# Bi-axial Strain Measurement of Woven-Webbing Inflatable Structures Using Digital Image Correlation with RGB Filtering

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**Crewed inflatable softgoods structures can significantly reduce launch volume for habitable pressure vessels. To ensure the operational safety of these structures, NASA has developed an extensive testing program to evaluate the structural capability on ground test articles. This paper will discuss a current challenge faced by test engineers evaluating the strain of large-scale inflatable space structures during ground testing. Namely, the difficulty that arises using monochrome digital image correlation (DIC) to evaluate bi-axial strain for woven-webbing restraint layers. This report provides insight into a novel method of photogrammetry using red-green-blue (RGB) filtering in conjunction with DIC to evaluate the strain in each direction on a test article experiencing bi-directional strain. To evaluate this concept, a uniaxial tensile test was performed that represented a biaxial woven architecture using orthogonally interfaced straps. The resulting analysis demonstrates promise for this novel approach for isolating a specific region and direction of strain, reducing the effects of straps not in the area of interest, while allowing for a larger region of analysis. Moreover, it was shown that the application of a white basecoat prior to applying photogrammetry patterns significantly reduced data loss while performing RGB filtered DIC.**

## I. Introduction

Inflatable softgoods structures have been demonstrated as an effective solution for addressing launch volume constraints of space habitats for low Earth orbit and beyond. Recent advancements in inflatable technology, as demonstrated by the Bigelow Expandable Activities Module (BEAM) aboard the International Space Station (ISS), have bolstered further acceptance and development of inflatable structures. This increase in development has generated the need for novel analysis methods for understanding woven textile structures' behavior under load. Crewed inflatable softgoods structures are typically constructed of a multi-purpose fabric shell that includes an exterior environmental and thermal blanket; a micrometeoroid and orbital debris shield; a structural restraint layer; and an internal air barrier. Upon inflation, the structural load is carried by the restraint layer, which is constructed using high specific strength materials, such as Kevlar or Vectran, often arranged in a woven pattern [1].

Due to the complex nature of woven fabrics, and variation in performance due to material layup, these inflatable structures require extensive testing, both on a sub-scale and full-scale level, to understand how these materials behave in their fabricated configurations. In addition to exhibiting anisotropic properties, measuring strain under pressure on complex softgoods architectures can be difficult. To address this, numerous strain sensing devices have been evaluated, including fiberoptic sensing systems, high elongation strain gages, resistive strain gages, conductive threading, and monochrome digital image correlation (DIC). Of these, monochrome DIC has shown the greatest success in accurately capturing strain during the deformation of a single strap [2], and has been shown to provide

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reliable results when testing on a sub-scale woven article [3]. While DIC is currently the leading technique for measuring strain in softgoods materials, the approach has difficulties when performing analysis on a woven-webbing restraint layer [4,5]. Traditional DIC methods and software assume a solid material substrate with a monochrome speckle pattern where a set of stereo cameras track the movement of the speckles across the substrate. For woven restraint layers, the substrate is made of uniaxial straps that are woven in a bi-directional pattern, which can cause errors in the strains calculated by the DIC software. Physical overlapping and stretching of the straps are seen as large deformations, especially at edges and the intersection of two straps. The intricate nature of an interwoven inflatable architecture demands a considerable investment of time and effort in parsing out the strains in each strap. This entails meticulously identifying areas of interest wherever the strap is visible, demonstrated by the current analysis region in Fig. 1. To mitigate these issues, a novel approach was established using red-green-blue (RGB) filtering. This approach leverages post processing capabilities to filter out red or blue photogrammetry patterns, allowing for tunable isolation of a particular color pattern while converting the image to monochrome for DIC analysis. Additionally, this novel approach aims to reduce analysis time by leveraging advanced thresholding methods to decrease the need for multiple areas of interest. This advancement is illustrated in Fig. 1 through the comparison of the current analysis region and the preferred analysis region.

