Impact Damage Characterization in Hybrid Fiber-reinforced Composites Using Terahertz Imaging in Time and Frequency Domain

Junliang Dong*† , Alexandre Locquet*† , Nico F. Declercq*‡ , D. S. Citrin*†
* UMI 2958 Georgia Tech-CNRS, Georgia Tech Lorraine, 2 Rue Marconi, 57070 Metz, France
† School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332 USA
‡ Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 30332 USA

Email: david.citrin@ece.gatech.edu

***Abstract*—A hybrid fiber-reinforced composite laminate with impact damage has been studied via terahertz imaging. Both of the impact-induced intra- and inter-laminar damages are successfully detected. Terahertz C-and B-scans in time domain show the damage evolution throughout the thickness. Intra- and inter-laminar damages at the same interface can be differentiated via polarization-resolved imagings, which can also be located with THz C- and B-scans in frequency domain.**

I. INTRODUCTION

TERAHERTZ (THz) imaging, which can provide a noninvasive, noncontact, and nonionizing method to imaging composites, is a promising modality for nondestructive evaluation of fiber composites. For carbon fiber composites, due to its conductivity, THz can only be used to detect near-surface defects; for glass fiber composites, THz can penetrate further to detect buried and underlying defects [1].

In this study, THz imaging is performed to detect impact damage in a hybrid fiber-reinforced composite laminate, comprised of unidirectional glass/epoxy and carbon/epoxy laminae with a cross-ply stack pattern $[0^{\circ G}_{\,2}/90^{\circ C}_{\,3}]_s$. The dimension of the laminate is 120 mm x 120 mm x 1.65 mm. Damage was generated by controlled free-fall impact: an impactor of 50 g struck the laminate at a 9.5 m/s, schematically shown in Fig. 1. Two indentations are visible on the bottom surface. THz C- and B-scans of the impact damage are obtained by a standard THz TDS system [2] both in the time and frequency domains.

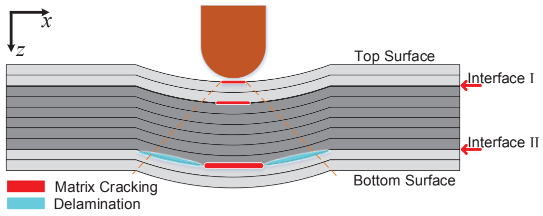

Fig. 1. Schematic diagram (edge view) of sample subjected to low-velocity impact damage with highlighted damage types.

II. RESULTS

The penetration of THz waves in carbon fiber composites depends on the relation of the THz polarization and the carbon fiber orientation. When the direction of carbon fibers is parallel to the THz polarization, nearly total reflection is obtained; when the direction of carbon fibers is perpendicular to the THz polarization, the reflection coefficient decreases and THz waves can reach the sub-surface of the laminae [3].

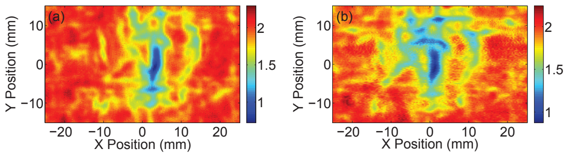

Fig. 2. THz C-scans of the top surface with polarization perpendicular (a) and parallel (b) to the carbon-fiber orientation in the time domain.

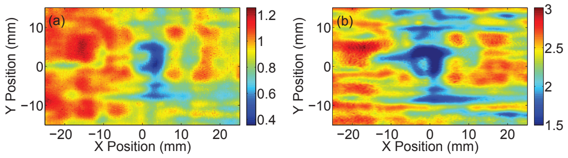

Fig. 3. THz C-scans of the Interface I with polarization perpendicular (a) and parallel (b) to the carbon-fiber orientation in the time domain.

THz C-scans in the time domain throughout the sample thickness are shown in Fig. 2 to Fig. 5. Polarization dependence in the C-scans associated with interface I and II is pronounced due to influence of carbon fibers, as shown in Fig. 3 and 4. In Fig. 3, Impact-induced matrix cracking and fiber distortion in the carbon/epoxy layer lead to the decrease of the reflection coefficient at interface I for both perpendicular and parallel polarizations. By contrast, we observe parallel polarization is more sensitive to the region with matrix cracking and fiber distortion, and leads to a further decrease of the reflected pulse amplitude compared with that for perpendicular polarization.

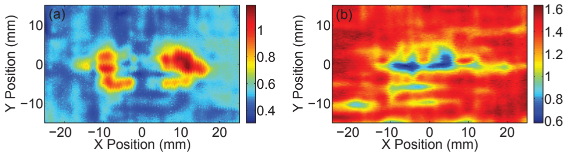

Fig. 4. THz C-scans of the Interface II with polarization perpendicular (a) and parallel (b) to the carbon fiber orientation in the time domain.

