International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 7, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijmee.v7n1.06
Journal homepage: https://wepub.org/index.php/IJMEE/index

Optimization of Digital Speckle Patterns and Its Application in Measuring Crack-Tip Deformation Fields of CNTs/PDMS Composites

Huan Liu *

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China
* Corresponding Author Email: 1121093688@qq.com

ABSTRACT

An improved algorithm for generating digital speckle patterns is proposed. This method introduces a minimum spacing constraint and a multi-shape random distribution strategy to overcome two common limitations of conventional approaches: limited morphological diversity and undesirable overlap at high densities. A comprehensive evaluation was performed using four key parameters: speckle size, mean intensity gradient, systematic error, and random error. The digitally designed speckle patterns were transferred onto a CNTs/PDMS composite via a non-destructive technique. This approach successfully enabled the measurement of deformation fields in the crack tip region under large-strain conditions. Based on the experimental results, the fan-shaped zoning characteristics of the deformation field near the crack tip were analyzed. The experimental results validate that the speckle patterns produced by the proposed algorithm are high-contrast and well-distributed, demonstrating significant potential for applications in fracture mechanics studies of flexible composites.

KEYWORDS

Digital Speckle; Digital Image Correlation (DIC); CNTs/PDMS Composite; Crack-Tip Deformation Field.

1. INTRODUCTION

In studies of flexible materials subjected to large deformations, the accurate characterization of the crack-tip deformation field is essential for analyzing failure mechanisms. Consequently, optical measurement techniques are widely used to quantify deformation states with high precision. Among these methods, Digital Image Correlation (DIC) tracks deformation by analyzing speckle pattern displacements on the specimen surface. This technique provides key advantages such as straightforward implementation, low cost, high accuracy, full-field measurement, and non-contact operation [1-2], rendering it particularly suitable for characterizing crack-tip deformation fields.

In digital image correlation (DIC), speckle patterns serve as an essential medium for encoding deformation information. Their quality directly influences the accuracy and reliability of the measurement results. Consequently, numerous speckle generation techniques have been developed to produce high-quality patterns. Conventional manual methods, such as painting or ink spraying, typically demonstrate significant randomness and limited reproducibility [3]. Although alternative methods like stencil printing [4] and photolithography [5] improve pattern uniformity and precision, they are often hampered by high cost, complex processes, and weak adhesion to flexible substrates (e.g., CNTs/PDMS composites). Recently developed digital speckle printing techniques—including water transfer printing [6], film-free water decal printing [7], and UV-curable printing [8]—offer viable solutions to these limitations.

High-density speckle patterns are essential for accurately measuring crack-tip deformation in flexible materials. However, excessively high density, especially when accompanied by substantial overlap, can severely reduce measurement accuracy. The proposed method incorporates a minimum spacing constraint and a multi-shape random distribution mechanism, thereby reducing printing-induced coalescence while improving feature diversity, matching accuracy, and robustness against matching ambiguity. Speckle pattern quality was evaluated using four metrics: speckle size, mean intensity gradient, systematic error, and random error. Additionally, a non-destructive transfer technique was employed to overcome the poor adhesion characteristics of CNTs/PDMS composites, which challenge conventional speckle application methods. The optimized digital speckle patterns were successfully transferred onto CNTs/PDMS specimens, enabling precise full-field deformation measurement around a Mode-I crack tip. This methodology successfully captured the evolution of the fan-shaped zoning angle under varying loads, elucidating the effect of external load on strain singularity near the crack tip.