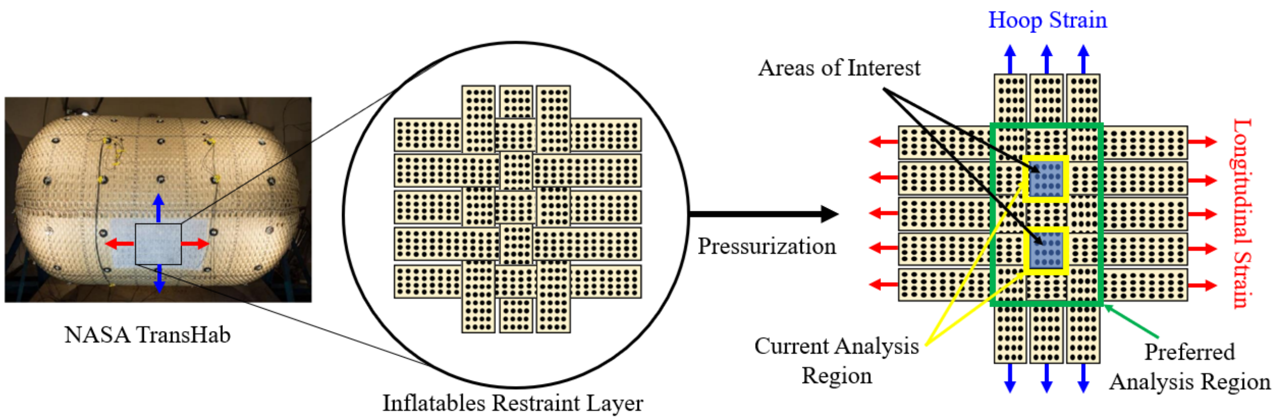



**Fig. 1 Digital Image Correlation Methodology for Inflatable Softgoods Structures.**

RGB filtering can provide a solution for mitigating low confidence measurements due to overlapping straps experiencing bi-directional strain by isolating a single strap direction. An illustration of this method is shown in Fig. 2. This report will evaluate the effectiveness of RGB filtering using tensile testing in coordination with a custom photogrammetry system developed at NASA. The results of this research will demonstrate the capabilities of RGB filtering to isolate a single tensile strap in a woven pattern. Furthermore, this report will investigate the necessity of applying a basecoat of white paint prior to the application of the speckled pattern for color DIC.

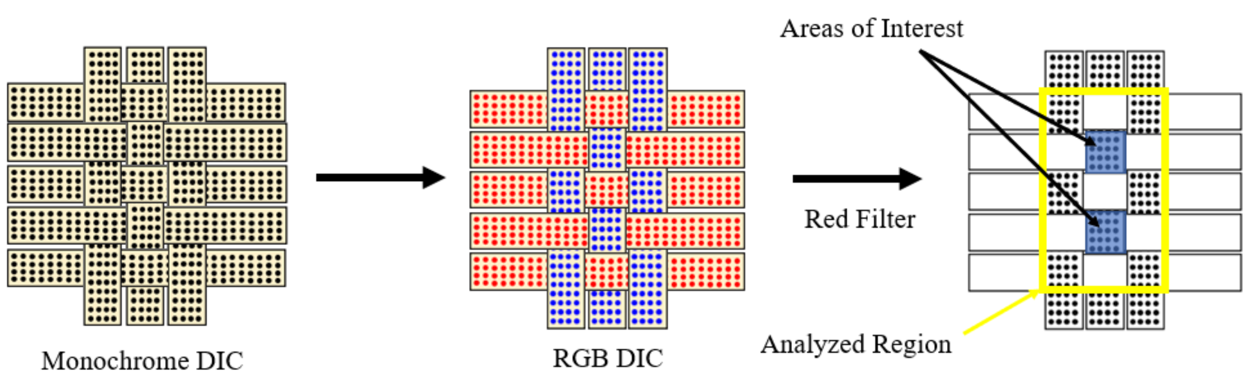



**Fig. 2 Novel Red-Green-Blue Filtering Approach for Digital Image Correlation.**

## II. Methodology

To investigate the capabilities of RGB filtering, an experimental procedure was designed to represent realistic conditions present during pressure testing of inflatable softgoods structures. Namely, tensile strap specimens were run through the same load cycles representative of an actual inflatable module, which included preconditioning to the operational load (approximately 25% of ultimate load) and then loading them at a comparable rate to a module level burst test, using an MTS uniaxial tensile machine. Additionally, an orthogonal woven pattern was utilized, representative of the design developed for TransHab, NASA's vanguard inflatables development project [1]. Due to equipment constraints, only one tensile strap was employed during experimentation with five static interfacing straps providing two areas of strain to be analyzed. To perform photogrammetry, two 5MP Basler ace cameras with 25mm lenses were situated at an incidence angle of 25 degrees, under ambient lighting. The experimental setup is shown below in Fig. 3. As the overall goal of this report is to evaluate the capabilities of RGB filtering, all results using filtered images will be compared empirically with the results achieved using purely monochrome DIC. Filtering was completed during post-processing using a custom Python code developed at NASA. A 10-second dwell, prior to loading, was used to collect images to determine a baseline noise level in the data.

