Chapter 6
Monitoring the Evolution of Matrix Cracking in a Cross-ply Laminate Subjected to Dynamic Loading: Comparison of Infrared Thermography and X-ray Imaging Results

Julien Berthe, Thomas Fourest, Gérald Portemont, Bastien Lammens, Jesús Pernas-Sánchez, José Alfonso Artero-Guerrero, José Manuel Rodríguez-Sereno, Adrian Cimadevilla, Georg Ganzenmüller, and Bratislav Lukić

Abstract In this study, tensile tests at different strain rates on a $[0/90_3]_s$ cross-ply laminate are carried out at the European Synchrotron Radiation Facility in Grenoble (ESRF) on the ID19 beamline. To cover a wide range of strain rates, two testing machines are used: the Universal Testing Machine (UTM), for tests up to intermediate strain rates, and Hopkinson tensile bars for higher loading rates. The installation of these testing machines on the synchrotron's ID19 beamline enables phase-contrast X-ray imaging at high speeds. In the context of this study, this enables us to monitor matrix cracking in the 90° central ply of the laminate under investigation. In addition, these results are compared with those obtained simultaneously using an infrared camera to observe the edge of the sample. These tests should make it possible to compare these two measurement techniques up to the highest loading rate.

Keywords Matrix cracking · X-Ray · Infrared Thermography

Introduction

Understanding and modeling the influence of strain rate on the damage behavior of unidirectional (UD) ply composite materials remains a challenge, largely due to a lack of experimental data. Current literature primarily relies on incremental cyclic tests conducted with high-speed hydraulic actuators. Recently, Berton et al.[2] highlighted several drawbacks of these cyclic tests, such as the relaxation phenomena occurring between cycles. They also noted that the macroscopic damage variable–based on shear modulus degradation–fails to capture rate dependency, even though local micrographs clearly show that loading speed influences damage development. This discrepancy suggests that a different stacking sequence is required to study rate-dependent damage. Consequently, a new methodology focusing on crack density evolution under dynamic loading in cross-ply laminates with high-speed infrared camera has been proposed [1] and applied [3]. As shown in Figure 1, a distinct rate effect was observed, particularly when reducing the thickness of the central 90° ply.

Julien Berthe · Thomas Fourest · Gérald Portemont · Bastien Lammens
DMAS, ONERA, 59000, Lille, France
e-mail: julien.berthe@onera.fr; thomas.fourest@onera.fr; gerald.portemont@onera.fr; bastien.lammens@onera.fr

Jesús Pernas-Sánchez · José Alfonso Artero-Guerrero · José Manuel Rodríguez-Sereno · Adrian Cimadevilla
Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avenida de la Universidad, 30, 28911 Leganés, Madrid, Spain
e-mail: jpernas@ing.uc3m.es; jartero@ing.uc3m.es; josemanr@ing.uc3m.es; acimadev@ing.uc3m.es

Georg Ganzenmüller
INATECH-Sustainable Systems Engineering, Albert-Ludwigs-Universität Freiburg, Emmy-Noether Str. 2, 79110 Freiburg, Germany
e-mail: georg.ganzenmueller@inatech.uni-freiburg.de

Bratislav Lukić
ESRF–The European Synchrotron, CS40220, CEDEX 09, 38043, Grenoble, France
e-mail: bratislav.lukic@esrf.fr

© The Author(s), under exclusive license to River Publishers 2026

Kaitlynn Fitzgerald et al. (eds.), *Fracture, Fatigue, Failure and Thermomechanics & Infrared Imaging, Volume 4, 2026*,
Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/rp-9788743816270

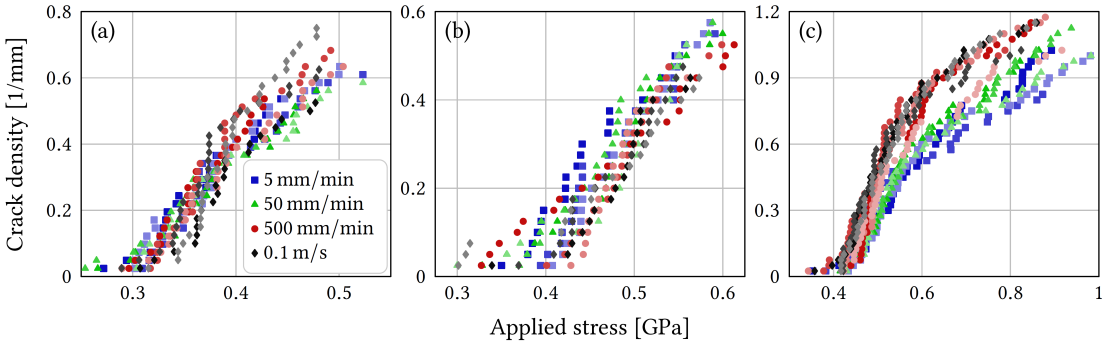


Fig. 1 Crack density evolution for the different studied configurations: (a) $[0/90_3]_s$, (b) $[0/90_2]_s$ and (c) $[0/90]_s$ [3].

