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Advanced speckle methods with high-speed imaging for impact testing of composites

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ABSTRACT

This study presents the implementation of two speckle-based optical measurement techniques—digital image correlation (DIC) and intensity-based dynamic speckle imaging (DSI)—integrated with high-speed camera acquisition for the dynamic characterization of composite materials under impact loading. The DIC method, relying on the correlation of printed or painted speckle patterns recorded before and after deformation, enables precise quantification of displacement fields. In parallel, the DSI approach captures temporal variations in speckle intensity, improving the detection of subsurface defects and the visualization of velocity distribution associated with internal processes. Our results demonstrate that DSI serves as a valuable complementary tool to the DIC technique.

Keywords: DIC, DSI, speckle, image correlation, material testing, image processing

1. INTRODUCTION

Accurate deformations measurement and dynamic processes monitoring methods are crucial in many areas of science and engineering, particularly for the study of composite materials under high strain rates, impact loads, and multi-factor stresses. Among the many optical metrology tools, Digital Image Correlation (DIC) and Dynamic Speckle Imaging (DSI) are two powerful, non-contact, and full-field measurement techniques for characterizing surface and sub-surface response to dynamic loading.

DIC is a widespread optical method based on observing and correlating grayscale patterns on the object surface for a sequence of images before and after deformation. The procedure involves several key steps: creation of random speckle pattern on the surface, image acquisition under deformation, subsets selection and correlation analysis, sub-pixel displacement registration, and finally generation of full-field displacement and strain maps. DIC offers high spatial resolution and accuracy, and has been extensively applied in material science, structural health monitoring, biomechanics, and civil engineering to investigate mechanical properties, damage evolution, and failure mechanisms [1–3].

DSI is a coherent optical intensity-based technique which exploits the time-varying nature of the speckle pattern created when a rough surface illuminated by a laser beam undergoes micro-changes due to ongoing processes in the object. The intensity fluctuations, provoked by dynamic events on the surface or within the material, are measured and statistically analyzed in order to produce the so-called "activity maps." The activity maps point out regions of different rates of internal motion, microstructural change, or local energy dissipation. DSI is especially well adapted for processes monitoring and non-destructive testing in industrial and biomedical environments, and its sensitivity is high because speckle is sensitive to small changes in surface topography, reflectivity, or refractive index [4–6].

This paper presents a comparative study of DIC and DSI, both implemented with with high-speed camera acquisition, for dynamic characterization of composite materials subjected to impact-type loading conditions. Although DIC remains the standard in full-field deformation measurement, it relies on the deposition of a stable printed speckle pattern on the specimen surface that may become unrealizable in high-temperature or high-strain-rate conditions. In such cases, the printed speckle pattern may be damaged or removed from the surface, resulting in false measurements or tracking loss. To address this drawback, laser speckle creation in DSI offers a contact-free solution in such that measurements can be obtained in cases where printed speckle patterns fail to adhere. One of the primary motivations behind this work is to assess the possibility of using DSI in high-speed impact problems and see if it can serve as a

trustworthy supplement or substitute to DIC in extreme experimental environments. Through the application of high-speed imaging systems, we aim to capture the transient mechanical responses of composite materials under impact and compare the resolution of each technique against displacement fields, strain evolution, and internal activity signatures. The combination of the two methods would offer a more comprehensive and robust suite of diagnostic tools for dynamic material testing and structural integrity evaluation.

2. EXPERIMENTAL SETUP AND MATERIALS

To compare and evaluate the performance of DIC and DSI under dynamic loading, a series of impact tests were conducted using a high-speed acquisition system. The experimental procedure consisted of a gas gun capable of launching projectiles at approximately 55 m/s. Various composite and metallic plates were impacted while their surface behavior was recorded.

