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MULTIPLE CRACK INITIATION IN CROSS-PLY LAMINATES UNDER SPECTRUM LOADINGS

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ABSTRACT

The present work investigates the damage evolution in glass/epoxy cross-ply laminates under variable amplitude spectrum loadings. The attention is focussed on the effect of variable amplitude loadings on the life to the initiation of transverse cracks and the crack density evolution. Cross-ply specimens were manufactured through the infusion process using unidirectional glass fibres and an epoxy matrix to obtain a semi-transparent material, where transverse cracks could be detected using a back-illumination system. During the fatigue tests the damage was monitored by taking periodical front images using a full-frame camera. These were then processed to obtain the number of cracks and their length throughout the test.

Tensile fatigue tests were carried out using an MTS 809 tensional/torsional machine with a frequency of 10 Hz. Load-controlled sinusoidal cycles were applied. The load ratio R, i.e. the ratio between the peak and the valley of the applied cycle, was equal to $R = 0.05$. The variable amplitude spectra were generated having each defined peak followed by a valley at that specified load ratio. Three types of tests were carried out:

1) Constant Amplitude (CA) fatigue tests;
2) Repeated two-stage block loadings with different block duration;
3) Spectrum tests performed at different maximum stress levels.

The CA tests were necessary for calibrating the material parameters necessary for predicting the multiple crack initiation under cyclic loadings, according to the procedure proposed in Ref. [1].

In a previous work by the authors [2], it was proved that the linear damage accumulation rule was suitable and formally correct for predicting the transverse crack initiation under block loadings, provided that the duration of the blocks was high enough. Thus, two-stage repeated small blocks were applied here to investigate the effect of the block length on the suitability of the linear damage accumulation rule. Two load levels were chosen (H: high, L:low). Three combinations of the block duration were adopted, namely 1+40, 10+400, 100+4000, where 1, 10 and 100 high-load cycles were followed by 40, 400 and 4000 low-load cycles, respectively. Each sequence was repeated until the saturation of the crack density.

In the initial stages of the fatigue life, transverse cracks are in general far from each other and do not interact. The initiation of cracks at different number of cycles is thus controlled by the statistical distribution of the fatigue strength to crack initiation alongside the ply volume. According to Ref. [1], the total crack density (number of cracks/observation length) in the non-interactive (NI) regime is given by the following expression (for a cross-ply laminate):

$$\rho^{NI} = \frac{w}{l_0 \cdot c_0} \cdot \left(1 - \exp\left(-\left(\frac{LHS_{max}}{K_0 \cdot N^a} \right)^m \right) \right) \qquad (1)$$

where LHS_{max} is the maximum cyclic value of the Local Hydrostatic Stress (LHS) driving the crack formation, K_0 and m are the Weibull distribution parameters for crack initiation [1], *a* is the slope of the crack initiation SN curve in log-log scales, w is the specimen width and l_0 and c_0 the dimensions of the crack initiation volume, as defined in Ref. [1]. It was found that Eq. (1) provides reliable predictions for long blocks [2], as well as for the 100+4000 sequence tested in this work. Conversely, as the number of cycles in the blocks is decreased (10+400 and, mainly, 1+40), Eq. (1) provides a significant underestimation of the crack density.

Spectrum loadings were then applied. Three types of spectra were generated:

- Uniform spectrum: 500 random peaks were generated according to a uniform distribution;
- Gaussian spectrum: 500 peaks were generated according to a normal distribution;
- WISPERX-R0.05: the WISPERX spectrum peaks (12831) from Ref. [3] were considered, each followed by a valley respecting the R=0.05 ratio, not to include a further source of influence on the fatigue behaviour.

In all cases, the single spectrum block made of 500 or 12831 cycles was repeater periodically in time. Three different maximum load levels were chosen for each spectrum type.

The results showed that Eq. (1) provides underestimations of the total crack density in all the conditions, but mainly for the uniform and Gaussian spectra, characterised by a higher number of load changes with respect to the WISPERX-R0.05 load case. The latter is, indeed, characterised by several blocks of different duration and few spikes, different from the first two spectra in which the load amplitude changes after each single cycle.

The load level was also found to have an influence: for lower load levels, the underestimation provided by Eq. (1) is more pronounced.

The problem has been analysed from a mechanistic point of view and an analytical treatise was developed, leading to an expression to account for the influence of the spectrum profile on the total crack density prediction.

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