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BACKWARD INCREMENTAL DIGITAL VOLUME CORRELATION FOR HIGH-FIDELITY INTERNAL DEFORMATION MAPPING IN IDOX/ESTANE PARTICULATE COMPOSITES

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ABSTRACT

In-situ X-ray micro-computed tomography (μCT) combined with Digital Volume Correlation (DVC) has become a cornerstone for quantifying internal deformation and damage in particulate composite materials. However, conventional DVC often struggles to maintain accuracy when materials undergo large nonlinear deformations accompanied by severe cracking and structural discontinuity. This paper addresses these limitations by implementing a robust backward incremental DVC approach to analyze the failure mechanisms of a mock plastic-bonded explosive (PBX) composite. The experimental setup involved a cylindrical specimen composed of IDOX crystals (75–150 μm) embedded in a polyurethane-based Estane binder. During unconfined compression, sequential μCT scans were acquired to capture the internal structural evolution. Unlike conventional forward-marching methods, the backward approach performs correlations in reverse, processing from the most deformed and fragmented state back to the original undeformed configuration through incremental steps. This methodology significantly enhances displacement tracking fidelity, particularly in regions where severe cracking and interfacial failure typically cause a loss of correlation in traditional frameworks. The results demonstrate that backward incremental DVC provides superior resolution of displacement and deformation fields near crack-affected regions. This high-fidelity mapping allows for the detailed observation of critical failure stages, including grain-binder interface delamination and subsequent crack coalescence. By successfully capturing these complex, grain-scale interactions, the study provides a vital dataset for the validation of high-fidelity numerical simulations. Ultimately, this approach offers a more reliable pathway for characterizing the intricate mechanical response and fracture evolution of heterogeneous particulate composites under extreme loading conditions.

INTRODUCTION

Quantifying the internal mechanical response and damage evolution of highly filled particulate composites, such as plastic-bonded explosives (PBXs), remains a formidable challenge in experimental mechanics. These energetic materials consist of a high volume fraction of crystalline particles embedded in a soft polymeric binder, a microstructural design intended to optimize both functional output and safe handling [1-3]. Due to the distinct stiffness mismatch between the rigid grains and the compliant binder, the macro-scale structural integrityof PBXs is highly dependent on complex, localized micro-scale interactions [4-6].

To avoid the hazards associated with live explosives, inert surrogate materials such as IDOX/Estane are heavily utilized in experimental characterization, exhibiting mechanical similarity to active composites across various thermal and loading regimes [3, 7-9]. While surface-based optical techniques like Digital Image Correlation (DIC) capture macroscopic failure patterns that eventually reached to the surface of the specimen, understanding subsurface behavior requires three-dimensional internal characterization. In-situ X-ray micro-computed tomography (μCT) coupled with Digital Volume Correlation (DVC) has thus emerged as the premier method for resolving volumetric deformation fields [1, 11].

Despite its advantages, standard DVC algorithms conventionally operate in a forward-marching manner, using the undeformed image as the continuous reference state. When dealing with particulate composites under compressive loads, severe cracking, interface delamination, and subsequent material fragmentation induce significant structural discontinuities. These events frequently cause conventional forward DVC algorithms to decorrelate, losing critical kinematic data exactly where damage localization is most severe. To overcome these fundamental limitations, this study utilizes a backward incremental DVC methodology [1]. By designating the heavily damaged, peak-deformed geometry as the initial reference and stepping backward toward the continuous undeformed state, the technique stabilizes correlation convergence and provides unprecedented resolution of crack coalescence and grain-binder interactions.

MATERIALS AND METHODS

Material Synthesis and Specimen Preparation

A high-fidelity inert surrogate was manufactured using recrystallized IDOX crystals with grain sizes ranging between 75 and 150 μm. These particulates were combined with a polyurethane-based Estane binder at a 19:1 weight ratio, achieving a 95% particle loading density characteristic of high-performance PBX formulations. Following blending, the composite mixture was hot-pressed at 50°C under 152.8 MPa of pressure for a duration of one minute. The compacted billets were subsequently machined into cylindrical specimens with optimized dimensions of 5 mm in both diameter and height, tailored specifically for unconfined compressive testing. (See also FIGURE 1.)