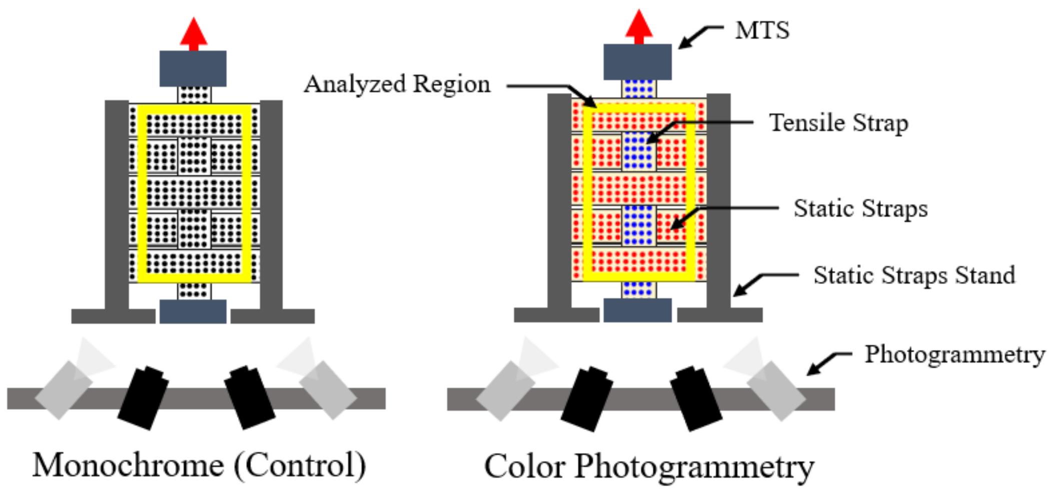


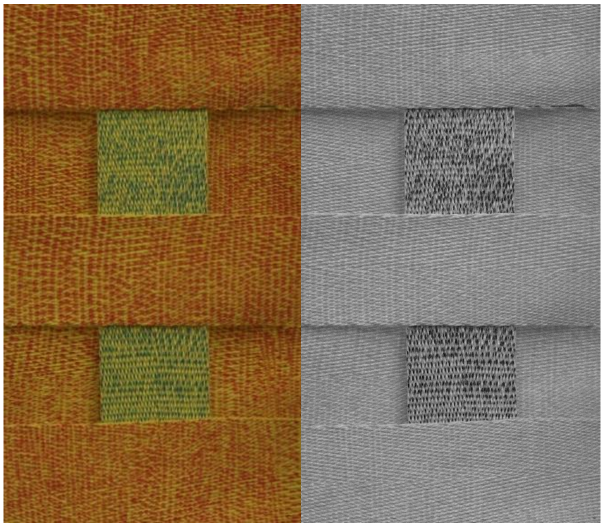

**Fig. 3 Strap Tensile Testing Setup.**

One of the most important contributing factors in DIC for ensuring high fidelity analysis is the contrast between the deforming speckled pattern and the rest of the material [6]. When performing DIC on inflatables, current techniques apply a basecoat of white paint to the surface of the fabric [3] on which the speckled pattern is then added. This basecoat is important to ensure the dot pattern added to the surface of the inflatable does not wick into the fabric and cause dot variation that may affect the analysis. From preliminary experimentation it was determined that dots created using oil-based paint pens do not wick into the fabric and thus, will also be examined during testing to evaluate if a white basecoat is required for increasing the analysis accuracy.