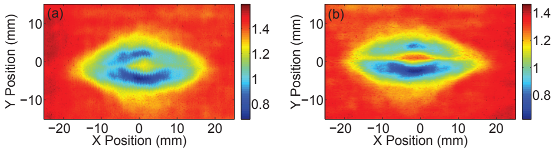

Fig. 5. THz C-scans of the bottom surface with polarization perpendicular (a) and parallel (b) to the carbon fiber orientation in the time domain.

In Fig. 4, C-scans of interface II show quite different damage patterns for the two polarizations. For parallel polarization, the damaged region shows lower contrast due to the existence of matrix cracking and fiber distortion. However, for perpendicular polarization, the damaged region shows higher contrast. This higher contrast indicates the existence of an air gap originating in the separation of the carbon/epoxy and glass/epoxy plies, i.e., delamination. Based on the analysis of time-of-flight waveforms in the damaged region with the two polarizations [4], we conclude that: (1) for C-scans with perpendicular polarization, the thickness of the delamination dominates the change of the contrast, and the C-scan reveals the delamination area at the interface; (2) for C-scans with parallel polarization, the reflection coefficient at the interface dominates the change of the contrast, and the C-scan in this case evidences the matrix cracking and fiber distortion in the carbon/epoxy layer.

B-scans obtained incident from the bottom surface are shown in Fig. 6. Typical damage features can be observed in depth, including surface bending, delamination, matrix cracking and fiber distortion. The total set of C- and B-scans exhibits the evolution of the impact-induced damage from the top to the bottom surface in three dimensions.

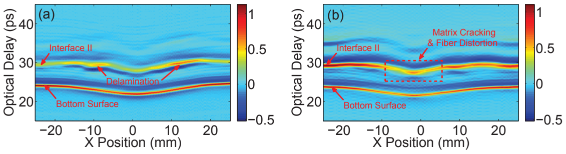

Fig. 6. B-scans incident from the bottom surface (along section y=0) and with polarization perpendicular (a) and parallel (b) to the carbon-fiber orientation in the time domain.

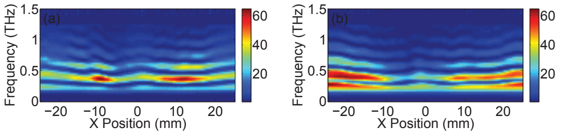

Fig. 7. B-scans incident from the bottom surface (along section y=0) and with polarization perpendicular (a) and parallel (b) to the carbon-fiber orientation in the frequency domain.

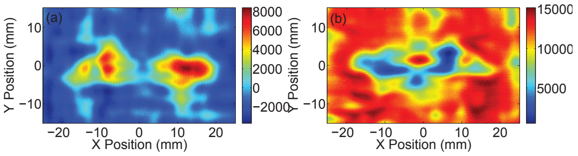

Fig. 8. THz C-scans with polarization perpendicular (a) and parallel (b) to the carbon fiber orientation in the frequency domain.

Fourier transform is performed on the raw THz data to obtain frequency domain information. THz B- and C-scans in frequency domain with the two polarizations are shown in Fig. 7 and 8. Highest contrast can be located between 0.3 THz and 0.5 THz. For perpendicular polarization, highest contrast locates the delamination area, and for parallel polarization, highest contrast shows the matrix cracking and fiber distortion area in the carbon/epoxy layer. THz C-scans in frequency domain can also be obtained in Fig. 8, which are in consistent with the results in the time domain.

III. CONCLUSION

THz imaging was explored to characterize the evolution of the damage in a hybrid fiber-reinforced composite laminate subjected to low-velocity impact in both time and frequency domain. Both intra- and inter-laminar damages in the sample are successfully detected. Matrix cracking and delamination at the same interface are differentiated via polarization-resolved imagings in both time and frequency domains.

ACKNOWLEDGMENT

We gratefully acknowledge the financial support of the Conseil Régional de Lorraine, and the Fonds Européen de Développement Régional (FEDER).

REFERENCES

[1] I. Amenabar, F. Lopez, and A. Mendikute, "In Introductory Review to THz Non-Destructive Testing of Composite Mater," Journal of Infrared, Millimeter, and Terahertz Waves, vol. 34, pp. 152-169, 2013.

[2] J. Dong, B. Kim, A. Locquet, P. McKeon, N. Declercq, and D. S. Citrin, "Nondestructive evaluation of forced delamination in glass fiber-reinforced composites by terahertz and ultrasonic waves," Composites Part B: Engineering, vol. 79, pp. 667-675, 2015.

[3] S.-H. Yang, K.-B. Kim, H. G. Oh, and J.-S. Kang, "Non-contact detection of impact damage in CFRP composites using millimeter-wave reflection and considering carbon fiber direction," NDT & E International, vol. 57, pp. 45-51, 2013.

[4] J. Dong, A. Locquet, N. Declercq, and D. S. Citrin, "Polarization-resolved terahertz imaging of inter- and intra-laminar damage in hybrid fiber-reinforced composite laminate subject to low-velocity impact," Composites Part B: Engineering, submitted.