Finally, recent developments at the European Synchrotron Radiation Facility (ESRF) enable the use of high-speed X-ray imaging to observe damage in composites under dynamic loading [4, 5].

The objective of the work presented in this paper is to compare these two imaging techniques for characterizing the evolution of matrix cracking in a cross-ply laminate. Various loading rates will be explored, ranging up to high-speed dynamic tensile tests conducted using a Split-Hopkinson Tension Bar (SHTB) apparatus. The remainder of this article will introduce the material studied and the experimental setups available on the ESRF's ID19 beamline used for this campaign. Tests conducted at different velocities will then be analyzed, followed by a detailed discussion on the limitations of the infrared camera used in this study.

Material and experimental setup

The tests described in this study were conducted on a cross-ply laminate with a $[0/90_3]_s$ stacking sequence. The material used is T700GC/M21, a carbon fiber-reinforced epoxy resin. The plates were manufactured in an autoclave following the manufacturer's recommended curing cycle. Finally, specimens were cut from the plates using a diamond saw to dimensions of 100×4.9mm, with an average thickness of 2.18mm for the chosen layup.

Experimental testing was performed on the ID19 beamline at the European Synchrotron Radiation Facility (ESRF). Due to its unique capabilities, this beamline allows for phase-contrast X-ray imaging at high acquisition rates of up to 1 MHz. This makes it possible to track the evolution of damage mechanisms in cross-ply laminates under dynamic loading. The beamline is also equipped with dynamic loading devices for in-situ characterization. As illustrated in Figure 2, an Universal Testing Machine (UTM) is used for intermediate strain rates, reaching approximately $1\ s^{-1}$. To achieve higher strain rates, the beamline is also equipped with a Split-Hopkinson Tension Bar (SHTB) system. Both testing devices, along with the specimen gripping system, are described in detail by Jakkula et al. [4] and will not be further detailed here for the sake of conciseness.

Specimens were bonded to aluminum tabs using Loctite 401 adhesive, enabling a standardized gripping system across both testing platforms. It should be noted that in some cases, the ultimate failure of the specimen could not be reached due to debonding between the tabs and the sample. The acquisition settings for the various cameras at each tested speed are detailed in Table 1.

Table 1 Summary of camera configurations

	Infrared Camera	X-Ray Visible Camera
Low speed tests	1000 Hz	50 Hz
Intermediate speed tests	20 kHz	20 kHz
High speed tests	72 kHz	72 kHz

In this study, a Telops Fast M3k was employed for infrared thermography, a Photron Fastcam SA-Z for X-ray imaging, and a Phantom TMX 6410 for Digital Image Correlation (DIC). DIC results are not presented in this paper. All cameras were synchronously triggered by the acquisition systems dedicated to each testing machine.

