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Interpreting acoustic emission signals by artificial neural networks to predict the residual strength of pre-fatigued GFRP laminates

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Abstract

Artificial neural networks (ANNs) were used to predict the residual strength of glass fibre-reinforced plastic beams pre-fatigued in flexure up to different portions of their fatigue life. To this aim, the acoustic emission signals recorded during the tests for the measurement of the residual strength, and the associated applied stress, were provided as input. An optimisation of the network configuration was carried out, using the root-mean-square error calculated in the training stage as the optimisation parameter. The predictive accuracy of the optimised ANN, consisting of two nodes in the input layer, four nodes in the hidden layer, and a single node in the output layer, was tested by the ''leave-k-out'' method. From the results obtained, ANN provided quite reliable predictions when the applied load was sufficiently far from the failure load, performing better than a previous theoretical model, relying on fracture mechanics concepts. Therefore, ANN was shown to be a valid tool in the non-destructive evaluation of composite materials employed in fatigue-sensitive applications.

Keywords: Polymer–matrix composites A; Fatigue B; Acoustic emission D; Artificial neural networks

1. Introduction

Some authors [1] have shown that carbon fibre-reinforced laminates subjected to fatigue loading preserve their original strength along almost all their fatigue life. Only immediately before fatigue failure, the material strength decreases suddenly [2], supporting the definition of ''sudden death''.

Apparently, glass fibre-reinforced plastics (GFRPs) behave in a different way, with a continuous strength decrease with elapsing fatigue cycles [3,4]. Consequently, the knowledge of the residual strength in a fatigue-critical application not only yields direct information on the current safety factor, but from it also the previous history of the component can be somehow inferred.

In a previous work [5], GFRP specimens were pre-fatigued up to predetermined portions of their fatigue life under assigned loading conditions. After that, monotonic tests were carried out to measure their residual strength, and the acoustic emission (AE) event counts were recorded. The evolution of the AE cumulative events was found to be very sensitive to the number of pre-fatiguing cycles applied. Therefore, it was concluded that the study of the AE response could be used to resort to the material residual strength. In an attempt to achieve this goal, a previous fracture mechanics model was employed [6], from which a good correlation was found between the theoretical predictions and the experimental data. However, the results also showed that the method proposed was inaccurate in the case of lightly fatigued specimens: for them, the change in rigidity

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was a better marker of the cycles elapsed than the AE signature.

In the last years, artificial neural networks (ANNs) have proved able to solve many engineering issues, being successfully employed in process control, optimisation procedures, as well as in non-destructive evaluation [7–10]. In particular, they seem to be an ideal tool when multi-variate problems, for which no analytical models are available, but a large experimental database has been collected, are under concern.

In this work, ANNs were used to interpret the AE data generated in [5]. Different network configurations were tested to optimise the ANN accuracy. Two optimised architectures were individuated, and their predictive ability was ascertained. The application of ANNs allowed for reliable estimates of the residual strength, providing better results than the theoretical model discussed in [5].

2. Materials and experimental methods

The laminate studied in this work was made of 13 layers of glass/epoxy prepreg by Ciba Composites, containing 305 g/m^2 plain weave fabric embedded in a M9/M10 modified resin. The laminae were stacked with coincident warp/weft direction, and the cure process was accomplished by hot pressing, following the procedure recommended by the base material supplier. The nominal thickness of the cured laminate was 3.9 mm, and its fibre content by volume $V_f = 0.40$.

The specimens adopted in the experiments were under form of rectangular beams 80 mm × 12 mm, whose major dimension coincided with the warp direction of the reinforcing fabric. All the tests were carried out in four-point bending, adopting an outer span 66 mm and an inner span 22 mm, in an Instron 8501 servo-hydraulic testing machine.

To measure the laminate virgin strength, 16 samples were loaded monotonically in stroke control at a cross-head speed $v = 100$ mm/min. This high loading rate was chosen to approximately match the loading rate conditions attained in the subsequent fatigue tests. From the monotonic tests, the mean value of the failure load, P_r, was calculated, and used to appropriately select the governing parameters in the fatigue stage.

Five specimens were brought to complete failure in fatigue adopting a maximum load $P_{max} = 0.48P_r$ and a minimum load $P_{min} = 0.1P_{max}$. The fatigue tests were performed in load control, using a sinusoidal waveform and frequencies in the range 0.8–2 Hz. From them, the fatigue life of the material, i.e., the number of cycles N resulting in failure, was determined, obtaining $N \approx 11{,}000$. This information was useful in setting the number n of pre-fatiguing cycles to impart to the 17 specimens destined to residual strength evaluation. In fact, n was chosen in the range 200–9000. The operating parameters in the pre-fatiguing tests were coincident with those previously specified for the fatigue tests up to failure.

The pre-fatigued specimens were monotonically loaded in stroke control, at a crosshead speed $v = 5$ mm/min, to measure their residual strength. During these tests (Fig. 1), their AE activity was recorded by a 150 kHz resonant sensor and a PAC 3004 instrumentation. Amplification was 58 dB, threshold level 0.5 V, high-pass filter cut-off frequency 100 kHz, and dead time 0.1 ms. Among other typical AE parameters, such as event amplitude, duration, energy, and the ring-down counts of an event, the total event count, N_t, was used as the input AE parameter in the construction of ANNs. In fact, N_t seems to be particularly significant when the residual strength of a composite laminate is under evaluation [6,11].

3. Results and discussion

3.1. Mechanical tests

The results of the experimental tests considered in this work were discussed in deep elsewhere [5]. Only the aspects relevant to the present objectives will be recalled here.

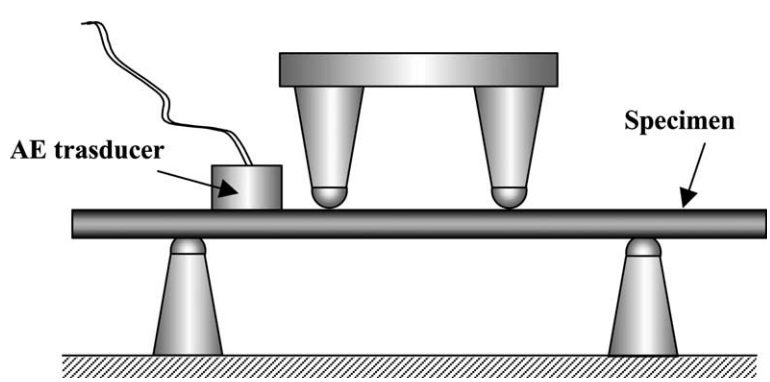

Fig. 1. Schematic of the experimental set-up used in the residual strength tests.