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Gabor Wavelet Transform Contours for the Detection of Uniaxial Tensile Damage in Woven Fiberglass/epoxy Composites

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Abstract

Evaluating damage progression in fiber-reinforced polymeric composite structures is critical for effective condition-based monitoring techniques of these structures. In this study, three sets of woven fiberglass/epoxy specimens were investigated under axial loading and unloading conditions using embedded and surface-mounted piezoelectric wafers. The noisy ultrasonic waveforms were denoised and analyzed with Gabor wavelet transforms and their contour plots, in particular normalized contour perimeters. It was found that the trend of the selected contour parameters captures the specimens' strain reasonably well in some samples, replicating loading, unloading and residual strain. This technique shows promise for tracking damage progression, residual strains, and pending failure in fiber-reinforced polymeric composites.

Keywords: wave propagation; fiber-reinforced polymer composites; wavelet transform

1. Introduction

Fiber-reinforced polymer composite structures offer many challenges to ultrasonic inspection. These include: a) manufacturing defects, which may cause false positives; b) anisotropy and inhomogeneities, which lead to complex propagation, dispersion, scattering and mode conversion of ultrasonic waves; c) designed and unforeseen hygro-thermo-mechanical load scenarios, affecting wave propagation and condition-based monitoring; d) potential stress raisers from sensors/wires.

The objective of this multi-year project was to develop a signal processing technique able to capture the onset and progression of damage in woven fiberglass/epoxy composite as they were subjected to laboratory-controlled axial static and fatigue loading. Detecting individual cracks was not the scope of this project. Ultrasonic transducers were the sensors of choice for this project. Many authors have reported successful results from bonded piezoelectric transducers applied to metallic and composite structures (e.g. reviews of Chopra, 2002, Giurgiutiu, 2008, and Su et al., 2006). Waveforms acquired during the tests by the transducers are a signature of how the structure and the transducers themselves change in response to the given input loading. However, the signal interpretation in the time domain and in other domains (e.g. Fourier transform, wavelet transform, etc.) is difficult. When proposing a new structural health monitoring method, any interpretation should be validated by independent measures of damage (unrelated to the waveform acquisition process), such as (in a laboratory environment) testing machine data logs, strain gauges, or live measure/assessment of crack formation and propagation. In this paper, a signal processing technique based on Gabor wavelet transforms and their contour perimeters is presented, and applied to noisy signals acquired from transducers operated in a pitch-catch mode during the testing of fiberglass/epoxy composites. If validated for on-line condition-based monitoring, the successful use of this technique would require sensors' baseline data collected from the loaded as-manufactured structure. Although wavelet transforms have appeared as methods for the analysis of composite materials' behavior before (Quek et al., 2001, Salamone et al., 2009, Gaul and Hurlbaas, 1997, Paget et al., 2003, etc.), the techniques and the results discussed herein are new.

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2. Materials and Methods

This paper is based on a multi-year study, with data acquired in 2010 (Sets 1-2) and 2011 (Set 3), and processed the first time with an earlier version (La Saponara et al., 2011a, Tang et al., 2011) of the signal processing technique proposed in **Section 3**. The outcome of the first round of analysis on Set 1 was not conclusive (La Saponara et al., 2011b), hence the project was set aside. A breakthrough in the signal processing technique was achieved recently, when the revised technique was applied successfully to smart sandwich composites under creep bending (La Saponara et al., 2014). This led to revisiting Sets 1-3 data again, and to this paper.

2.1 Materials and Manufacturing

The specimens in this study were fabricated with a predominantly unidirectional E-glass fabric (type 7715, Applied Vehicle Technology), with an 8-ply lay-up given by $[(0/90)_2]_s$. The specimens were infused with epoxy/hardener (Proset 117LV/237) through a conventional low-cost out-of-autoclave Vacuum Assisted Resin Transfer Molding technique. The cure cycle consisted of four hours at 52 deg. C, followed by sixteen hours at 60 deg. C. The specimens' dimensions were 25.25 ± 0.2292 mm width $\times$ 1.683 ± 0.09070 mm thickness $\times$ 152.4 ± 0.7523 mm gauge length. In-plane mechanical properties were measured following ASTM standards (D3039/D3039M and D3518/3518M), and consist of $E_{11} = (37.6 \pm 2.22)$ GPa, $E_{22} = (12.0 \pm 0.682)$ GPa, $G_{12} = (3.42 \pm 0.192)$ GPa, $\nu_{12} = 0.254 \pm 0.0131$.