2. DESIGN AND IMPLEMENTATION OF DIGITAL SPECKLE IMAGES

The digital speckle patterns utilized in this study were generated by a custom algorithm implemented in MATLAB. The duty cycle is defined as the ratio of the total speckle area to the entire region of interest. The speckle patterns were designed based on the following expression:

$$L = \frac{D}{2}\sqrt{\frac{\pi}{\rho}} \tag{1}$$

where L denotes the grid spacing, D is the speckle diameter (in mm), and ρ is the duty cycle. To improve distribution randomness, a random perturbation mechanism was implemented, which applies a random displacement to each grid point.

$$\Delta = (\Delta X, \Delta Y) = (rand(-1,1)\times\delta\times\frac{L}{2}, rand(-1,1)\times\delta\times\frac{L}{2}) \tag{2}$$

where ΔX and ΔY represent the random displacements along the x and y directions, respectively; $rand(-1,1)$ denotes a uniformly distributed random number within the range $[-1,1]$; δ is the perturbation intensity coefficient; and $\frac{L}{2}$ sets the maximum allowable displacement.

According to Ref. [9], a speckle density of approximately 50% and a speckle size of 3–5 pixels provide an optimal balance between resolution and measurement accuracy in digital image correlation (DIC). The speckle size is defined as follows:

$$B = \frac{L}{F}\times G \tag{3}$$

where L is the field of view length, F is the camera resolution, and G is the number of pixels corresponding to the speckle diameter. The speckle size depends on both the field of view length and the resolution of the DIC camera. Owing to printing limitations, the minimum achievable speckle size was set to 0.3 mm, since sizes below 0.2 mm could not be reliably achieved. Using a duty cycle of 50% and a perturbation intensity coefficient of 0.5, circular digital speckle patterns were generated, as illustrated in Fig. 1(a).

To improve matching accuracy in DIC, a multi-shape speckle pattern composed of 50% circular and 50% polygonal speckles was developed, as shown in Fig. 1(b). Circular speckles serve as stable positional references, whereas polygonal speckles contribute distinctive, orientation-variant features that enhance matching accuracy and reduce ambiguity. By combining the benefits of both shapes, this hybrid approach effectively addresses the limitations of single-shape speckle patterns. The method exhibits strong robustness under various practical scenarios, including changes in distance, lighting, and deformation, thereby supporting more reliable and accurate motion tracking.

In the initial design phase, the algorithm produced speckle patterns with excessively high density. This led to overlapping regions merging into continuous patches during printing, adversely affecting the accuracy of strain calculations. To overcome this limitation, the random distribution algorithm was enhanced through the introduction of a minimum spacing constraint and dynamic adjustment of speckle density, resulting in a final duty cycle of 50%. This strategy effectively maintained both pattern discreteness and recognizability. The resulting optimized speckle pattern is presented in Fig. 1(c).

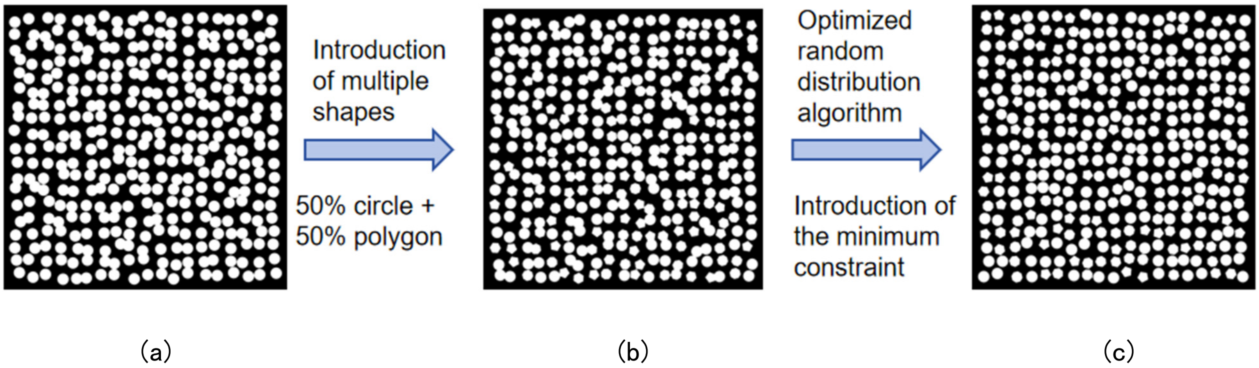

Fig 1. Speckle optimization process: (a) initial circular digital speckle pattern; (b) hybrid-shape digital speckle pattern; (c) overlap-free hybrid-shape speckle pattern.