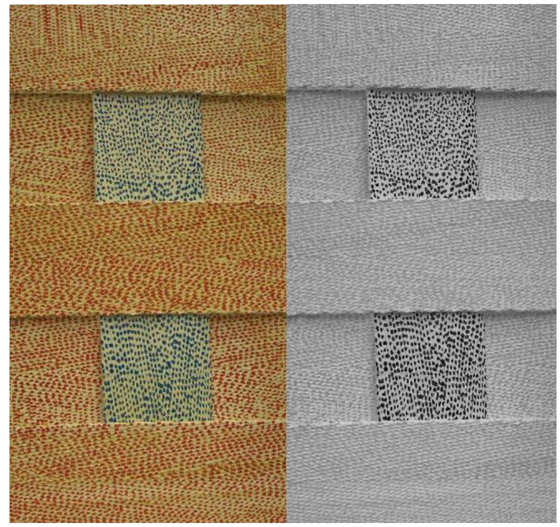
It is also imperative to evaluate the accuracy of measured strain for both fine and coarse dot patterns, as producing speckled patterns is currently one of the most time-consuming parts of preparing a large inflatable for testing when using photogrammetry. The dots are created on each test article by hand using an oil-based marker. If a coarse dot pattern can be used it could significantly decrease the amount of time spent preparing the straps of an inflatable module prior to burst testing.

## III. Results and Discussion

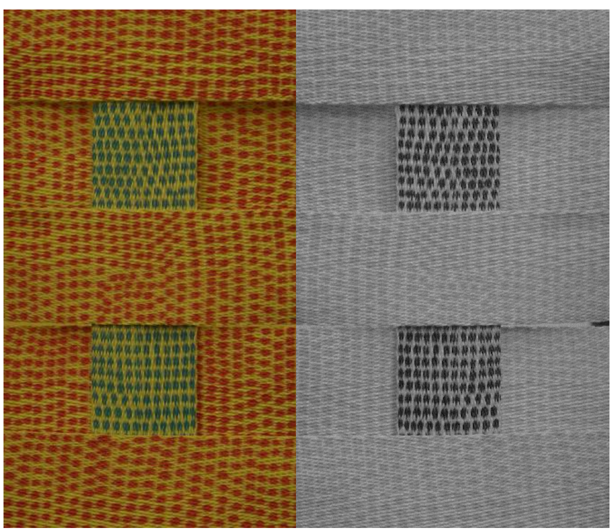
Tensile testing was performed at NASA Johnson Space Center's Structural Test Lab at a rate of 1 in/min, to a load of 4,000 lbf (50% of the ultimate strength of the Kevlar strap material used for this test), collecting photogrammetry data at a rate of 1 Hz. To improve results, the noise floor during each test was evaluated to ensure the measured strain remained accurate. From this assessment, each test experienced an error of less than ±100 micro-strain, indicating the measured data remained accurate and consistent throughout the test series. After testing, sample images at the start of each test were investigated to demonstrate the system's color filtering capabilities and the red pigment was removed. Results for each test are presented in Fig. 4. Evaluating the filtered images, the dot pattern on the tensile strap could be isolated from the static interfacing straps for all samples. Additionally, the filtering capabilities appear nearly identical for each sample with and without a white basecoat. Such results indicate that a white basecoat is not required to develop sufficient contrast for analysis, assuming the strap was sufficiently lit by external lighting.