For DIC measurements, a stereoscopic setup was established using two high-speed cameras - FASTCAM Mini AX200 and FASTCAM NOVA S6. The sample under test was illuminated using white LED sources. The sample surface was painted with white acrylic paint and a printed speckle pattern applied using a special Speckle Pattern Application Kit. The real and schematic setup of the DIC arrangement are presented in Figure 1.
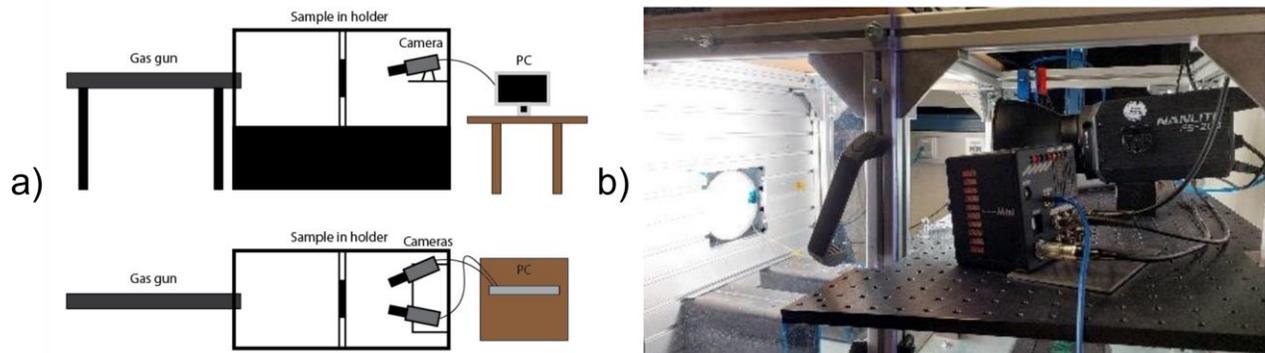

Figure 1. a) Schematic of 3D DIC set-up (side view and the top view); b) 3D DIC set-up

For the DSI setup, a single high-speed camera (FASTCAM Mini AX200) was used in conjunction with coherent laser illumination provided by a Coherent Verdi 6 W laser at 532 nm. White light illumination was turned off during the acquisition of DSI measurements to avoid interference with the speckle contrast and increase of the short noise. The laser beam was expanded to ensure uniform illumination across the sample surface, creating a dynamic speckle pattern. The diagram of the DSI setup and its implementation are presented in Figure 2.
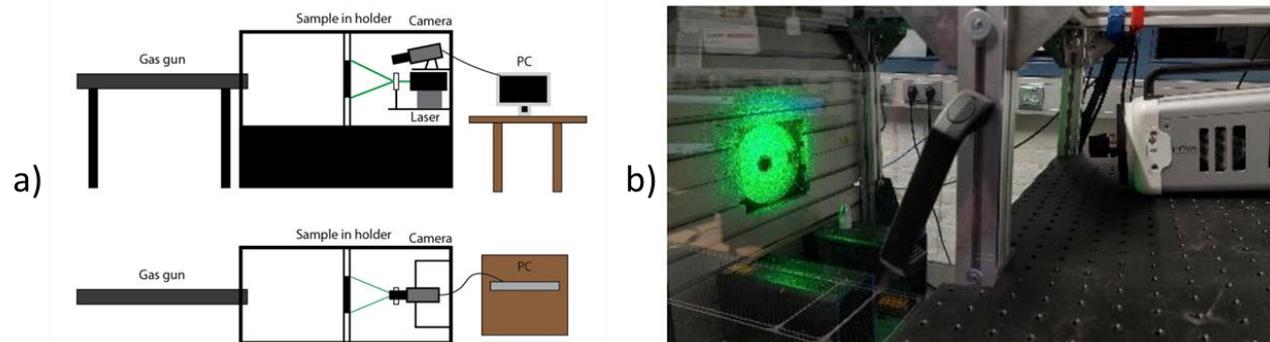

Figure 2. a) Schematic of DSI setup for impact testing with a high-speed camera placed at an angle (top) and normally (bottom) to the plate surface; b) DSI set-up with laser speckle

There were three kinds of square test plates (200 mm × 200 mm) utilized for impact testing:

- Aluminum plate, 3 mm thick

- Woven thermoplastic CFRP, 3 mm thick

- Cytec 977-2 CFRP, 4 mm thick

The images were captured with a high temporal resolution of 10 µs (i.e., 100,000 frames per second) and a spatial resolution of 256×128 pixels and pixel pitch of 20 µm. In this paper, we will describe results, obtained for Cytec 977-2 CFRP plates.