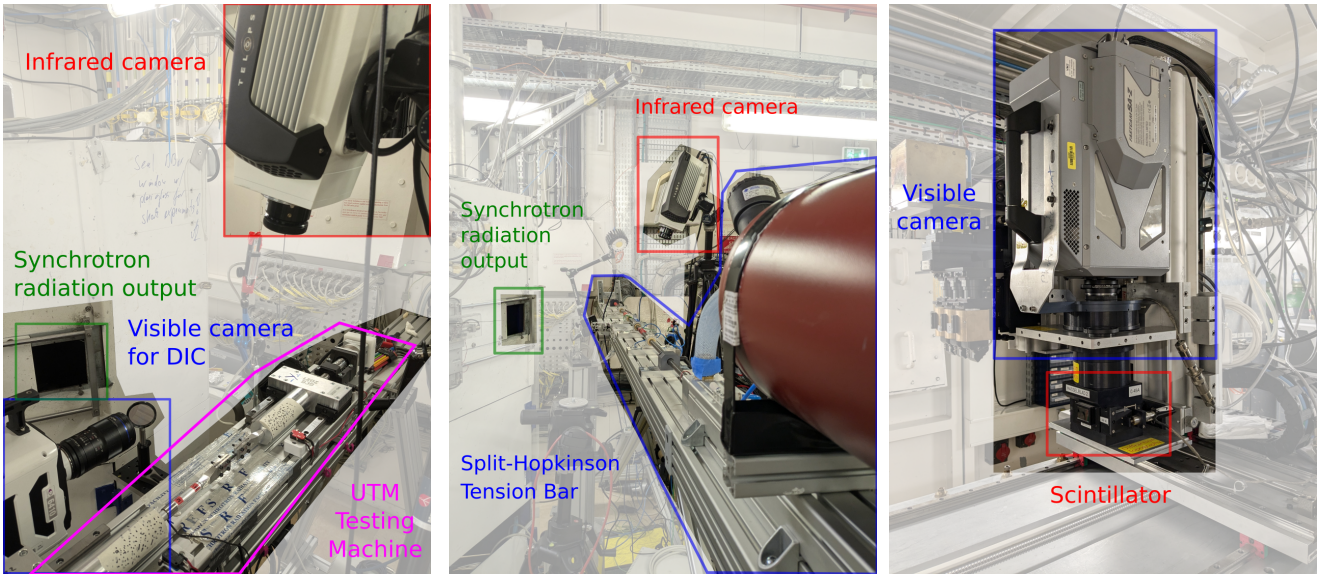


Fig. 2 Description of the experimental setups: on the left, the assembly for tests up to intermediate speeds; in the center, the setup for high-speed testing; on the right, the configuration for X-ray imaging acquisition used in this study.

Results

Comparing the two imaging techniques for assessing matrix crack density is not a straightforward task. Following the methodology proposed by Coussa *et al.* [3], a post-processing technique was employed to generate a spatio-temporal map of matrix crack evolution. This approach typically involves extracting a single line of pixels from each frame, parallel to the specimen's longitudinal axis and centered within the thickness of the 90° ply. In the present work, this methodology was slightly modified to enhance crack detectability by integrating (summing) the pixel intensities across the entire thickness of the 90° ply. By plotting these integrated values over time, a comprehensive map of the cracking process is obtained, as illustrated in Figure 3a. Since time can be directly correlated with the applied load, the resulting map is plotted as a function of the applied stress. Finally, several metrics can be employed to represent pixel intensity:

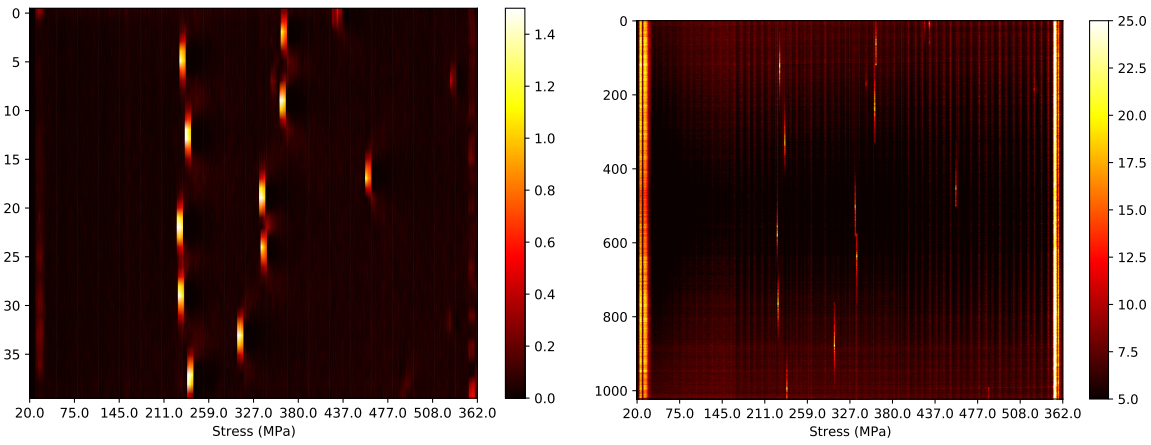
1. the absolute temperature measured during the test;
2. the temperature variation relative to a reference image captured prior to loading;
3. the temperature variation relative to an image captured a fixed interval (xx seconds) earlier.

In the work of Coussa *et al.* [3], the second post-processing technique was adopted. However, a major drawback of this approach is that it yields inconsistent results when comparing different loading rates. At low strain rates, the test duration allows for significant thermal diffusion of the heat generated by crack formation. Conversely, during high-speed tests lasting only a few milliseconds, this diffusion is negligible. To address this discrepancy, the third post-processing technique is used in the present study to reduce the influence of diffusion of the obtained map. By comparing Figures 3a and 4a, it clearly appears that the diminution of the diffusion during the test for the intermediate loading rate is no longer influencing the obtained map.