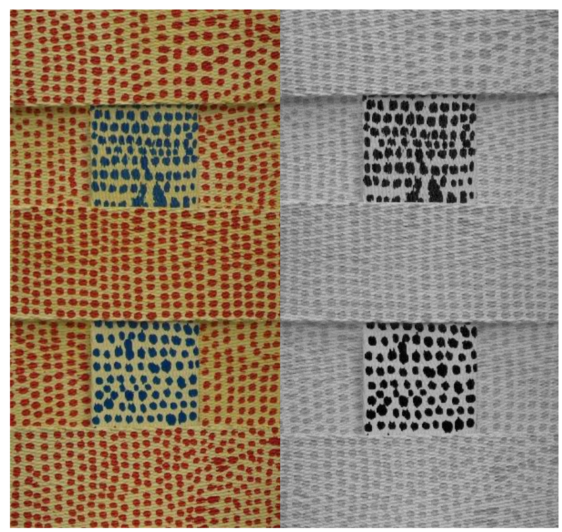
(a) Fine Dots – No White Basecoat



(b) Fine Dots – White Basecoat



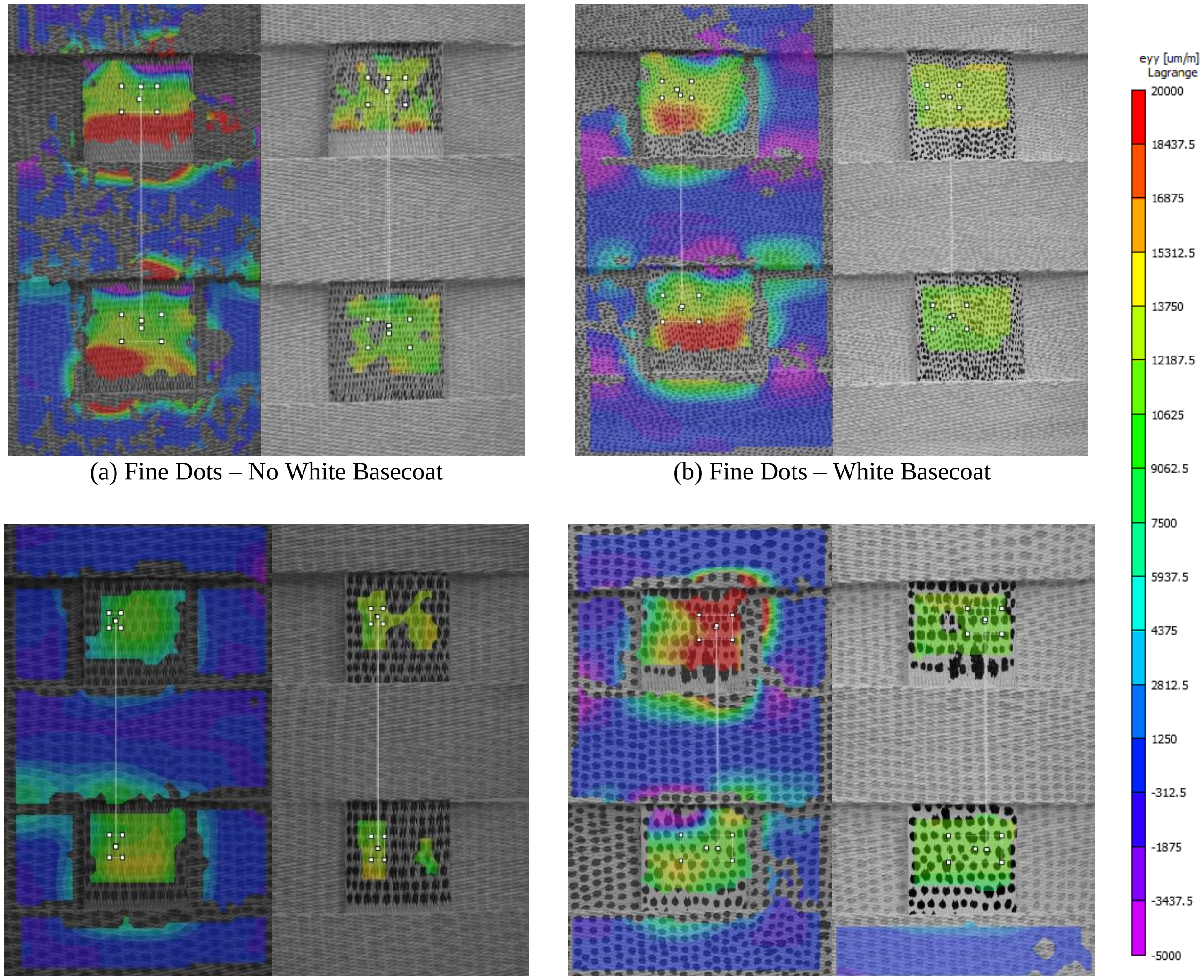
(c) Coarse Dots – No White Basecoat



(d) Coarse Dots – White Basecoat

**Fig. 4 Strap RGB Filtering.**

After the images were filtered, VIC-3D was used to perform DIC analysis and the strain in the direction of the applied load for each case was evaluated. The measured strain fields while the strap experienced maximum applied loads are illustrated in Fig. 5. Considering the monochrome DIC for each test, it is evident that the interfacing orthogonal straps have a significant effect on the areas of interest. This effect is demonstrated by the unrealistic hotspots present in the areas of interest and can result in inaccurate strain data extraction. Such hotspots, indicated by red areas, are caused by the analysis software considering the analyzed region as a solid surface and incorrectly representing deformations much larger than those present during testing. Using the RGB filtered method for each test, these unrealistic hotspots are eliminated, and a consistent region of strain is observed across the entire area of interest. The elimination of false hotspots is extremely important as it will allow for the observation of actual hotspots that may be present and produce a more accurate representation of how the strain varies along the areas of interest. It is also relevant to mention that, for the coarse dots with a white basecoat, shown in Fig. 5a, the orthogonal static strap fell within the matchability threshold but did not affect the areas of interest or produce any hotspots. This anomaly is likely due to the color mismatch between the applied red dots and ideal computer-generated primary color for red used during the filtering process. This effect is more prevalent on larger dots due to the increased area of variation that may occur due to light reflection and may be mitigated by applying dots that closely match ideal primary colors or through the use of additional coatings and lighting conditions that minimize reflection.




(a) Fine Dots – No White Basecoat

(b) Fine Dots – White Basecoat

(c) Coarse Dots – No White Basecoat

(d) Coarse Dots – White Basecoat

