced in a previous work, was implemented. The model, based on a conventional acoustic emission descriptor, predicted tensile strength degradation after constant or variable amplitude fatigue. Although established and validated on $[\pm 45]_S$ specimens undergone tensile $R = 0.1$ constant amplitude loading, the scheme also proved applicable in the $[90]_7$ coupon configuration, under all *R*-ratios examined. More important, both tensile and compressive residual strength was predicted. With the principal damage mode in all cases being matrix cracking, model performance in coupon residual strength estimation was remarkable.

1. Introduction

Matrix cracking is one of the major damage mechanisms encountered in FRP composites during service. Although sometimes considered less critical than fibre breakage and delaminations, propagation and coalescence of matrix cracks promote more severe failure modes. Characteristic consequences of matrix-dominated failure are debondings at the trailing edge of wind turbine rotor blades or between stiffening components and the skin, and also material degradation due to ingress of fluids, e.g., in composite pipe structures. However, since formation of matrix cracks begins at sub-critical loading stages, an appropriate non-destructive tool should contribute to damage assessment throughout service.

An overview of publications on the use of acoustic emission (AE) for the detection of distributed damage in composites, e.g., due to cyclic loading, is given in Philippidis and Assimakopoulou [1]. In most studies mentioned therein, however, AE is not suggested as a stand-alone tool, but is rather used to indicate qualitative trends or to complement other methods in the investigation of damage progression. Regarding transverse matrix cracks in particular, Tang and Henneke [2] and Toyama et al. [3] examined acoustic signals, monitored in specimens subjected to tensile static or fatigue loading, in terms of modal characteristics. In Hill et al. [4], transverse fibre-resin bonding was evaluated through statistical Weibull parameters extracted during AE monitoring of tensile tests.

Although appropriate AE descriptors could be correlated to damage accumulation in most published research, actual strength prediction was seldom accomplished. A quantitative life prediction scheme, for instance, was proposed in Bhat et al. [5]. Therein, AE data was recorded throughout tensile fatigue loading, performed at one particular stress level. Data was then clustered into three classes, using pattern recognition (PR) algorithm. These classes were shown to correspond to three basic failure mechanisms, characterizing the successive stages of fatigue life. However, the class presumed to consist of matrix-crack-induced AE events bore no useful conclusions. Instead of continuous AE monitoring during fatigue, Nkrumah et al. [6] used a static proof-loading to estimate remaining life. Albeit interesting trends were revealed, developed procedures relied on limited experimental data sets. Reliable residual strength predictions were provided in Caprino et al. [7] and Leone et al. [8], using a conventional AE parameter (AE counts). Again, one single stress level was investigated.

In a recent work (Philippidis and Assimakopoulou [1]), however, a robust and reliable model for tensile residual strength prediction, based on conventional AE measurements, was presented. The model was established and validated on a statistical population of 87 ISO standard 250-mm $[\pm 45]_S$ Gl/Ep specimens, undergone constant amplitude (CA) fatigue loading at stress ratio $R = 0.1$. Several stress level and life fraction combinations were accommodated. The model also proved applicable for specimens loaded under a tensile variable amplitude (VA) spectrum as well as for a set of coupons made of another resin matrix, under $R = 0.1$ CA loading.

* Corresponding author. Tel.: +30 2610 969450x997235; fax: +30 2610 969417.
E-mail address: philippidis@mech.upatras.gr (T.P. Philippidis).

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As argued in Philippidis and Assimakopoulou [1], the developed AE model is recommended in cases where matrix cracking is the dominant damage mode, at least until the proof-loading magnitude. Adopting this outcome in the present work, the model was applied on an additional coupon configuration, 145-mm long $[90]_7$ specimens, made of the same material as the original model dataset. Results from $R = 0.1$, $R = -1$ and $R = 10$ CA loading are presented, indicating that the AE model is applicable in tensile, reversed and also compressive fatigue.

The same model was also implemented for compressive residual strength estimation. Indeed, for $R = -1$, both tensile and compressive residual strength tests are presented. Although the respective failure modes are distinguished in state-of-the-art failure criteria (Puck and Schürmann [9]) as being of different severity, model response seems to follow a universal trend, dominated by polymeric matrix failure.

2. Background

This work was performed during an extensive 52-month experimental program, conducted in the frame of EC-funded research project OPTIMAT BLADES [10]. The aim was to investigate strength degradation of a Gl/Ep unidirectional (UD) laminate, due to fatigue, using non-destructive techniques. The corresponding experimental series, i.e., residual strength tests, was thus enriched with acoustic emission monitoring, stiffness degradation measurements and acousto-ultrasonic scanning. Some findings from the AE measurements are demonstrated herein.

In a previous publication, Philippidis and Assimakopoulou [1], acoustic emission recorded during proof-loading of fatigued $[\pm 45]_S$ specimens was used to assess shear strength degradation of the respective UD laminate. Applied fatigue loading was tensile, under stress ratio $R = 0.1$. Two validated engineering models for residual strength prediction were introduced, based on a conventional AE parameter, AE counts (CNT). These residual strength models were denoted as «model A» and «model B» and the respective AE descriptors as «AE_1» and «AE_2». Strength degradation, for the particular specimens and loading configuration, was attributed to matrix cracking. To avoid confusion with matrix failure modes A and C, discussed below, models A and B are henceforth denoted as «M_1» and «M_2».