Two types of PZT (lead zirconium titanate) wafers were used: a) 'type a', a PZT-5A transducer, with nominal 7 mm diameter and 0.2 mm thickness, published piezoelectric constants $d_{33} = 440 \times 10^{-12}$ m/V, $d_{31} = -190 \times 10^{-12}$ m/V (type SM412 from Steiner Martins, Inc.); b) 'type b', a PZT-4 transducer, with nominal 5 mm diameter and 0.4 mm thickness, published piezoelectric constants $d_{33} = 300 \times 10^{-12}$ m/V, $d_{31} = -130 \times 10^{-12}$ m/V (type SM121 from Steiner Martins, Inc.). Pairs of these transducers (for pitch-catch ultrasonic testing) were placed either inside the specimens (one ply below the surface, in specimen Sets 1-2) or on the specimens' surface (Set 3), at a distance of 94.16 ± 1.837 mm from each other¹, see details in **Table 1**. Embedded transducers (actuators and sensors) may be required by engineering applications demanding smooth aerodynamic surfaces (Dürr et al., 1999).

Table 1. Information on specimens and waveform acquisitions.

Specimens	Waveform acquisitions
Set 1	
A PZT: 1 ply below surface/type a	pristine, load, 1k cycles (load/unload), 6k cycles (load/unload), 11k cycles (load/unload), stopped at 11k cycles; mean = 9.14 kN, ampl = 0.65 kN.
B PZT: 1 ply below surface/type a	N/A, load, 1k cycles (load/unload), 6k cycles (load/unload), 11k cycles (load/unload), failed at 16,000 cycles before acquisition; mean = 9.14 kN, ampl = 0.65 kN. <i>Not included in the analysis.</i>
C PZT: 1 ply below surface/type a	pristine, load, 1k cycles (load/unload), 6k cycles (load/unload), 11k cycles (load/unload), failed at 16,000 cycles during acquisition; mean = 9.14 kN, ampl = 0.65 kN.
D PZT: 1 ply below surface/type a	pristine, load, 1k cycles (load/unload), 6k cycles (load/unload), 11k cycles (load/unload), 14k cycles (load/unload), 16k cycles (load/unload), stopped at 19,000 cycles; mean = 9.14 kN, ampl = 0.65 kN.
E	pristine, load, 1k cycles (load/unload),

¹ The distance reported is the inner distance between the two circumferences, not the distance between the two centers of the disks.