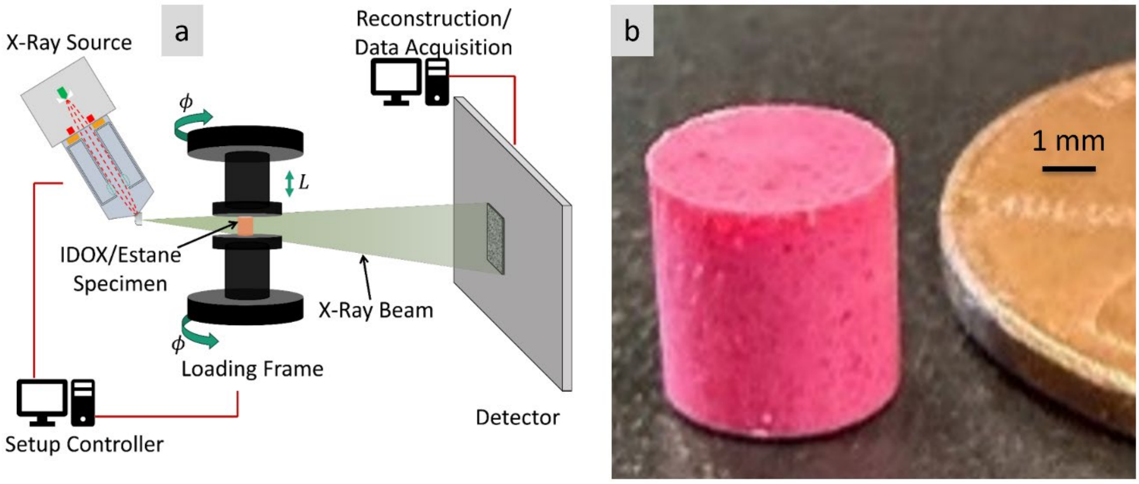

FIGURE 1: (a) Schematic of the in-situ X-ray micro-computed tomography system (b) IDOX/Estane Composite Specimen.

In-Situ Micro-Computed Tomography (µCT) Setup

The compression testing was conducted entirely in-situ within a ZEISS Xradia 520 Versa X-ray microscope, equipped with a customized unconfined compression loading stage. To mitigate frictional barreling artifacts at the boundary interfaces, the top and bottom surfaces of the composite cylinder were lubricated prior to testing. The loading platen compressed the specimen at a quasi-static displacement rate of 0.5 mm/min. Volumetric image datasets were acquired at six specific engineering strain (ϵ_z) intervals: 0.0%, -4.0%, -8.0%, -12.0%, -13.2%, and -14.4%. At each load step, the µCT system captured projections over a full 360° rotation using an X-ray source set to 160 kV and 50.3 µA, with an 8-second exposure time per projection. This procedure yielded highly detailed reconstructions featuring an isotropic voxel resolution of 12.93 µm, which were subsequently cropped to 601x601x501 pixel volumes to streamline computational correlation.

Backward Incremental Digital Volume Correlation

To evaluate the complex internal deformation, an open-source correlation tool (i.e., iDVC) was utilized. A critical advantage of this framework is its reliance on the local correlation of discrete subvolumes, effectively bypassing the need to formulate a global coupled stiffness matrix that frequently destabilizes during severe material fracture. Because standard tracking algorithms fail when cracks open and introduce void spaces, a reverse-tracking scheme was implemented and adopted for partciculate composites with major fracture patterns and fragmentation. In this study, the analytical process began at the maximum compressive strain state ($\epsilon_z = -14.4\%$) and systematically traced material points backward to the pristine, undeformed state (ϵ_z =0.0%). This reverse orientation ensures that control points remain anchored exclusively in solid material. Kinematic data was resolved by minimizing a normalized sum of squared differences (NSSD) function, which evaluates intensity variations between the reference and deformed configurations. The computational analysis employed 40-pixel cubic sub-volumes populated with 10,000 random sampling points. Sub-voxel precision was attained via tricubic interpolation, while the Newton-Raphson numerical method drove the minimization convergence.

RESULTS AND DISCUSSION

The in-situ tomographic scans provided a clear, uninterrupted timeline of internal degradation within the IDOX/Estane specimen. Initially, up to a compressive strain of -4.0%, the composite deformed homogeneously with only minor rigid body rotation and no visible fracturing. The critical damage occurred before -8.0% strain, marked by the rupturing of the polymeric binder, separation at the grain-binder interfaces, and the fracture of individual IDOX crystals. As the compressive load reached the final evaluated state (-14.4%), these isolated defects rapidly expanded and merged. The resulting fracture morphology presented a fragmented fracture profile throughout the specimen. This localized damage divided the cylindrical specimen into a relatively intact inner core surrounded by heavily fragmented peripheral wedges.

Standard forward-marching correlation attempts collapsed during the early stages of crack formation due to the rapid introduction of discontinuities. Conversely, by treating the most severely damaged configuration as the baseline, the backward incremental approach effectively modeled a virtual unloading process. Control points were securely positioned within intact material regions, successfully navigating around the complex crack networks. This method yielded exceptional computational stability; even during the most demanding correlation step where major fractures were virtually closed, the failure rate for control points was a mere 0.23% (representing only 10 points out of 4298). The algorithm maintained high-quality NSSD metrics, processing each load step in 1000 to 2485 seconds using a dual Intel Xeon workstation.