The post-processing methodology for X-ray imaging was closely adapted from the IR imaging workflow. First, following standard practice, each raw frame was normalized by dividing it by the median of a series of flat-field reference images captured without the specimen immediately after the test. Subsequently, a differential analysis was performed for all processed frames, calculating the difference between the current image and one captured a few moments prior (typically using a three-frame offset for quasi-static tests). Finally, the pixel intensities were summed across the specimen width to generate the spatio-temporal maps shown in Figures 3b and 4b.

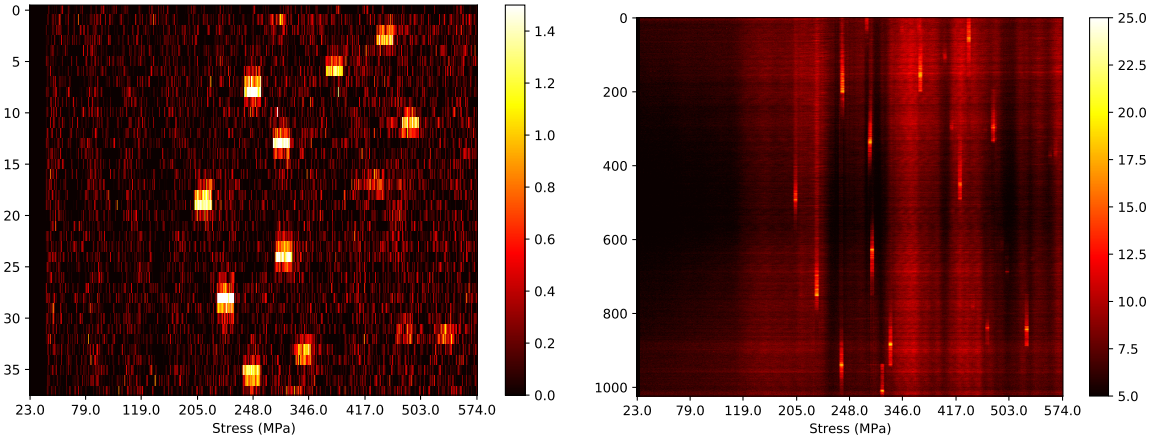
Consequently, Figures 3 and 4 allow for a direct comparison of the spatial distribution of cracks along the specimen's free length by analyzing the vertical axis. Along the horizontal axis, crack initiation and development are directly correlated with the applied stress. These figures demonstrate excellent agreement between the results obtained from the two imaging techniques at both quasi-static and intermediate strain rates, confirming the reliability of the proposed methodologies.

The same methodologies were applied to the images acquired during the Split-Hopkinson Tension Bar tests. For these experiments, which typically lasted around 350 μs, the spatio-temporal maps in Figure 5 highlight several inherent technical



(a) (b)

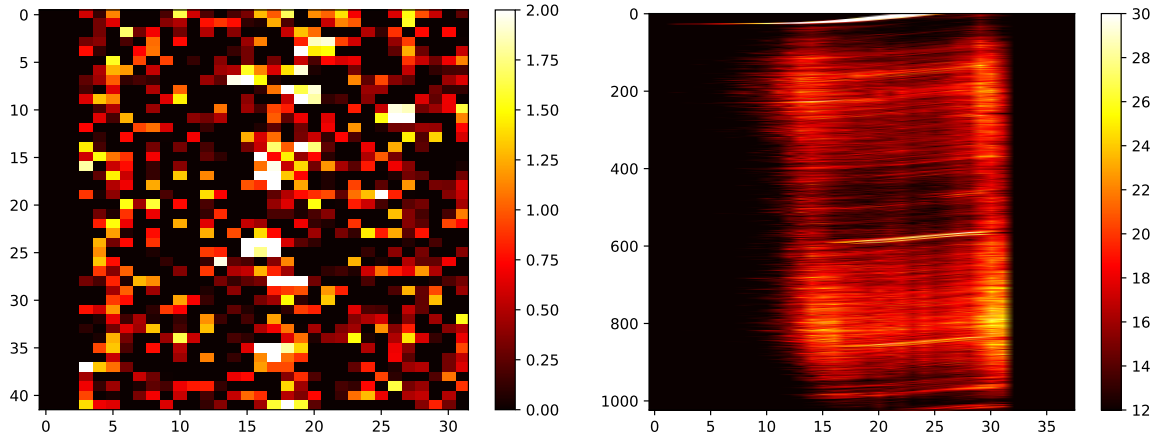
Fig. 3 Spatial distribution of cracking events as a function of applied stress for a quasi-static test: IR imaging results (left) and X-ray imaging results (right)