3. EVALUATION OF DIGITAL SPECKLE QUALITY AND ACCURACY ANALYSIS

3.1. Evaluation Parameters

High-quality speckle patterns are crucial for achieving accurate and reliable measurements in digital image correlation (DIC). Speckle pattern evaluation parameters are typically divided into two categories: global parameters (e.g., mean intensity gradient, speckle size, and duty cycle) and local parameters. A comprehensive evaluation of speckle quality should include both systematic and random errors to ensure robustness [10]. In practice, global parameters are more practical for assessing the overall quality of speckle patterns [11]. Therefore, this study used global parameters—mean intensity gradient and speckle size—to evaluate speckle patterns comprehensively, with additional validation based on random and systematic errors.

The Mean Intensity Gradient (MIG) serves as a critical indicator for assessing the texture richness and correlation accuracy of speckle patterns. It characterizes the magnitude of local intensity variations in an image. Typically, a higher MIG corresponds to greater matching precision. It is defined as follows [12]:

$$\delta_{\mathrm{f}} = \frac{\sum_{i=1}^{W}\sum_{j=1}^{H}\left|\nabla f\left(xij\right)\right|}{W \times H} \tag{4}$$

where W and H are the width and height of the image, respectively, and $\left|\nabla f\left(xij\right)\right| = \sqrt{fx\left(xij\right)^2 + fy\left(xij\right)^2}$ is the magnitude of the intensity gradient vector at each pixel. Here, $fx\left(xij\right)$ and $fy\left(xij\right)$ denote the intensity derivatives at pixel $\left(i, j\right)$ in the x- and y-directions, respectively. The gradient is computed via the central difference method.

Speckle size refers to the physical dimensions of individual speckles. It directly affects both the amount of feature information within a correlation subset and the susceptibility to interpolation or random errors. Excessively large speckles yield grayscale subsets with inadequate features, thereby increasing random errors. Conversely, overly small speckles can lead to image undersampling, resulting in higher interpolation errors.

3.2. Evaluation Results

Images of traditional (spray-painted) speckles, initial circular digital speckles, hybrid-shaped digital speckles, and optimized overlap-free digital speckles were captured using a CCD camera. All digital speckle patterns and their corresponding physical counterparts were uniformly cropped to 500 × 500 pixels for subsequent testing, as shown in Fig. 2.

