Internal stress determination in a polymer composite by Coda wave interferometry

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Abstract. Coda wave interferometry (CWI) is largely employed in geotechnical applications to monitor changes due to cracks in materials but it is still not used for composite materials. In this paper, the technique is proposed to study internal stresses in a composite laminate [0°/90°]_6 and was compared with the traditional acoustic technique. It is shown that the Coda wave interferometry has better precision and sensibility than the method based on the first arriving time of flight (TOF) measurement, especially when the fiber orientation is normal to the wave propagation. This method is found to be promising for residual stress evaluation in composite materials.

1. Introduction
Polymer based composites are thought to have a great advantage for industry application because of their high specific weight, stiffness and strength. Internal stresses, especially residual stresses generated during the composite fabrication remains a problem and can cause premature failure of parts and/or warpage[1]. Due to their high sensitivity, FBG (Fiber Bragg Grating) is now often integrated in mold for deformation prediction [2, 3]. It is embedded in the host material and considerable calibration is needed for this 1D information [4]. Ultrasonic method is thought to be a powerful tool for the non-destructive detection and has been widely used for chemical reaction inspection [5] and crack detection in composites [6]. Referring to acoustoelastic property [7], the wave velocity is sensible to stresses imposed to materials. This is found for all types of materials although based on different physical reasons with a general form under small strains [8,15]:

\[ V_{ij} = V_{ij}^0 (1 + \beta_{ij} \bar{\sigma}) \]  

(1)

Where \( V_{ij} \) is the ultrasonic wave velocity that depends on averaged stress \( \bar{\sigma} \) where i is the wave propagation direction and j is the wave polarization direction. The superscript ‘0’ indicates for the velocity without stress, \( \beta_{ij} \) is the acoustoelastic constants. Such relation gives an access to the stresses generated during processing under averaged stress and isotropic material assumption.

Few works are devoted to polymer composites related to acoustoelasticity. Mase et al. [9] measured the acoustoelastic coefficients in Kevlar 49/SP 328 composites with different ply sequences by longitudinal and shear waves. Such coefficients vary according to different laminated structures. Santos et al. [10] used critical refractive longitudinal waves (Lcr) to address the stress influence in carbon/epoxy composite. This technique is characterized by the wave propagation parallel to and right below the surface. It can inspect the body from the surface because of the difficulty of access to the thickness of the composite. The time of flight (TOF) [8] is inversely proportional to the stress applied
with 0° fiber direction sample. In 45° and 90° fiber direction samples, this proportionality is 3-4 magnitude order lower. However, when the composite becomes thicker, the scattering phenomenon comes to be strong and makes the TOF measurement more challenging.

Coda Wave Interferometry (CWI) [11, 12] or seismic doublet method [13] is a technique for monitoring changes in media using acoustic waves. It is widely used in geophysics and civil engineering [14, 15], but not yet for composite materials. In the latter case, the waves will be multiple scattered by heterogeneities (fibers) and Coda waves will be generated. This technique can be promising for composite manufacturing inspection in solving problems as in quality control with different structures.

The changes in the waveforms can be quantified by computing the time shifted cross-correlation parameter $R(t_s)$ over a time window with center time $t$ and width $2T$ [12]:

$$R(t_s) = \frac{\int_{t-T}^{t+T} u(t')u(t'+t_s)dt'}{\sqrt{\int_{t-T}^{t+T} u^2(t')dt'}\int_{t-T}^{t+T} u^2(t')dt'}$$

(2)

where $u(t')$ is the unperturbed wave and $u(t')$ is the perturbed wave, $t_s$ is the time shift of the perturbed waveform relative to the unperturbed waveform. If the waves are not perturbed, then:

$$u(t') = u(t)$$ and $R(t_s=0)=1$.

(3)

When the perturbed wave is a time shifted version of the original wave, then:

$$u(t') = u(t'-\delta t)$$ and $R(t_s)$ attains its maximum $R_{max}$ for $\delta t=t_s$.