(a) (b)

Fig. 4 Spatial distribution of cracking events as a function of applied stress for an intermediate loading rate test: IR imaging results (left) and X-ray imaging results (right)

challenges. First, achieving an acquisition frequency of 72 kHz for IR imaging requires a very short integration time – set at 5.04 μs for these tests. The temperature rise associated with matrix cracking was typically between 1 and 1.5°C. Capturing such a subtle thermal signal with a configuration characterized by a low signal-to-noise ratio proved challenging, resulting in the noisy and less informative map shown in Figure 5a. Regarding the X-ray imaging, the difficulties primarily stemmed from the necessary compromise between spatial and temporal resolution. To maintain a field of view and spatial resolution comparable to those of the quasi-static and intermediate tests, the acquisition frequency was limited to 72 kHz. Consequently, only 25 images were captured during the 350 μs test, leading to significant specimen displacement between successive frames. This explains why, in Figure 5b, cracking events no longer appear as 'hot spots' but as 'lines' with an angle related to the crack displacement until the end of the test. With the continuous improvement of sensor technologies, such technical limitations could potentially be overcome in the coming years. Despite these limitations, X-ray images still allow for reliable assessment of crack density at high deformation rates, based on conventional crack counting in the various images. In contrast, the analysis of the raw IR data remains challenging due to the inherently low signal-to-noise ratio at such acquisition speeds.



(a) (b)

Fig. 5 Spatial distribution of cracking events as a function of applied stress for a high loading rate test: IR imaging results (left) and X-ray imaging results (right)

Conclusion and Future Work

This study successfully demonstrated the effectiveness of synchronized high-speed X-ray phase-contrast imaging and infrared thermography for monitoring matrix cracking in $[0/90_3]_s$ cross-ply laminates across a broad range of strain rates. The implemented spatio-temporal mapping methodology, enhanced by pixel intensity integration, provided a reliable tool for localizing cracking events and correlating them with applied stress. At quasi-static and intermediate loading rates, the two imaging techniques showed excellent agreement. However, high-speed tests conducted with the Split-Hopkinson Tension Bar highlighted the current technical limits of infrared thermography, where low signal-to-noise ratios at high acquisition frequencies hinder crack detection. While X-ray imaging also faced challenges related to temporal sampling and motion-induced displacement at these rates, it remained a viable method for quantifying crack density. These findings establish a robust experimental framework at the ESRF for in-situ damage characterization. Future work will leverage this methodology to investigate the influence of ply thickness on rate-dependent behavior, as previously explored by Coussa *et al.* [3], to further clarify the observed phenomena.

Acknowledgments The authors would like to acknowledge the European Synchrotron Radiation Facility (ESRF) for the provision of synchrotron radiation facilities. We are grateful to the staff of the ESRF Grenoble for their assistance and support in the operation of the ID19 beamline. Financial support from the DGAC (France) within the framework of the Physafe II project is also gratefully acknowledged. Furthermore, we would like to thank Matthieu Ragonet for his significant contribution to the preparation of this experimental campaign.

References

1. J. Berthe and M. Ragonet. Passive infrared thermography measurement of transverse cracking evolution in cross-ply laminates. *Strain*, 54(6):e12293, 2018.
2. J. Berton, F. Coussa, J. Berthe, E. Deletombe, and M. Brieu. Experimental investigation of the loading rate dependency of the non-linear damageable behaviour of carbon/epoxy laminates. In *Comptest 2023*. Universitat de Girona. Grup de Recerca en Anàlisi i Materials Avançats per al Disseny Estructural (AMADE), 2023.
3. F. Coussa, J. Berthe, and M. Ragonet. Rate dependency and ply thickness influence on transverse cracking evolution in cross-ply laminates. *Journal of Theoretical, Computational and Applied Mechanics*, May 2022.
4. P. Jakkula, A. Cohen, B. Lukić, D. Levi-Hevroni, A. Rack, G. Ganzenmüller, and S. Hiermaier. Split hopkinson tension bar and universal testing machine for high-speed x-ray imaging of materials under tension. *Instruments*, 6(3):38, 2022.
5. J. M. Rodríguez-Sereno, J. Pernas-Sánchez, J. A. Artero-Guerrero, J. López-Puente, and B. Lukić. Experimental study of off-axis compression behaviour in dynamic loading: The open hole effect. *Composites Part A: Applied Science and Manufacturing*, 173:107653, 2023.