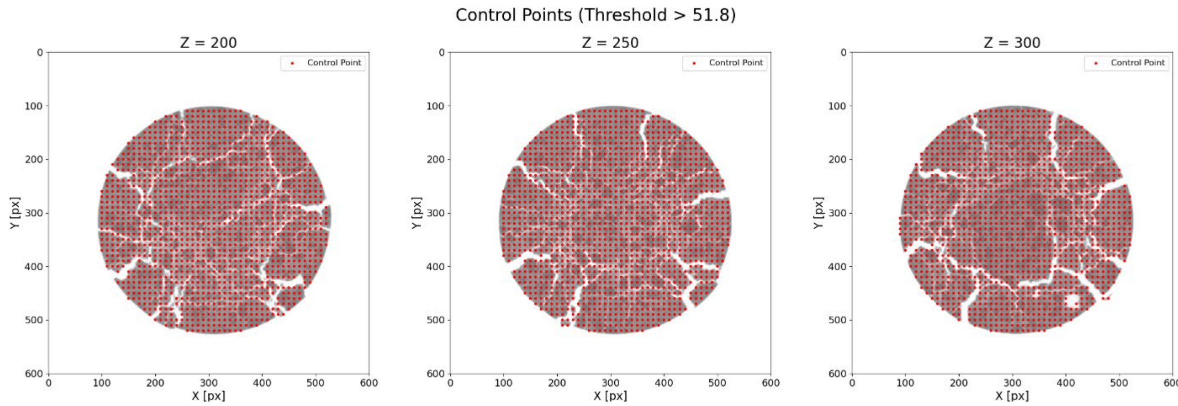

FIGURE 2: The distribution of control points throughout the sample shown in multiple slices.

By mathematically inverting these reverse trajectories, accurate forward-oriented displacement fields were successfully recovered. These 3D maps highlighted severe kinematic disparities across the fractured zones. For instance, following the primary fragmentation event, there is a further expansion in crack morphology in different sections of the sample up to the last step of the compressive strain (i.e., -14.4%). Furthermore, displacement magnitudes in the upper portion of the composite were nearly an order of magnitude greater than those at the fixed base, directly reflecting the downward influence of the moving platen.