3. METHODOLOGY

3.1 DIC Data Acquisition and Processing

The DIC method was utilized to determine full-field displacement and strain maps in impact testing. The applied to the sample surface printed speckle pattern is an optical marker that deforms with the material and from which the local displacements are retrieved by the correlation algorithm.

During the experiments, images were captured with a stereoscopic system using two synchronized high-speed cameras to record 3D deformation. The white light sources utilized for illumination were positioned in a manner to prevent shadows and reflections.

3.2 DSI Data Acquisition and Processing

Camera FASTCAM Mini AX200 captured speckle patterns formed on the specimen surface upon illumination by a uniform beam from a 6 W, 532 nm Coherent Verdi laser. Darkroom conditions were employed to capture DSI raw data to avoid interference by ambient light. The raw speckle data comprised image sequences recorded over the period of around 10–15 milliseconds after impact. For monitoring the fast developing non-stationary process during the impact, we processed only two images to build an activity map at a given instant. The map corresponded to a certain time lag, $m\Delta t$, where m is an integer and $1/\Delta t$ is a frame rate. The images are 2D arrays of intensity values $I_{kl,n}$ and $I_{kl,n+m}$ with k, l giving the pixels coordinates $(k\Delta, l\Delta), k = 1...N_x, l = 1...N_y$, where Δ is the pixel pitch and the index n indicates the instant $n\Delta t, n = 1...N$. By changing n, tracking the process in the time becomes possible. We find the absolute value of the difference of intensities in both images $D_{kl,n}^m = \left| I_{kl,n} - I_{kl,n+m} \right|$. Exemplary speckle patterns from the image sequence acquired for the Cytec 977-2 CFRP plate are shown in Fig. 3.
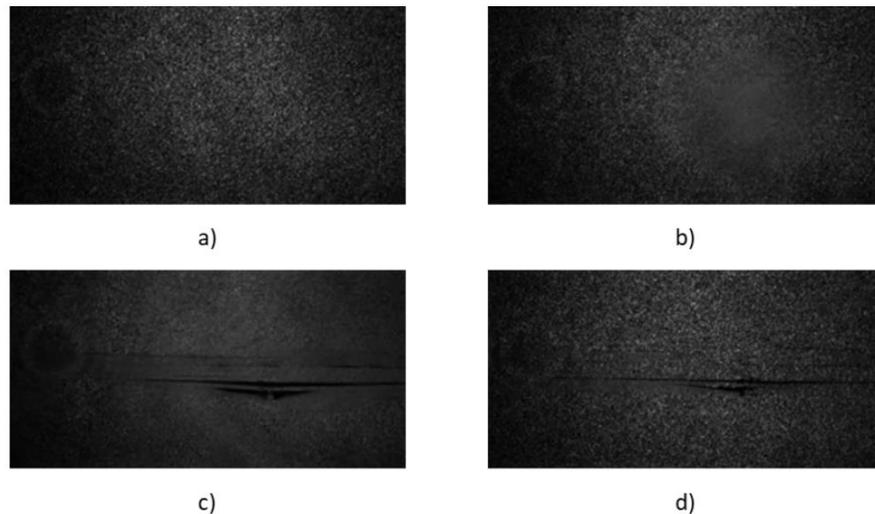