PZT: 1 ply below surface/type b	4k cycles (load/unload), 7k cycles (load/unload), 10k cycles (load/unload), 13k cycles (load/unload), failed at 13,697 cycles; mean = 9.12 kN, ampl = 0.95 kN.
F PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load/unload), 4k cycles (load/unload), 7k cycles (load/unload), 10k cycles (load/unload), failed at 10,605 cycles; mean = 9.12 kN, ampl = 0.95 kN.
Set 2	
G PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load), 5k cycles (load), 9k cycles (load), 13k cycles (load), 17k cycles (load), failed at 19,587 cycles; mean = 9.12 kN, ampl = 0.95 kN.
H PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load), 5k cycles (load), 9k cycles (load), 13k cycles (load), failed at 15,864 cycles; mean = 9.12 kN, ampl = 0.95 kN.
I PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load), 5k cycles (load), 9k cycles (load), 13k cycles (load), 17k cycles (load), failed at 18,926 cycles; mean = 9.12 kN, ampl = 0.95 kN.
J PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load), 4k cycles (load), 7k cycles (load), 10k cycles (load), failed at 12,977 cycles; mean = 9.12 kN, ampl = 0.95 kN.
K PZT: 1 ply below surface/type b	pristine, load, 1k cycles (load), 3k cycles (load), 5k cycles (load), 7k cycles (load), 9k cycles (load), 11k cycles (load), failed at 12,153 cycles; mean = 9.12 kN, ampl = 0.95 kN.
Set 3	
1 PZT: surface/type b	pristine, 9.12 kN, 9.12 kN after 2k cycles, 8.12 kN, 8.62 kN, 9.12 kN, 9.62 kN, 10.12 kN, 0 kN, failed at 396 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.
2 PZT: surface/type b	pristine, 9.12 kN, 9.12 kN after 2k cycles, 0 kN, 5.12 kN, 8.12 kN, 9.62 kN, 10.12 kN, 0 kN, 8.12 kN, 10.62 kN, 9.12 kN, 11.12 kN, 0 kN, failed at 376 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.
3 PZT: surface/type b	pristine, 9.12 kN, 9.12 kN after 2k cycles, 0 kN, 5.12 kN, 8.12 kN, 9.62 kN, 10.12 kN, 0 kN, 8.12 kN, 10.62 kN, 9.12 kN, 11.12 kN, 0 kN, failed at 363 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.
4 PZT: surface/type b	pristine, 9.12 kN, 9.12 kN after 2k cycles, 0 kN, 5.12 kN, 8.12 kN, 9.62 kN, 10.12 kN, 0 kN, 8.12 kN, 10.62 kN, 9.12 kN, 11.12 kN, 0 kN, failed at 377 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.
5 PZT: surface/type a	pristine, 9.12 kN, N/A after 2k cycles, 0 kN, 5.12 kN, 8.12 kN, 9.62 kN, 10.12 kN, 0 kN, 8.12 kN, 10.62 kN, 9.12 kN, 11.12 kN, 0 kN, failed at 367 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.
6 PZT: surface/type a	pristine, 9.12 kN, 9.12 kN after 2k cycles, 0 kN, 5.12 kN, 8.12 kN, 9.62 kN, 10.12 kN, N/A, 8.12 kN, 10.62 kN, 9.12 kN, 11.12 kN, 0 kN, failed at 353 MPa. Fatigue cycles with mean = 9.12 kN, ampl = 0.95 kN.

For Sets 1 and 2, resin pockets may have formed around the transducers during resin infusion of the woven composites, due to their size and shape as compared to the ply thickness ($210 \pm 11.33 \mu\text{m}$). This may have impacted the vibration of the transducers, affecting life to failure, and contributing to

scattered average powers of the acquired signals, and scattered signal processing outputs. Several specimens from Sets 1-2 broke around the transducers (see **Figure 1 right**), which acted as stress raisers and led to scatter in the vibration properties. The reduced durability under axial tension is consistent with the outcome observed by some authors (Dürr et al., 1999), who considered factors such as the formation of resin pockets, mismatches of thermal expansion and stiffness properties between the polymer composite and the embedded ceramic transducer. However, other authors reported no such effects (Paget et al., 2002). As opposed to Sets 1-2, all Set 3 specimens broke away from the transducers in the gauge section (**Figure 1 center**). For Set 3, electrical contact to the bottom PZT surface was made possible by conductive epoxy partially surrounding the transducer (visible in **Figure 1 left**), which biased the vibration properties as well.

Figure 1. (Left) a Set 3 specimen during testing; (center) a Set 3 specimen broken near the center of the gauge section (note that the bottom transducer detached when the specimen failed); (right) a Set 2 specimen after its failure across the top transducer.

The arrows show locations of failure and transducers. Nominal specimen's width = 25.4 mm.

2.2 Loading Profiles, Acquisition of Edge Replication

The selection of the loading profiles for Set 1 was the result of prior work by Tang et al. (2011). The authors proposed a signal processing technique based on Gabor wavelet transforms and the area enclosed in one of the contours. They hypothesized that the output was indirectly correlated with the formation, accumulation and eventually the coalescence of “transverse cracks” in the woven fiberglass/epoxy composites. Herein, transverse cracks are meant as cracks in the fill plies and cracks in the matrix-only regions between warp (longitudinal) and fill/weft (transverse) plies. These transverse cracks form under uniaxial tensile loading, and accumulate in a nonlinear manner following the well-established “characteristic damage state” (Highsmith and Reifsnider, 1982; Berthelot, 2003), causing progressive loss of stiffness and global damage. The signal processing technique discussed in this paper cannot identify individual transverse cracks², but it quantifies changes in the ultrasonic guided waves, which are indeed interacting with the transverse cracks, and therefore indirectly demonstrating global damage.

