Image-based ultrasonic fatigue testing of composites

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Abstract: Composite materials are known to be prone to fatigue. This phenomenon can be evaluated through the loss of stiffness with the number of cycles, as a damage variable. Here, an ultrasonic rig is used in conjunction with an ultra-high speed (UHS) camera to evaluate the material Young's modulus transverse to the fibres, using the acceleration as a load cell. The set-up is used to monitor stiffness degradation with number of cycles. Extension of the methodology to off-axis configurations is also explored.

Introduction

The Novel Image-based Ultrasonic presented in [1] was used to identify the mechanical behaviour of a polymer over a large range of strain rates and temperatures in a single test. The same setup is used here to test orthotropic carbon fibre reinforced polymer (CFRP) composites. The first configuration considered here is a 90° unidirectional specimen. The evolution of the modulus transverse to the fibres, E_{22}, with the number of cycles represents a way to characterize its fatigue behaviour. The main advantage here is that thanks to the 20 kHz loading frequency, fatigue tests can be undertaken dramatically more quickly than on a traditional test machine [2] (minutes rather than days for millions of cycles). This idea is then extended to an off-axis configuration for which both E_{22} and G_{12} can be identified and monitored for fatigue damage. The strain rate range achieved with this test is typically [50 – 500] s^{-1}.

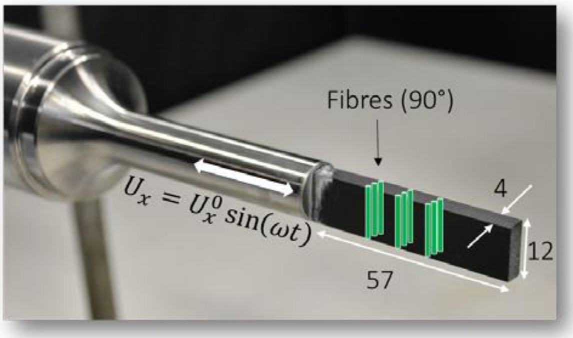

Figure 1: Ultrasonic testing configuration

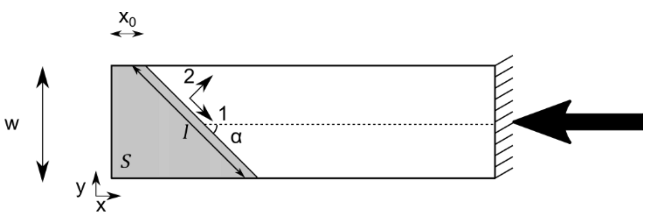

Figure 2: Global and local coordinate

Experimental set-up

CFRP prismatic samples were bonded onto the tip of an ultrasonic horn using cyanoacrylate glue (Figure 1). The specimen length was selected so that its first longitudinal resonance frequency matched that provided by the transducer (20 kHz). The horn vibrates at 20 kHz with amplitude variable up to ±60 µm. A grid pattern is attached to the surface using flatbed printing[1], the pitch used here is 0.9 mm. Images of the grid are captured at 500 kfps with a Shimadzu HPV-X (400 x 250 pixels) camera. The grid is sampled at 6 pixels per period. From those images the displacement fields are determined using the grid method [3]. One of the issues is specimen heating up during the tests. To mitigate this effect, an infrared camera was used to monitor the temperature. Blocks of one second of excitation were performed consecutively, while in between loading blocks, the specimen was cooled down for a few seconds. This downtime was also used to download the images from the camera sensor to the computer hard drive before a new test block could be performed. During each block, 128 images were recorded (256 µs, approximately 5 cycles) and the modulus is obtained using the approach detailed below and in [1].
The same set-up is envisaged for the off-axis configuration. In this case, the specimen will be cut so that the fibres are at a certain angle α from the specimen edge (Figure 2).

From acceleration to stress

From the global equilibrium of the test specimen, at a certain section of coordinate x_0 from the free edge, the average axial stress $\overline{\sigma_{xx}}$ over the cross-sectional area at x_0 can be expressed as [1]:

1 http://photodyn.org/wp-content/uploads/2016/03/Report_UniversityPrintCentre.pdf

$$\overline{\sigma_{xx}} = x_0 \rho \overline{a_x} \tag{1}$$

Where $\overline{a_x}$ is the average of the acceleration between the cross-section at x_0 and the free edge and ρ is the material density, assumed to be constant here and unaffected by the small deformations. Since the strains can be obtained from the displacements, the longitudinal component can be averaged across the width and stress-strain curves can be obtained.