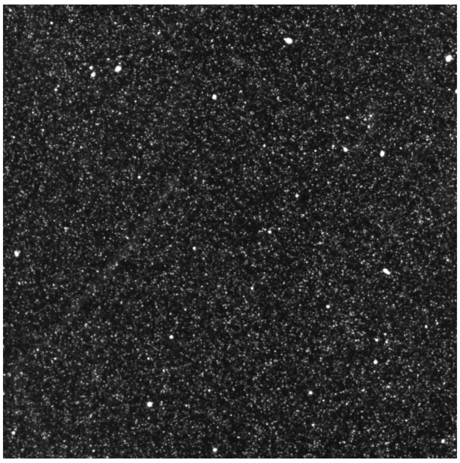

Fig 2 (a)Traditional spray paint spatter

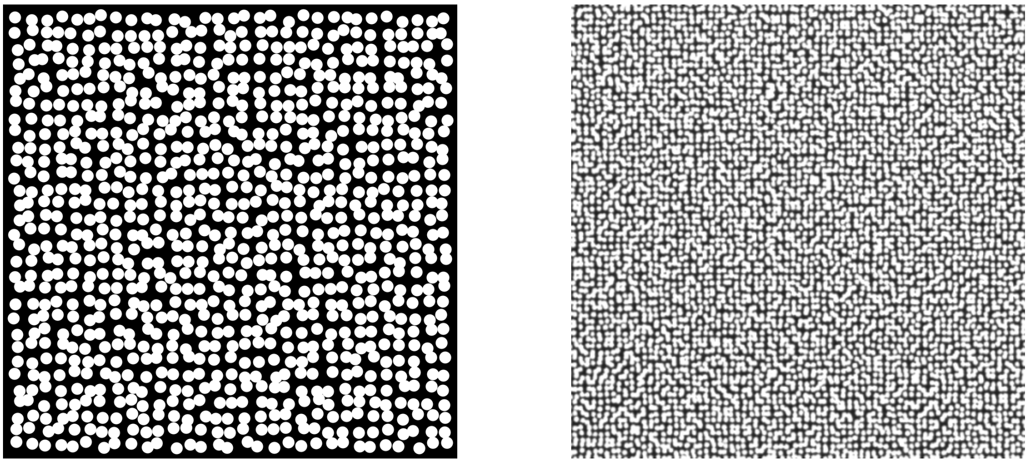

Fig 2 (b)Initial circular digital speckle pattern (left) and corresponding physical image (right)

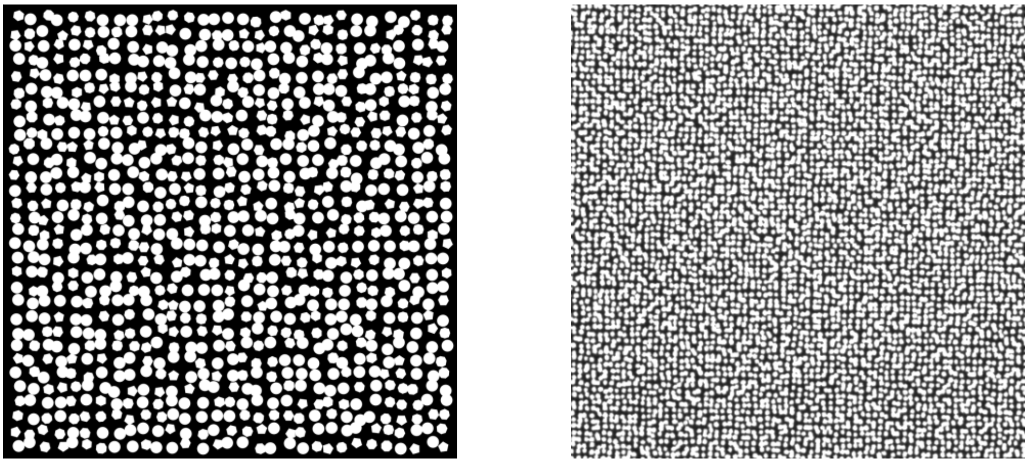

Fig 2 (c)Hybrid shape digital speckle pattern (left) and corresponding physical image (right)

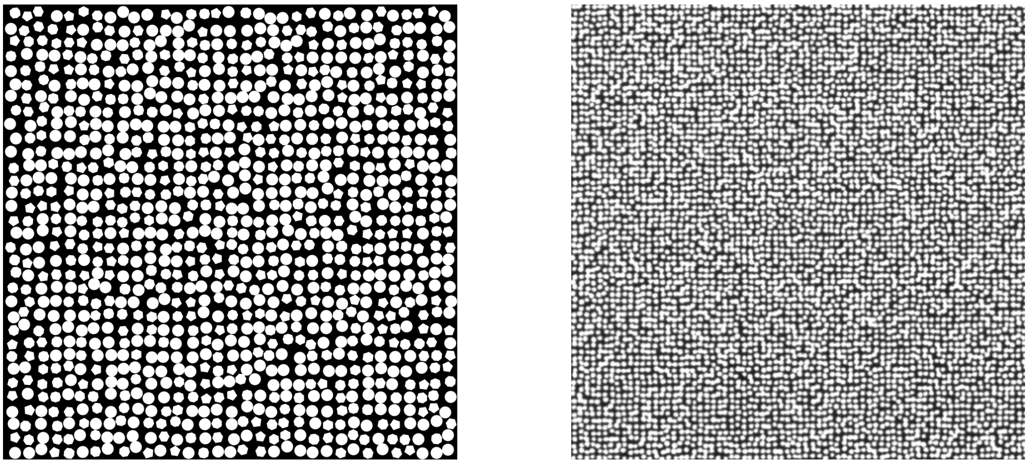

Fig 2 (d)Non-overlapping hybrid shape digital speckle pattern (left) and corresponding physical images (right)