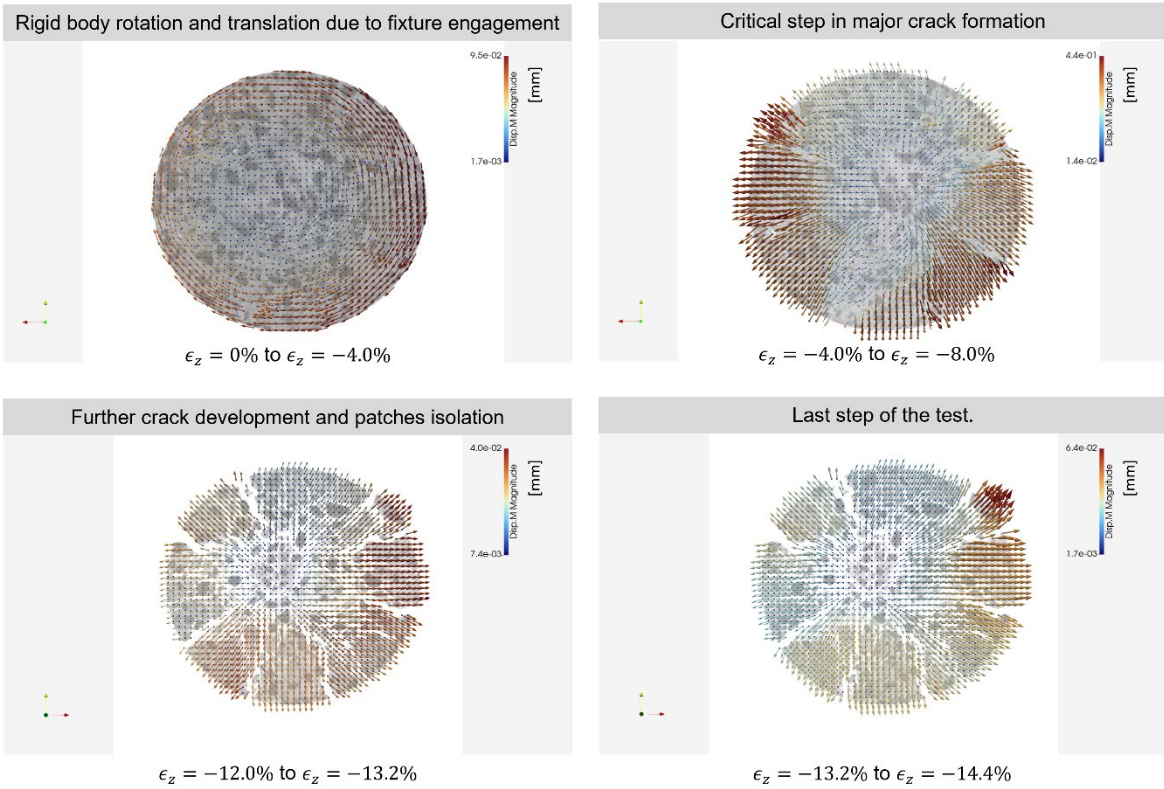

FIGURE 3: Post-processed incremental displacement vector field.

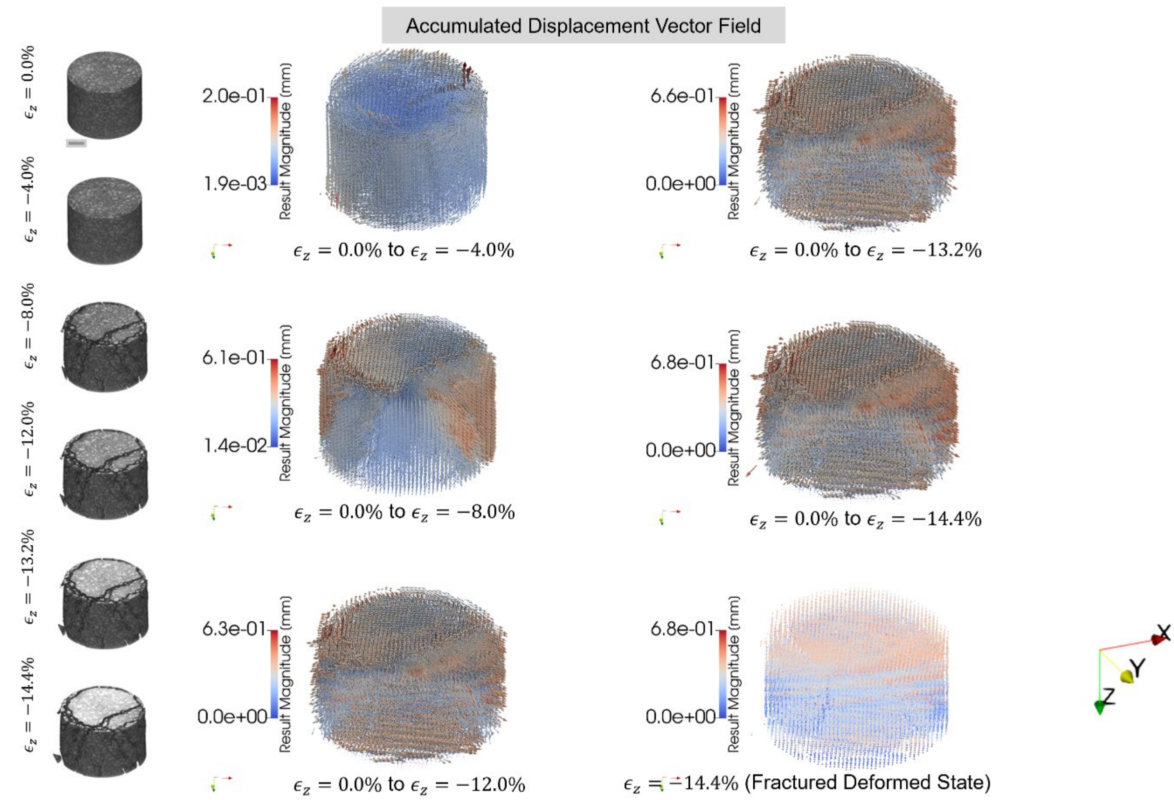

FIGURE 4: Full field cumulative displacement vector field post processed from backward DVC results.

CONCLUSION

This research demonstrates the efficacy of a reverse-marching correlation strategy for mapping the complex internal mechanics of dense particulate systems. Using the IDOX/Estane composite as a structural analog for high-explosive formulations, the study successfully captured the macroscopic shift from uniform viscous flow to catastrophic brittle failure. The analysis identified two distinct failure mechanisms: localized, patchy fracturing driven by microstructural grain interactions, and the eventual development of dominant, shear-driven macroscopic bands.These high-resolution kinematic fields serve as crucial validation targets for advanced multiscale numerical simulations. Subsequent investigations will leverage these 3D datasets to formulate micromechanical damage models and extend the backward tracking methodology to evaluate failure mechanisms in KelF/F50 polymer sand composites under diverse loading regimes.

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