² Transverse cracks appear simultaneously as a distribution of cracks in the fill plies, which is a feature that helps identifying them in microscopy images such as **Figure 2**. The spacing among cracks decreases as the composite becomes more damaged, until a saturated “spacing” is reached. To complicate matters, fill plies may have different shapes, and consequently stress distributions because they may be compacted differently in the manufacturing process (see for example fill plies in **Figure 2**). The transverse crack system is highly heterogeneous.

To validate or disprove the hypothesis of Tang et al. (2011), the loading profile for Set 1 was designed to include a series of fatigue cycles followed by unloading to zero, and loading back to the mean load, before additional fatigue cycles. In **Table 1**, in the “Waveform acquisitions” column for Set 1, “load” is the mean load of these fatigue tests, while “unload” is 0 kN. As an example, “1k cycles (load/unload)” means that there were 1,000 cycles applied to the specimen, followed by the waveform acquisition as the machine was paused (with specimen loaded at the mean load), followed by unloading of the specimen to 0 kN. Then the specimen was ramped back to the mean load, and subjected to more cycles. The mean load of 9.14 kN was chosen based on prior static tensile tests. The fatigue cycles had nominal amplitude equal to 0.65 kN (for 3 specimens of Set 1) and 0.95 kN (for 2 specimens of Set 1³, and all the specimens of Sets 2-3). These values were a compromise between the need to obtain fatigue failure within a reasonably short time, and the need to have enough waveform acquisitions. It is possible that the heat generated inside the material by the high testing frequency of 10 Hz may impact the failure onset and propagation process, but this is not addressed here.

During the testing, edge replication (or “replicas”) identified the formation of opening and closing transverse cracks. This well-established procedure (see for example Stinchcomb, 1986; Berthelot, 2003) consisted of applying a cellulose acetate replicating tape (type 44858, Ted Pella) cured with acetone (administered carefully with a dropper) on one edge of the specimen loaded at the mean load, while the machine was paused. The result is an impression of the specimen edge, which could be viewed later in an optical microscope (in this case, a Nikon Labophot-2A), **Figure 2**. One idea was to measure crack density and correlate it with the output of the signal processing technique under loading/unloading steps. However, assorted technical problems (with microscopy equipment) and a non-ideal storage of these viscoelastic replica films after testing eventually impeded a systematic and statistically robust count of transverse crack density for the specimens of this study. The image in **Figure 2** is a representative sample of the heterogeneity of the material under exam, and the various patterns of microscale damage, which eventually cause global failure.

Figure 2. Microscopic image from replica of specimen 5, Set 3, at load 10.12 kN. The diamond-tip arrows indicate cracks. The average ply thickness is 210 μm .

³ In Set 1, 3 specimens had mean load and amplitude respectively equal to 9.14 kN and 0.65 kN, while 2 specimens had mean load and amplitude respectively equal to 9.12 kN and 0.95 kN. This occurrence may be seen as an unplanned departure from nominal conditions. However, the strain distribution of the entire set is Gaussian, as obtained from a Lilliefors test for normality. Hence, the scatter of the entire set falls within the Gaussian distribution. Because of this, the results of the 5 specimens are presented together.

Because of the neutral results from Set 1 (La Saponara et al., 2011b), the loading scenario was modified for Set 2 specimens: the plan became to accrue fatigue damage and assess whether there was a “red flag” from the signal processing technique before failure.

Finally, for Set 3 specimens, the transducers were bonded on the surface to avoid the occurrence of stress raisers, and the loading scenario was mostly quasi-static: after a ramp to the value of 9.12 kN, the specimen was subject to 2,000 cycles. This number of cycles was sufficient to trigger the formation of surface cracks, which were visible on the replica films. After acquiring waveforms and replicas at the mean load with a paused testing machine, the specimens were subject to a number of loading and unloading steps in quasi-static conditions at different load levels, sometimes with small increments, and with few instances of unloading back to 0 kN. At the end, the specimen was brought to failure. In Set 3, the first specimen tested had a different and shorter load profile (**Table 1**), which was then modified for the other five specimens, to include more acquisitions.