Fig 2. Speckle pattern images for evaluation

Table 1 summarizes the evaluation parameters for each speckle pattern, including the mean intensity gradient (MIG), speckle size, and systematic error. The average speckle size of traditional speckles was measured as 1.92 pixels, whereas the digital speckles fell within the optimal range of 3–5 pixels. This difference stems from the high randomness, low reproducibility, and non-uniform distribution associated with traditional methods, whereas digital patterning allows precise control of uniformity and dispersion. The designed digital speckle pattern has a mean size of 3.31 pixels, within the optimal range. This design ensures that each subset contains adequately rich and distinguishable features, thus reducing random matching errors. caused by excessively small speckles. Additionally, it prevents image undersampling due to oversmall speckles.

The three non-transferred speckle patterns all showed high mean intensity gradient (MIG) values, with a clearly increasing trend. Algorithmically, the hybrid-shaped design—especially its overlap-free version—produces speckle patterns exhibiting stronger grayscale variations and more distinctive features, thus providing a robust foundation for high-precision matching.

The mean intensity gradient (MIG) of the physical speckle pattern represents the most critical performance metric, as it reflects the actual usable quality of the speckle after physical realization, including printing and image acquisition. Factors such as blur, distortion, and noise introduced during this process often lead to a reduction in MIG. All digital speckle patterns exhibited significantly higher MIG values than traditional ones, showing an improvement factor of approximately 6–7. These results indicate that the digital speckle design effectively mitigates quality degradation during physical implementation.

Table 1. Evaluation parameters for different speckle patterns

Speckle evaluation parameters	Traditional spray paint spatter	Initial circular speckle pattern and its physical image	Hybrid Shape digital speckle pattern and Its physical image	Non-overlapping hybrid shape digital speckle patterns and their physical images
Speckle size	1.92	3.75	3.72	3.31
unshifted average gray-scale gradient	-	75.92	80.80	81.6674
Average gray-scale gradient of physical speckles	7.4918	49.6297	50.7066	52.7344
Systematic error	0.01151	0.0044	0.00432	0.00392

Systematic error serves as a direct metric for assessing the accuracy of DIC measurements when speckle patterns are used. Lower systematic error values correspond to more reliable measurement outcomes. Traditional speckles showed the highest systematic error, consistent with their poorer image quality and notably low grayscale gradient. Blurred features elevate matching uncertainty, thereby introducing higher systematic errors. In comparison, all digital speckle patterns yielded systematically lower errors than traditional ones, improving accuracy by approximately 2–3 times. Among the digital speckles, the overlap-free hybrid-shaped pattern—exhibiting the highest image quality—also achieved the lowest systematic error (0.00392). This finding reinforces the fundamental principle that higher grayscale gradients contribute to greater measurement precision.

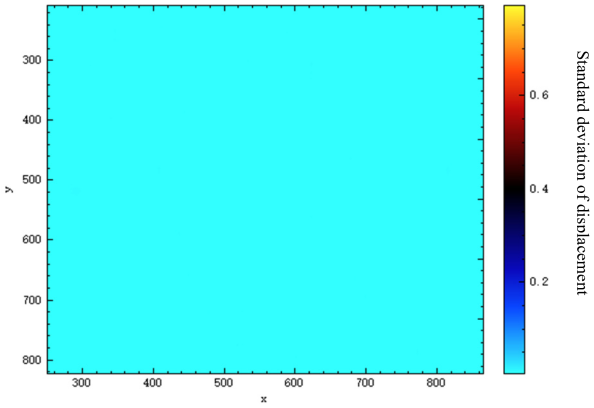

Fig 3. Random error contour of the overlap-free hybrid-shaped digital speckle pattern