**Fig. 5 Lagrange Strain Analysis Results.**

Comparing the results of RGB filtering with and without a white basecoat we must first consider how VIC-3D tracks the applied patterns. During analysis, the pattern consistency is compared to neighboring dots and a statistical confidence is used to evaluate the variance between each image [7]. Tracked patterns that fall outside the consistency threshold and confidence margin are omitted from the measured strain field. Considering the results where no white basecoat was applied, Fig. 5a and Fig. Fig. 5c, a significant portion of data is lost. This loss of data is likely due to two factors: the quality of the applied dots, as well as the local dot pattern breakdown caused by local shifting of fibers while under tension. This omission of data is especially evident for coarse dots, where the effect of fiber shifting is more prevalent. Considering the results where a white basecoat is applied, Fig. 5b and Fig. Fig. 5d, the loss of data is minimal.

While RGB filtered DIC can produce more consistent results across the entire area of interest, a trained technician can ignore false hotspots and extract relevant strain data using only monochrome DIC, however it is time consuming. For the results presented in this study, strain data was extracted from within the areas of interest that produced the lowest data variation in the direction of strain. From this method, reliable strain data can be collected from VIC-3D for biaxial woven softgoods architectures more efficiently than via the use of typical monochrome DIC. The measured strain during the load profile beginning at 0 lbf, loading to 4000 lbf, and decreasing the load back to 0 lbf is illustrated for each test case in Fig. 6, comparing the strain obtained from traditional monochrome DIC and the novel RGB filtered DIC method. Considering the case of coarse dots with a white basecoat, a significant variation in measured strain is observed when analyzing a large region. This large variation is due to the significant hot spot error that occurred during analysis, which can be corrected using the RGB filtering method. It is important to note that similar results can be achieved by manually decreasing the size of the analysis region to that of the areas of interest. While this method has been proven effective in prior testing, analysis can become very time extensive for large, complex inflatable structures.