For the off-axis situation, similar equilibrium equations can be derived using the principle of virtual work. In the material coordinate system, as shown in Figure 2, the average stress along a slice following the fibre direction can be obtained by selecting the following two sets of virtual fields:1) $U_1^* = 0$; $U_2^* = 1$ and 2) $U_1^* = 1$; $U_2^* = 0$

$$\overline{\sigma_{22}} = \frac{S}{l} \rho \overline{a_1} \;\; ; \;\; \overline{\sigma_{12}} = \frac{S}{l} \rho \overline{a_2} \tag{2}$$

Where S is the surface between the free-edge and the slice and l the length of the slice (figure 2). Using transverse and shear strain averages, stress-strain curves can also be reconstructed and both E_{22} and G_{12} determined and monitored for fatigue damage.

Results

Figure 3 shows a stress-strain curve obtained just before fatigue failure after 416000 cycles, for a Gurit SE70 90° carbon/epoxy specimen. One can see a slight hysteresis evidencing damping. From all stress-strain curves obtained for all runs and all sections, the E_{22} modulus has been calculated and reported in Figure 4. One can clearly see two locations where the modulus decreases before failure, and final separation occurs at one of the two locations (dashed line).

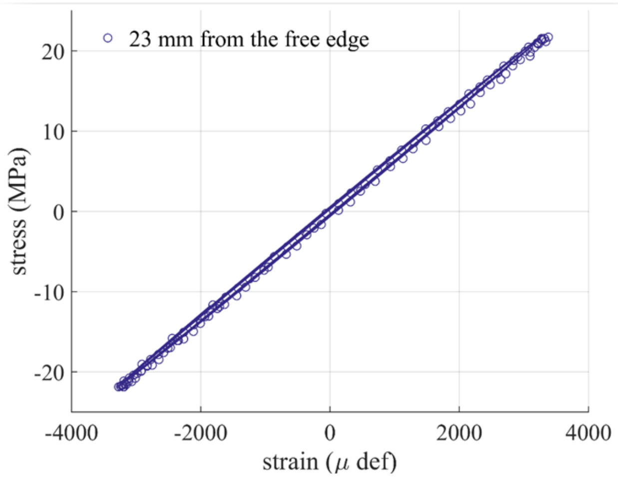

Figure 3: Stress-strain curve just before fracture

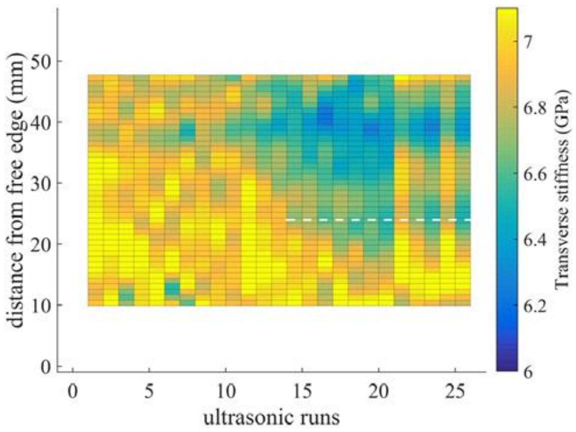

Figure 4: Modulus evolution in space and time

Results for more test specimens and different off-axis configurations will be provided during the presentation.

Conclusion

The use of an ultrasonic rig in to determine Young's modulus using the acceleration as a stress-gauge had been previously demonstrated [1]. Here new developments to this method are presented concerning composite materials. It was shown that the method was sensitive enough to record a change of modulus with number of cycles, evidencing a fatigue process. By extending this to an off-axis configuration, the fatigue processes under combined transverse tension and shear will be studied.

References

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[3] Grédiac, M., F. Sur, and B. Blaysat, *The Grid Method for in-plane displacement and strain measurement: a review and analysis*. Strain, 2016. **52**(3): p. 205-243.