The random error of the overlap-free hybrid-shaped digital speckle pattern was evaluated, as illustrated in Fig. 3. The minimal random error, indicated by a displacement standard deviation approaching zero, serves as a strong indicator of high speckle pattern quality, which reflects uniform feature distribution and high information entropy. Consequently, highly stable and reliable displacement fields are obtained in DIC computations.

Collectively, the quantitative assessment of four key parameters—including a high mean intensity gradient (≈52.73), an optimal speckle size (≈3.31 pixels), low systematic error (≈0.00392), and negligible random error (≈0)—provides comprehensive evidence for the superior quality of the speckle patterns produced by the improved algorithm presented in this work.

The exceptional quality is due to two algorithmic improvements: a minimum spacing constraint successfully mitigates speckle overlap, preserving the distinctness and recognizability of each feature, and a multi-shape hybrid strategy (50% circular, 50% polygonal) greatly enriches feature diversity and orientation dependence. As a result, both matching accuracy and robustness against matching ambiguity are significantly enhanced. In summary, the speckle patterns produced by the proposed algorithm demonstrate exceptional quality and are highly suitable for applications involving flexible materials subjected to large deformations.

4. APPLICATION IN DEFORMATION FIELD MEASUREMENT OF CRACK TIPS IN CNTS/PDMS MATERIALS

4.1. Experimental Equipment and Methods

The digitally designed speckle patterns were deposited onto the CNTs/PDMS composite surface via a non-destructive transfer technique [13]. The Mode-I fracture behavior of the material was studied using a digital image correlation (DIC) system integrated with an IBTC-300SL micro in-situ mechanical testing system. The experimental setup is shown in Fig. 4. The specimen had dimensions of 34 × 34 × 2 mm and featured a centered, single-edge prefabricated crack measuring 8 mm in length, as depicted in Fig. 5.

Fig 4. Photograph of the experimental setup

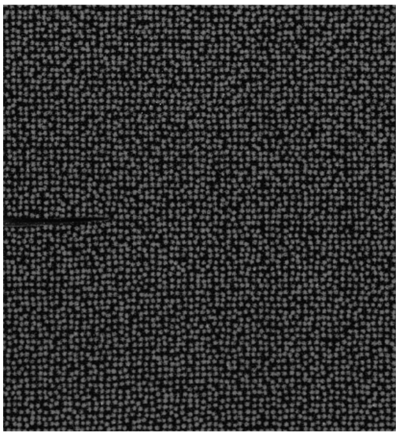

Fig 5. Speckle pattern on a CNTs/PDMS composite specimen with a prefabricated crack

First, the object distance of the DIC camera was set to 600 mm, and the image resolution was configured to 1000 × 1000 pixels according to the actual speckle size. The specimen was clamped in the micro in-situ mechanical testing machine, and uniaxial tensile load was applied normal to the crack direction at a rate of 4 mm/min (0.066 mm/s). Simultaneously, the CCD camera initiated image acquisition at a frame rate of 4 frames per second (fps). The acquired images were processed using DIC analysis software, and the crack-tip region was defined as the region of interest (ROI). The computation parameters were configured with a step size of 1 and a subset size of 13. A low-pass filter was applied during preprocessing to reduce noise. Finally, the displacements of seed points on the specimen were computed and evaluated.