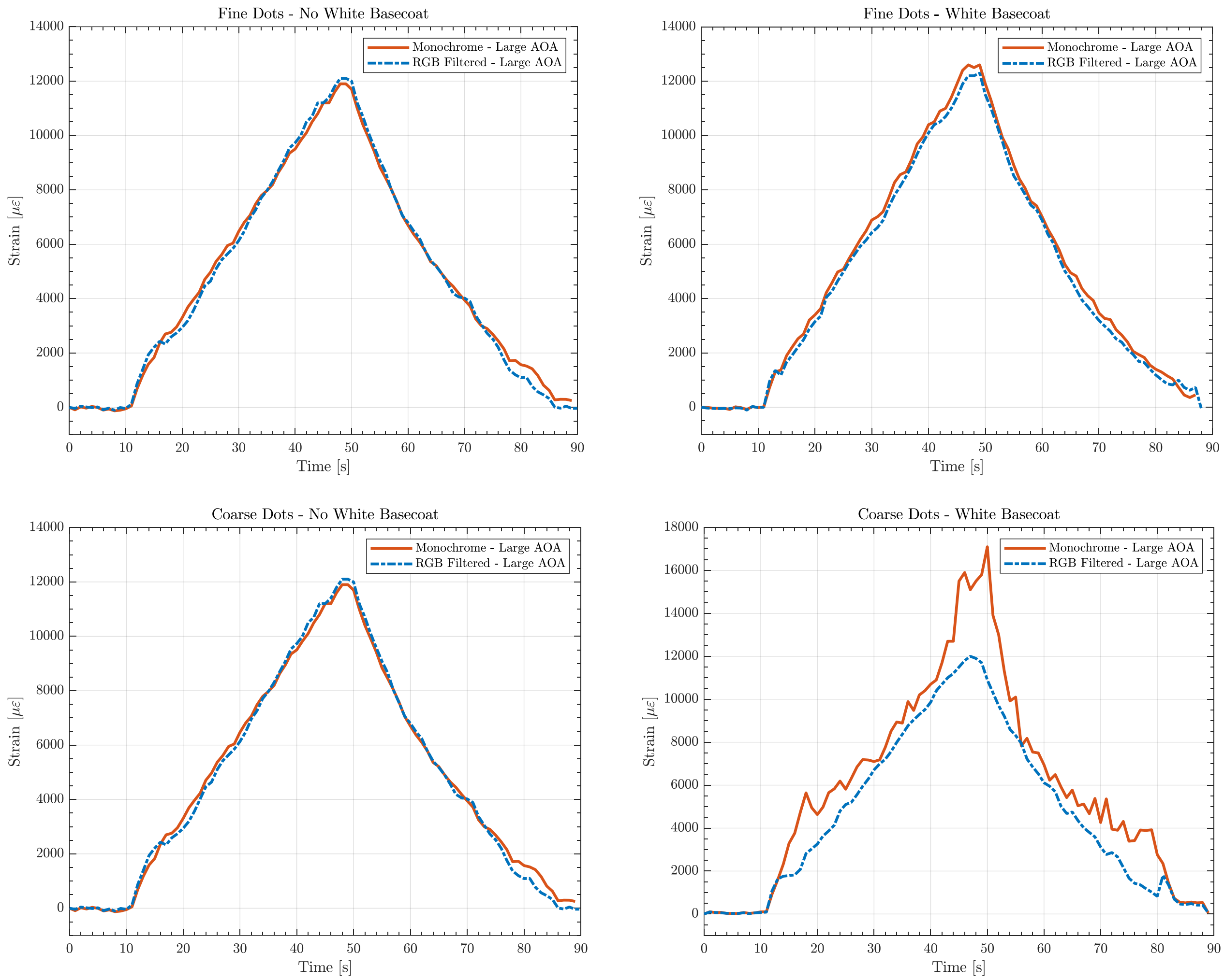



**Fig. 6 Monochrome and RGB DIC Strain Comparison**

## IV. Conclusion

In summary, the reported tests successfully demonstrated the use of RGB color filtering in conjunction with DIC to evaluate a single direction of strain on a bi-directionally woven test specimen. RGB color filtering yielded well-contrasted images that were analyzed using VIC-3D, demonstrating improved strain field accuracy compared to monochrome DIC. Notably, the implementation of RGB filtering allowed for the selection of a larger area of interest that resulted in minimal influence from orthogonal straps, streamlining the analysis process, which would significantly reduce the time needed to analyze a large structure. Regarding error, the average noise-floor for each test was less than ±100 micro-strain, indicating that the measured data remained accurate and consistent for each test. It was also shown that a white basecoat significantly reduced the amount of data loss due to the consistency threshold and confidence margin applied during analysis, but no substantial differences were observed between fine and coarse dot sizes on the strap level.

While this novel DIC approach shows promise for analyzing bi-axially woven materials, it is clear that further testing is needed to validate the scalability and reliability of this approach. Other considerations required for this method include the need for color cameras and a colored speckle application method. Future investigations should encompass replicating the experiment on a bi-axial testing machine, increasing the quantity of areas of interest, and evaluating the method's performance on a cylindrical structure. Additionally, exploratory studies may be conducted to ascertain the method's applicability to other structures where strain isolation is a key consideration.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