For all specimens, the baseline corresponded to the acquisition of the waveform when the specimens have zero load inside the machine grips, at the very beginning of the tests (“pristine/no load”). In one specimen only (specimen B of Set 1), this baseline data was lost (“N/A” in **Table 1**), and that specimen was eventually excluded from the analysis.

2.3 Generation and Acquisition of Ultrasonic Waveforms

The transducers operated in a pitch-catch fashion. The tests were controlled by the commercial MATLAB Instrument Control toolbox, connected to a function generator (Agilent 33220A) and a four-channel oscilloscope (Agilent DSO6014A). The transmitted signal was a five sinewave pulse modulated by a Hamming window, selected because it is used in the literature to obtain well-separated guided waves in composite materials (e.g. Seale et al., 1998; Paget et al., 2003; Guo and Cawley, 1993). The input was amplified to 160 V_{pp} (by an A.A. Lab Systems Ltd. A303 High Voltage Amplifier and Modulator), and launched at center frequencies ranging from 10 kHz to 50 kHz, with increments of 2 kHz for Sets 1-2, and 5 kHz for Set 3. Guided waves at these low ultrasonic frequencies are expected to have limited attenuation. The transmitted signal had also a reduced distortion from the amplifier. Moreover, it was desired to work with low frequencies, in order to identify global damage in a medium that would appear homogeneous to those wavelengths (Castaings et al., 2000).

3. Signal Processing Technique

The signal processing technique consists of three steps based on the use of wavelet transforms: a) denoising through wavelet thresholding; b) calculation of the Gabor wavelet transform; c) computations based on contour plots of the Gabor wavelet transform.

3.1 Wavelet Thresholding

A time-domain waveform, $f(t) \in L_2$, which is a noisy, non-stationary signal, is processed in the joint frequency-time domain (s, t) through a wavelet transform CWT_f , which is given by the operation

$$CWT_f(s, \tau) = \int f(t) h_{s, \tau}^*(t) dt \quad (1)$$

where the symbol “*” means complex conjugate. The variable s is the “scale”, which has the units of the inverse of a frequency, while τ is the time translation factor. The wavelets $h_{s, \tau}$ are the result of scaling and translating of a function $h(t)$, the “mother wavelet”:

$$h_{s, \tau}(t) = \frac{1}{\sqrt{s}} h\left(\frac{t - \tau}{s}\right) \quad (2)$$

In the denoising technique called “wavelet thresholding”, the signal is transformed in the joint time-frequency domain, and its wavelet coefficients are set equal to zero when they are below a set threshold.

Different wavelet families may be used for this purpose. The signal is transformed back into the time domain with a lower noise level. The software utilized for this scope is WaveLab 850, an open-source library of routines written in MATLAB, developed by Stanford researchers D. Donoho and collaborators (<http://www-stat.stanford.edu/~wavelab>), and adopted by several researchers (see La Saponara et al., 2014, for a list). In this study, two thresholding routines (“ThreshWave” and “WaveShrink”) denoised the 20833 x 1 acquired signals after they were zero-padded to the appropriate length (32768 x 1) required by the thresholding routines. The average power W of the denoised $x_i(t)$ signals was computed as

$$W = \frac{1}{N} \sum_{i=1}^N x_i^2(t) \text{ where } N = 32768, \text{ for all the center frequencies of Sets 1-3 from acquisition to}$$

acquisition. For Set 3, the transducers were mounted on the surface of the specimens with conductive epoxy, to have electrical contact. This partially constrained the transducers’ sides (for example, **Figure 1**). Out of the 77 acquisitions of Set 3, 61% had the highest average power at a 50 kHz center frequency, while 26% acquisitions had the highest average power at a 10 kHz center frequency. For Sets 1 and 2, there were 180 acquisitions, with the highest average powers varying across the entire range of 10 kHz to 50 kHz center frequencies. The following analysis was carried out at the center frequency of 50 kHz for all specimens. The 50 kHz center frequency signal was acquired in 0.45 ms with 20833 samples and a sampling interval of 2.4×10^{-8} s.