The travel time perturbation can be expressed as

$$\delta t = -\frac{\delta V}{V}t$$

(4)

where the relative velocity perturbation $\frac{\delta V}{V}$ can be obtained after the determination of $\delta t$, from which the influence of the stress could be known. Recently Larose et al. [16] and Niederleithinger et al. [17] have used Coda wave interferometry to study the weak stress effect in heterogeneous medium, as for example testing of concrete samples. They have found that it was possible to link the weak stress change to the velocity variation when analyzing the Coda waves [16], according to:

$$V-V^0 = \frac{\partial V}{\partial \sigma} \Delta \sigma + o(\sigma)$$

(5)

where $V^0$ is the velocity at stress-free state, $\Delta \sigma$ is the uniaxial stress and

$$\beta = \frac{1}{V^0} \frac{\partial V}{\partial \sigma}$$

(6)

is defined as an effective acoustoelastic coefficient.

Here the Coda wave interferometry is proposed to study internal stresses in another type of heterogeneous medium like polymer composites, based on the fiber displacement.

2. Experiments

A $[0^\circ/90^\circ]_{63}$ glass/epoxy composite sample of $34.62 \times 35.42 \times 87.47 \text{mm}^3$ in dimension, as shown in figure 1 fabricated from our laboratory is used for acoustic tests. It is a thick composite made of crossed unidirectional plies. It is scanned with tomography (Micro XCT400, Xradia) as shown in figure 2. The average thickness of each ply is 273.5μm. The Young’s modulus in each direction is
evaluated first by compression test with an INSTRON machine: in-plane moduli $E_1=E_3=27.9$ GPa, out-of-plane modulus $E_2=3.4$ GPa.

The composite specimen was subjected to uniaxial loading during the ultrasonic measurement. The applied uniaxial load was increased from 0 kN to 100 kN in five steps of 20 kN with ultrasonic acquisition at each force increment. The loading speed is 0.002 mm/s. The sample is always under elastic state with strain less than 1%. Kaiser effect should be considered in composites in case of defects or damage existence, which is often included during CWI measurement in concrete. Longitudinal sensors (MSW-QC 2.25 MHz, General Electric) were used to generate Coda in transmission mode, fixed by a laboratory made system. A universal couplant ZG-F (General Electric) is used here under ambient temperature. Waveforms were registered by a commercial ultrasonic recorder (Krautkramer USN60, General Electric). Two compression schemes (a) and (b) shown in figure 3 were tested and analyzed.

Figure 1. Composite sample

Figure 2. Tomography image in plane 12

Figure 3. Two compression schemes (a) Measurement in direction 3, compression in direction 2 (b) Measurement in direction 2, compression in direction 3

3. Results and discussion

3.1. Force applying in a perpendicular direction to the composite ply

Force was applied along direction 2 and sensors were positioned perpendicularly direction 3 as shown in compression scheme (a) in figure 3. All the raw signals (time interval $\Delta t=0.076 \mu$s, total length $T_r=22 \mu$s) are stored and treated with matlab. Interpolation was done on the signals with ‘cubic’ type by $\times 20$ zoom to improve the signal resolution. A correlation window length equal to $T=T_r/10$ is chosen. The center time $t$ is shifted each $\Delta t$. The Coda waves at 0 kN and at 100 kN in figure 4(a) are compared at first. For the interval early in time, the waveforms are very similar. But for the later interval (Coda), the waveforms are distinctly different, where one of the waveforms is a time shifted version of the other. The same analysis can be done for the other loads.
According to equations (2)-(4), the travel time perturbation $\delta t$ in figure 4(b) and cross-correlation parameter $R$ in figure 4(c) can be calculated when shifting the center time in the interval $[21\mu s, 30\mu s]$.

![Figure 4](image)

**Figure 4.** (a) The variation of the amplitude versus the time at 0kN and 100kN (b) Travel time perturbation versus the time (c) Cross-correlation parameter value versus the time (Equation (2))

The curve in figure 4(c) can be decomposed into two parts: the first part where the Coda can be used and the second part where $R$ decreases sharply indicating a failure correlation. Only the first part in the range $[21\mu s, 26\mu s]$ is used, and the mean of $R_{\text{max}}$ and $\delta t$ are computed in this domain. The whole procedure is repeated for every applied load, and the results are listed in table 1.