4.2. Analysis of Experimental Results

The displacement field in the Cartesian coordinate system was derived from DIC software analysis. It was then transformed into radial displacement u_r and circumferential displacement u_θ by applying coordinate transformation formula (5).

$$\begin{cases} u_r = u\cos\theta + v\sin\theta \\ u_\theta = v\cos\theta - u\sin\theta \end{cases} \tag{5}$$

Using the experimental results under a load of 2.9 N as an example, Fig. 6 shows the corresponding displacement contour. A clear zero contour of radial displacement u_r was observed near $\theta \approx 25°$, suggesting negligible radial displacement of material points in this region. Inside the region bounded by the zero contour, u_r was consistently negative, indicating that material points moved toward the crack tip. Outside this region, where $u_r > 0$, material points displaced away from the crack tip.

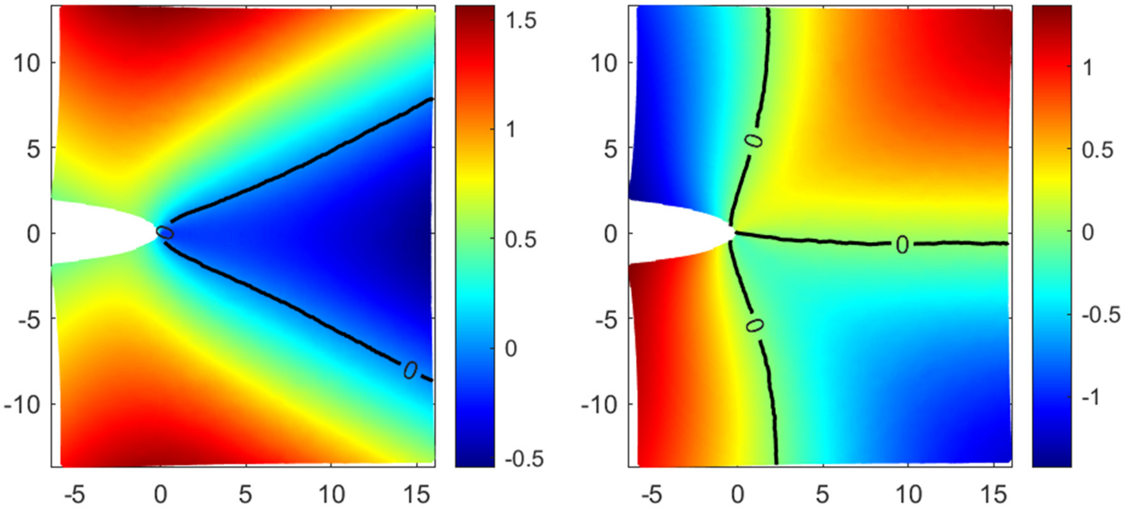

Fig 6. Contours of Radial Displacement u_r and Circumferential Displacement u_θ

A well-defined zero-isoline was also identified in the circumferential displacement field u_θ, near $\theta \approx 0°$ and $\theta \approx 80°$, indicating negligible movement of material points in the circumferential direction within these regions. For $\theta > 0°$, positive displacement values indicated counterclockwise rotation around the crack tip. For $\theta < 0°$, negative values suggested clockwise rotation, accompanied by an overall outward expansion of the material. In contrast, near $\theta \approx 80°$, the material exhibited a tendency for inward contraction.

To better characterize material point motion near the crack tip, the resultant displacement vector field—obtained by combining radial and circumferential displacements—was analyzed. The vector field shows that within the sector $\theta \approx \pm 25°$, material points moved toward the crack tip, primarily due to circumferential expansion under loading. This region is defined as the expansion zone (EX). n contrast, in sectors where $\theta > 25°$ or $\theta < -25°$, material points moved away from the crack via circumferential contraction, defining the contraction zone (SH).