3.2 Gabor Wavelet Transform

The transform chosen for this work and earlier work (La Saponara et al., 2011a-b, Tang et al., 2011, La Saponara et al., 2014) is Gabor wavelet transform (GWT), which has been successfully used for structural engineering research (e.g. Gaul and Hurlbauss, 1997; Quek et al., 2011). The mother wavelet of Gabor wavelet transform is:

$$h(t) = \frac{1}{\sqrt[4]{\pi}} \sqrt{\frac{2\pi}{\gamma}} \exp\left(\frac{-(2\pi/\gamma)^2 t^2}{2} + j2\pi t\right) \quad \gamma = \pi\sqrt{2/\ln 2} \quad (3)$$

The output of Gabor wavelet transforms applied to the denoised waveforms is a scalogram, a plot of (i, j, c) vectors where, in this project, i = 1, ..., 32768 (number of zero-padded time acquisitions), j = 1, ..., 132 (number of scales equal to 11 octaves x 12 voices per octave), and c is the value of the wavelet coefficients, which is color-coded in the scalogram (see also Tang et al., 2011, La Saponara et al., 2014, for a brief discussion on the choice of octaves and voices per octave).

3.3 Contour Technique

Contour plots were computed for the absolute value of Gabor wavelet transform. A parametric study of the number of contours (La Saponara et al., 2014) demonstrated that the contour values change in a consistent manner, with a shifted-upward trend when increasing the number of contours; hence, selecting a given number of contours for the analysis of all specimens is deemed sufficient.

The perimeters of the n = 13 contours, indicated as $c_n(k)$ with $k = 1, \dots, n$, were computed. Since the variations between time $(i+1)^{\text{th}}$ and time $(i)^{\text{th}}$, measured as $\frac{c_{13}(k)|_{i+1} - c_{13}(k)|_i}{c_{13}(k)|_i} \times 100$, are approximately

the same for $k=1, \dots, 13$, the analysis was continued using the contour perimeter $c_{13}(13)$. In Tang et al. (2011), changes of one area inside one contour were tracked with respect to fatigue damage. The technique seemed to correlate with the formation of transverse cracks, following the characteristic damage state approach. In La Saponara et al. (2014), where the creep performance of smart sandwich specimens was investigated, the perimeters of the $c_{13}(13)$ contours were found to track reasonably well the creep displacements, showing transient and steady-state regimes, and reproducing different levels of creep deformation, consistent with the different viscoelastic behavior of the sandwich specimens. The

contour parameter curves also distinguished very well the three facesheet orientations ($[0]_8$, $[\pm 45]_4$, $[90]_8$ deg.) from each other.

Based on the success of these findings, the signal processing technique built on contour perimeters from the Gabor wavelet transform was applied to Set 3 specimens first, then to Sets 1 and 2. Results are discussed in that order. In particular, the “normalized contour parameter” mentioned herein is defined as $\left((c_{13}(t) - c_{13\text{pristine}}) / c_{13\text{pristine}} \right)$, where $c_{13}(t)$ is the perimeter of the 13th contour at time t . $c_{13\text{pristine}}$ is the value of that perimeter when the specimen is pristine (unloaded in the testing machine’s grips at the very beginning of the tests). The absolute value of this parameter appears in the following figures. This normalization seems sufficient to eliminate the bias from different dimensions/capacitances of the transducers.

4. Results and Discussion

Figure 3 shows the absolute value of the normalized contour parameter versus the normalized strain, defined as $\text{strain}/(\text{strain to failure})$, for specimen 1 of Set 3, which had a different loading sequence with respect to the other specimens of Set 3, and a total of nine acquisitions. As the specimen accrued damage, the pattern of the normalized contour parameter seemed directly proportional to the normalized strain, with the exception of acquisitions 2 and 3: it was expected that acquisition 2 (9.12 kN before the 2k cycles) would have had a lower normalized value than acquisition 3 (9.12 kN after 2k cycles), but it did not happen. At the last acquisition, the 9th, the specimen is unloaded down to 0 kN. The residual strain is 3.75% of the strain to failure, while the normalized wavelet parameter is equal to 13%. Therefore, it was hypothesized that the signal technique can show the existence of residual strain, and thus global damage.