Descriptor AE_1, used to formulate model M_1, is a function of fatigue maximum stress, σ_{max}, and the cumulative number of recorded AE counts until a static proof-load 10% higher than σ_{max}, named «CNT_{max}». AE_1 was given by:

$$\mathrm{AE}_1 = (\mathrm{CNT}_{max})^{\frac{\sigma_{max}}{\mathrm{UTS}}} \tag{1}$$

In Eq. (1), «UTS» is the ultimate tensile stress of the specimen under consideration. Selection of a proof-load level of 110% σ_{max} was made in accordance to common practices in pressure vessel inspection as well as previous works performed on acoustic emission proof-testing of wind turbine rotor blades [11]. It should be underlined that although a σ_{max}-dependent proof-loading value was used, no AE monitoring was performed during fatigue. With residual strength denoted as X_r, model M_1 was then defined as:

$$\frac{\sigma_{max}}{X_r} = 0.1447\log(AE_1) + 0.3606 \tag{2}$$

Using this formulation, AE data from coupons loaded at various stress levels converged into the same scatter band. However, although M_1 provided excellent residual strength predictions, information on previous fatigue loading, i.e., the maximum applied stress value, was a priori required.

Model M_2, as described in Philippidis and Assimakopoulou [1], used an alternative stress value, σ_{AE}, to substitute σ_{max}. Stress σ_{AE} was defined as the stress above which at least 10 consecutive AE hits emanated at smaller than 2 MPa intervals. In practice, this expressed the actual acoustic emission onset. The corresponding descriptor AE_2:

$$\mathrm{AE}_2 = (\mathrm{CNT}_{AE})^{\frac{\sigma_{AE}}{\mathrm{UTS}}} \tag{3}$$

In Eq. (3), CNT_{AE} is the cumulative number of AE counts up to 110% of σ_{AE} and UTS the appropriate ultimate tensile stress value. Using M_2, information on σ_{max} was no longer needed and dependence on previous loading was eliminated. Moreover, the required static proof-loading was lower, in general, than the respective M_1 value. Model M_2 was therefore formulated as:

$$\frac{\sigma_{AE}}{X_r} = 0.1791\log(\mathrm{AE}_2) + 0.3425 \tag{4}$$

As shown in this work, M_2 is also applicable for residual strength prediction in compression. The model is expanded using a compressive proof-loading, instead of a tensile one, and substituting UTS in Eq. (3) with the ultimate compressive stress (UCS).

3. Experimental procedure

3.1. Test specimens and material characterization

Test coupons were made of Gl/Ep material and fabricated using vacuum infusion. Stacking sequence was $[90]_7$ and specimens dimensions 145×25, in mm. Reinforcement was a non-woven unidirectional glass roving of $1150\,g/m^2$, stitched with a CSM (chopped strand mat) layer of $50\,g/m^2$ and another layer of $50\,g/m^2$ of 90° fibres, resulting in total weight of $1258\,g/m^2$. The resin used was Prime 20 from SP Systems, mixed with a slow hardener. Fibre volume fraction was $55 \pm 3\%$ and nominal average thickness of each layer 0.88 mm, resulting in a specimen thickness of 6.16 mm. More details are given from the manufacturer, LM Glasfiber, in Jacobsen [12].

An extensive experimental program was conducted, prior to residual strength testing, in order to characterize the particular specimen configuration in terms of static mechanical properties and fatigue life. Ultimate tensile and compressive stress and elastic properties were determined through 25 tensile (STT) and 26 compressive (STC) static tests, to derive a reliable statistical static strength distribution of the stochastic behaviour of the Gl/Ep composite. A set of 15 coupons was tested in CA fatigue, $R = 0.1$, in load control and until specimen separation. Another 32 experiments were performed at $R = -1$ and 24 at $R = 10$. Test frequencies varied depending on stress ratio and stress level, to maintain constant dissipated energy per cycle. Details on static and fatigue test execution and results can be found in Philippidis et al. [13,14].

3.2. Interrupted fatigue loading, AE inspection and residual strength testing

Interrupted CA fatigue loading was performed at three stress ratios, $R = 0.1$, $R = -1$ and $R = 10$. For each coupon, one out of five specific fatigue stress levels was used, corresponding to expected fatigue lives, N, of 10^6, $2{\cdot}10^5$, $5{\cdot}10^4$, $5{\cdot}10^3$ or 10^3 cycles. The respective stress levels are given in Table 1 as fractions of the nominal UTS for $R = 0.1$ and $R = -1$ and of the nominal UCS for $R = 10$.

Duration of the CA loading reached up to 20, 35, 50% or 80% of the estimated life, derived using the respective S–N curve equation. The number of residual strength tests corresponding to each loading configuration is also listed in Table 1. At $R = 0.1$, a total of 17 coupons was used whereas 19 coupons were tested at $R = 10$. Residual strength tests of the respective specimens were tensile. However, at $R = -1$, from the total of