| F(kN) | $\sigma$(MPa) | $R_{\text{max}}$ | $-\delta t/t\times10^{-3}$ |
|-------|---------------|------------------|--------------------------|
| 20    | 6.5           | 0.93             | 1.0                      |
| 40    | 12.9          | 0.94             | 2.2                      |
| 60    | 19.4          | 0.93             | 3.2                      |
| 80    | 25.8          | 0.93             | 4.1                      |
| 100   | 32.3          | 0.93             | 5.7                      |

From that, the average velocity variation was computed and varied linearly with the applied stress as shown in figure 5. A linear regression of the data yields $\beta=1.75\times10^{-2}\text{MPa}^{-1}$ according to equation (6). A further comparison between CWI (Equation (4)) and TOF (Equation (1)) presented in figure 5 demonstrates that CWI gives a better linear behavior with a higher precision. It has a strong ability for the minor strain detection. TOF method becomes reliable only after 40kN with a similar slope of that of CWI.
3.2. Force applying parallel to the direction of the ply

A much more severe attenuation is encountered in measurement along direction 2 when the wave travels through the thickness of the plies as shown in compression scheme (b) in figure 3. The amplitude decreases quickly and sharply after the maximum peak which makes the use of Coda wave more challenging. A similar procedure is used as done in section 3.1. The results for 0kN and 100kN are presented in figure 6.

Figure 5. Velocity variation with external force applied (K is the coefficient of determination)

Figure 6. (a) The variation of the amplitude versus the time at 0kN and 100kN (b) Travel time perturbation versus the time (c) Cross-correlation parameter value versus the time (Equation (2))

The cross-correlation parameter R drops quickly after 19μs and the time domain between [15μs 19μs] is set for the R\textsubscript{max} computation. The value of δt/t from TOF is found much larger than that from CWI, which is shown in table 2.
Table 2. The average values of $R_{\text{max}}$ and $\delta t$ at each applied load and stress

| F(kN) | $\sigma$(MPa) | $R_{\text{max}}$ | $-\delta t/t(\times 10^{-4})$ |
|-------|---------------|-------------------|-----------------------------|
| 20    | 16.3          | 0.99              | 1.1                         |
| 40    | 32.6          | 0.99              | 1.7                         |
| 60    | 48.9          | 0.98              | 1.9                         |
| 80    | 65.2          | 0.98              | 2.0                         |
| 100   | 81.6          | 0.99              | 2.3                         |

Such large discrepancy is due to the too small velocity variation in this situation and a high precision is required for velocity calculation when the TOF technique is used. Based on a statistical time shift, CWI can prevent such problem, and a linear relationship is again found for this method with $\beta=2\times10^{-4}\text{MPa}^{-1}$.

The fiber orientation shows a strong effect on the detection of acoustic signals depended on the fiber displacement (deformation) and signal attenuation. In figure 7(a), CWI gives a good precision even at low stress level. In figure 7(b), the small deformation from the fiber dominated direction and strong attenuation makes the TOF measurement difficult. In this situation, TOF becomes not reliable, but CWI still works.

Figure 7. Velocity variation with external force applied (a) CWI (K is the coefficient of determination) (b) TOF

4. Conclusion
This study reports the first set of results from CWI technique for internal stress determination in a polymer composite subjected to uniaxial compression. The velocity variation can be obtained according to the travel time perturbation calculated from this technique. And the internal stresses can be estimated with a linear approximation to the velocity variation.

When the wave propagates parallel to direction of the ply, strong scattering waveforms are observed. Waveform shifts are found during loading due to the fiber displacement. The CWI result is comparable to that from the TOF technique but shows a better precision and sensitivity. A strong attenuation is noticed when the wave propagation direction are normal to the ply, although there is still
distinguishable Coda wave shift for the stress determination. TOF measurement under this situation needs a higher precision measurement for both strain and travelling time. The fiber displacement can be expected not to be evident under this situation because the loading direction is along the high stiffness fibers. Factors as temperature [13], humidity and matrix type need to be further investigated which will influence CWI measurements.

This method is applicable to composites with complex fibrous geometry such as fabric. It seems also promising for in-line inspection in composite processing: such as RTM (Resin Transfer Molding), autoclave, etc... The early part of ultrasonic wave (TOF measurement) could predict the major modulus variation during the polymerization of the resin and the later part (CWI) can give an indication when internal stress establishes and other factors take place.

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