Figure 3. Axial test of specimen 1, Set 3, with its 9 acquisitions.

The outcome for the other five specimens of Set 3 is in **Figure 4**, in the form of boxplots. In this paper, boxplots are utilized to include the effect of scatter, and are not meant for hypothesis testing: in fact, the boxplots are not independent of each other, and they include many times the same specimen throughout its load history until failure. The boxplots of the normalized wavelet parameters in **Figure 4** exhibit a high scatter and a lack of significant change among the different load levels, contrary to the strain boxplots. However, the boxplots related to the unloaded-to-zero acquisitions seem quite distinct by comparison. Some residual strain is present at those acquisitions (**Figure 4**), demonstrating that the wavelet contour technique appears to capture this feature.

Figure 4. Results for Set 3: (left) normalized contour parameter versus the number of acquisitions; (right) history of normalized strain. The boxplots are formed by 5 data points per acquisition, except for the cases indicated by “(4)”.

Figure 5 reports the results for Set 1. First of all, there seems to be no significant difference between the values of the normalized wavelet parameters obtained from surface-mounted transducers (y-axis values in **Figure 5**), and those from embedded transducers (y-axis values in **Figure 4**). The wavelet contour technique is successful in clearly discriminating loading from unloading-to-zero conditions, apparently more so than in the case of Set 3. Also, the wavelet contour boxplots for the acquisitions where the specimens are loaded (indicated with ‘1’) follow a similar trend with respect to each other as the strain boxplots (e.g. ‘11k’, ‘14k’, ‘17k’, ‘110k’ being in the same range, while ‘16k’ has higher values in the strain boxplot).

Figure 5. Results for Set 1: (top) absolute value of normalized contour parameter, with number of specimens in parentheses; (bottom) strain, with number of specimens in parentheses. Notes: some specimens were not brought to failure; specimen B is not included in either plot.

Results from Set 2 are in **Figure 6**, for five specimens. In both plots, there is a significant change from the pristine condition and the mean load before fatigue cycles (up to ~80% for the normalized wavelet contour, and up to ~90% for the normalized strain). This phase is consistent with the first stage of the characteristic damage state model, which is a sudden formation of microscale damage features, e.g. transverse cracks corresponding to a large loss of stiffness as the specimen is loaded.

At a given cycle, the symbols in the contour parameter plot may line up in a different order with respect to each other, as compared to the symbols in the strain plot. ~~for example, at 13,000 cycles, the normalized contour parameter of specimen I is lower than those of both specimens G and H, while specimen H has higher normalized strain than both G and I. On the other hand, the behavior at 17,000 cycles is mirrored well between the two plots.~~ So, the technique may not offer an exact one-to-one correspondence with strain, when the specimens are compared to each other. This may be due to the wavelet contour process being a sequence of nonlinear operations based on noisy signals. However, interesting patterns appear when following the same specimen across its life: a) the wavelet contour parameter varies little when the strain varies little (see specimens G and I); b) before the specimen fails, the wavelet contour shows a much larger change than the strain change acquired at those acquisitions (specimens H, J, K). In fact, the wavelet contour appears to reproduce more closely the behavior of the second and third stages of the characteristic damage state: namely, the second stage is a slow change of stiffness as macroscale features (e.g. shear failure in the warp plies, cracks in the neat resin region, delaminations), and the third stage is ultimate failure due to fracture of the strands at stress raiser locations. **Table 2** reports the coefficients of variations (COV% of f is the standard deviation(f)/mean(f) $\times$ 100). There are two coefficients of variations listed: COV₁, which includes the pristine condition, and COV₂, which does not. The COV₁ terms for the normalized wavelet parameter and the normalized strain are very similar to each other, which was unexpected: as mentioned, the wavelets are obtained as the outcome of a sequence of nonlinear operations (**Equations 1-3**) applied to noisy signals propagating in anisotropic materials. This finding seems to strengthen the argument of a ~~close~~ physically meaningful relation between this contour wavelet parameter and the strain. It should be noted that the parametric study on contour levels (La Saponara et al., 2014) supports this relationship for different number of contours, not just 13, since all perimeter values are shifted of the same quantity.