Figure 3. Cytec 977-2 CFRP 4 mm thick plate deformation a) image 1 (0 ms); b) image 800 (8 ms); c) image 1800 (18 ms); d) image 2000 (20 ms)

4. RESULTS AND ANALYSIS

For DIC, sequences of digital images were analyzed using VIC-3D software. This software breaks each image into a grid of small subsets (e.g., 16×16 or 32×32 pixels) and computes the cross-correlation between the corresponding subsets in reference (pre-impact) and deformed (post-impact) images. The output includes time-resolved displacement fields in all three spatial directions and related strain maps. Displacement in the Z-direction was particularly investigated for impact-induced out-of-plane deformation, as shown in Fig. 4 for Cytec 977-2 CFRP plate.
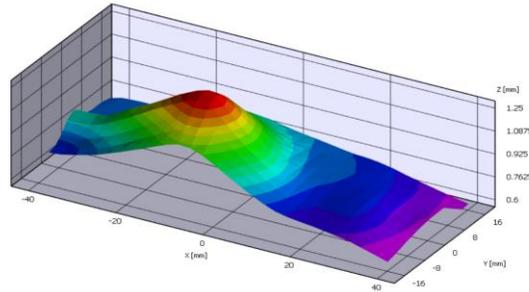

Figure 4. Moment of Cytec 977-2 CFRP sample deformation detected with the DIC method

For the DSI experiments, activity maps were calculated from the moment when projectile contacted with the sample. Fig. 5 presents the deformation pattern in a Cytec 977-2 CFRP plate, where wave propagation within the material can be observed. This image was obtained by subtracting the 4th and 5th frames captured after the projectile's impact. In this example, activity values range from 0 to 60, while in general, for 8-bit images, the full range varies from 0 to 255. Spatial averaging is applied to enhance contrast. Higher values indicate greater activity in the observed region. Activity map provides a qualitative visualization of dynamic changes, but it does not offer detailed quantitative information on deformation or mechanical parameters typically obtained through DIC. This limitation represents a primary drawback of the DSI technique.
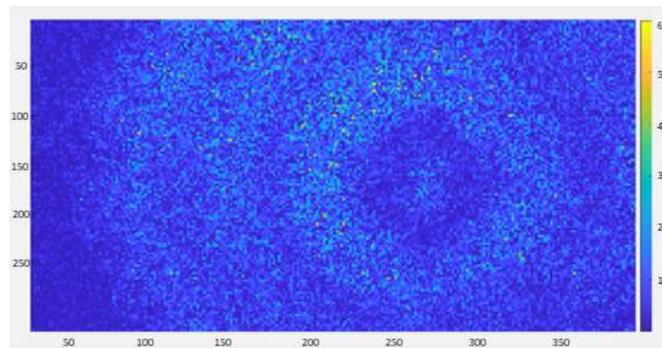

Figure 5. Moment of Cytec 977-2 CFRP sample deformation detected with the DSI method

5. CONCLUSIONS

In conclusion, we compared DIC and DSI methods for impact testing with high-speed imaging. DSI showed good results at dynamic imaging strain distributions across the sample surface. It allows for easy observation of propagating deformation waves and localized regions of high activity through activity maps.
However, this method cannot measure such values as displacement and strain, which are crucial in non-destructive testing field. In comparison, DIC offers high spatial and temporal resolution in its computation of full-field displacement and strain. It remains the gold standard in quantitative assessment for experimental mechanics. Nevertheless, its

dependence on surface-applied speckle patterns makes it less effective under extreme conditions such as high temperatures, high strain rates, or significant surface damage—conditions that can result in speckle pattern loss and reduced tracking accuracy.

The quantitative accuracy of DIC and the visual strengths of DSI form a highly complementary combination. While DIC achieves detailed mechanical parameters, DSI adds visualization of internal dynamics. Combined, the two techniques enable a more integrated impact testing approach—benefiting from both qualitative visualization and quantitative measurement.

ACKNOWLEDGMENTS

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