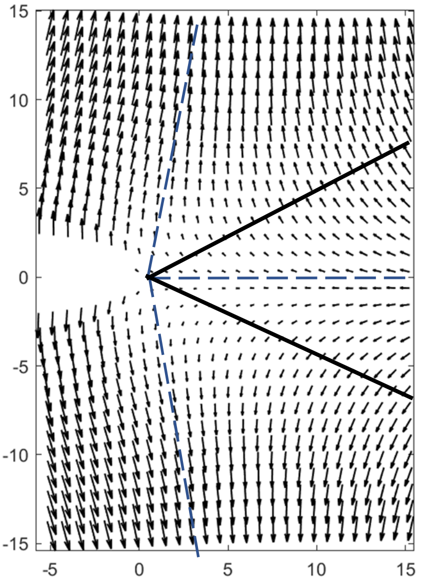

Fig 7. Resultant Displacement Vector Diagram in Polar Coordinates

5. SUMMARY

This study tackles critical challenges in measuring crack-tip deformation fields in CNTs/PDMS flexible composites under large strain through the development and validation of an optimized digital speckle generation algorithm. The approach improves feature richness and distribution while mitigating speckle overlap—a common issue in conventional methods—via a minimum spacing constraint and a multi-shape hybrid strategy incorporating both circular and polygonal speckles. Integrated with digital image correlation (DIC), the method was applied to study Mode-I fracture in CNTs/PDMS under large deformation, enabling systematic characterization of sectorial features near the crack tip. The proposed design provides a highly compatible and accurate speckle fabrication solution for DIC-based deformation measurements in flexible electronic materials.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] Zhan N, Zhang X, Ye J, et al. High-precision parameter-free optical distortion measurement and correction via digital image correlation[J]. Optics & Laser Technology, 2024, 177: 111129.

[2] Y. Lin-Tao, S. Xin-Xing, G. Liu-Ning, et al., "Research and application of camera arrangement strategies in multi-camera digital image correlation systems," Journal of Experimental Mechanics, vol. 40, no. 3, pp. 313–324, 2025.

[3] Z.-N. Chen, "Optimization of digital speckle patterns and its application," Ph.D. dissertation, Southeast University, Nanjing, China, 2018.

[4] Ghorbani R, Matta F, Sutton M A. Full-field deformation measurement and crack map on confined masonry walls using digital image correlation[J]. Experimental Mechanics, 2015, 55(1): 227-243.

[5] Zhu C, Ekinci H, Pan A, et al. Electron beam lithography on nonplanar and irregular surfaces[J]. Microsystems & nanoengineering, 2024, 10(1): 52.

[6] Jalilluddin A M, Nazri F M, Zulkefli M U. Prefabricated Speckle as Enhancement of Digital Image Correlation Speckle Patterning Efficiency for Masonry Testing[J]. MethodsX, 2025: 103577.

[7] Sanchez A C, Kim D K. Assessment of the Film-Free Water Decal Method for Speckle Pattern Application in Digital Image Correlation[J]. Sensors, 2024, 24(17): 5657.

[8] Luo H, Liu J, Luo H, et al. Parametric fabrication technique of high-temperature speckles for digital image correlation via free dispensing[J]. Optics and Lasers in Engineering, 2025, 186: 108752.

[9] Y. Su, "Research on evaluation criteria for speckle quality in digital image correlation technology," Ph.D. dissertation, University of Science and Technology of China, Hefei, China, 2016.

[10] Y. Su, Y. Gao, Z.-R. Gao, et al., "Guanghui: A free and open-source software for digital speckle pattern generation and evaluation," Journal of Experimental Mechanics, vol. 36, no. 1, pp. 17–28, 2021.

[11] Q.-T. Li, J. Zheng, X.-H. Wang, et al., "Evaluation of speckle quality in digital image correlation methods," Value Engineering, vol. 43, no. 26, pp. 133–135, 2024.

[12] B. Pan, D.-F. Wu, Y. Xia, "Quality evaluation of speckle patterns for digital image correlation," Journal of Experimental Mechanics, vol. 25, no. 2, pp. 120–129, 2010.

[13] Z. Wei, X.-L. Li, S.-L. Liu, et al., "Application of digital image correlation based on digitally designed speckle patterns in fracture crack detection," Journal of Hebei University of Technology, vol. 49, no. 6, pp. 69–75, 2020.