Figure 6. Results for Set 2: data plotted versus cycles/(cycles to failure) of (top) absolute value of normalized contour parameter; (bottom) normalized strain with respect to strain to failure.

Table 2. Analysis of Set 2. COV_1 is the coefficient of variation that includes the pristine condition, while COV_2 does not.

Specimen	Cycles/(cycles to failure), %	Abs(normalized contour parameter)	Strain/(strain to failure)
G	Pristine	0	0
	5.105	0.8342	0.8730
	25.53	0.8348	0.8863
	45.95	0.7880	0.8950
	66.37	0.8130	0.9036
	86.79	0.7904	0.9127
COV%		$COV_1 = 49.08$; $COV_2 = 2.792$	$COV_1 = 49.02$; $COV_2 = 1.717$
H	Pristine	0	0
	6.304	0.6773	0.8820
	31.52	0.6625	0.8963
	56.73	0.5922	0.9094
	81.95	0.7736	0.9203
COV%		$COV_1 = 57.17$; $COV_2 = 11.04$	$COV_1 = 55.94$; $COV_2 = 1.840$
I	Pristine	0	0

	5.284	0.5144	0.8612
	26.42	0.5049	0.8748
	47.55	0.5141	0.8859
	68.69	0.5464	0.8948
	89.82	0.4724	0.9031
COV%		COV ₁ = 49.30; COV ₂ = 5.183	COV ₁ = 49.03; COV ₂ = 1.867
J	Pristine	0	0
	7.706	0.5293	0.8694
	30.82	0.5572	0.8800
	53.94	0.5524	0.9544
	77.06	0.6348	0.8991
COV%		COV ₁ = 56.58; COV ₂ = 8.074	COV ₁ = 56.09; COV ₂ = 4.200
K	Pristine	0	0
	8.228	0.6251	0.8656
	24.68	0.6232	0.8736
	41.14	0.6367	0.8812
	57.99	0.8108	0.8885
	74.06	0.8467	0.8967
	90.51	0.7860	0.9091
COV%		COV ₁ = 46.69; COV ₂ = 14.40	COV ₁ = 44.14; COV ₂ = 1.783

Moreover, the hypothesis is suggested here that COV₂ terms may be used in correlation with stages 2-3 of the characteristic damage state: a large COV₂ may warn of upcoming fatigue failure. In this context, the wavelet contour parameter exhibits an amplified COV₂ and is a better gauge of pending fatigue failure with respect to the strain. Within the acquisition instances of **Table 2**, COV₂ would indicate the failure of specimens K, H, J, I, G in this order, with an 80% match (4 out of 5; in reality, G failed shortly before I, see **Table 1**). This hypothesis will be tested in future work for a much larger number of specimens.

5. Conclusions

Three sets of woven fiberglass/epoxy specimens were manufactured with embedded or surface-mounted piezoelectric transducers, and tested in axial conditions as the transducers operated in pitch-catch low-frequency ultrasonics. A signal processing technique based on the calculation of Gabor wavelet transform, its contours and its normalized contour perimeters was applied to the denoised acquired signals. The technique works equivalently well on noisy signals from embedded transducers (which acted as stress raisers), and those from surface-mounted transducers. The results support the ability of this technique to correlate reasonably well with the strain of a group of specimens (Set 1), replicating loading and unloading conditions even with a high level of scatter and noise. Moreover, it is hypothesized that the technique output may enable fatigue damage prognostics (based on the discussion about Set 2). This latter hypothesis will be tested in future work, with more axial tests to be conducted on laboratory-scale composite samples with surface-mounted transducers. The technique will also be tested on a limited number of loaded small-scale (~1 m) composite structures with different fiber orientations, to replicate a more realistic in-service condition.

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