Application of Image based technique in Qualification Testing of Spacecraft Structures & Components.


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ABSTRACT

Keywords: Structural Health Monitoring, Data evaluation and Image processing.

Several image based techniques are employed to ascertain strength, process quality, and dimensional stability of spacecraft components. Details of efforts, in using specifically technique of Digital Image Correlation, for Spacecraft structure and components are given here. To visualize strain distribution at selected small areas of Composite cylinder during static load tests DIC was used. The distribution gave insight into the uncertainty of strain gauge measurements due to its location on the honeycomb cell; whether it is on the cell wall or in the middle of the cell. Also presented in the paper is image data analysis to extract information of interest such as strain distribution around structural cutouts introduced by design to accommodate plumb lines, harness or even test load application elements. A case study of measurement of large strains on a propellant tank is presented. Effect of speckle pattern, sub set size selection is discussed.

1. Introduction

Digital Image Correlation (DIC) is commonly used technique to perform full field strain measurements. In practice a carefully composed ‘speckle pattern’ is applied on the specimen and camera images are taken first in the undeformed stage, which is the reference and then in various deformed states. The technique consists of comparing the image of deformed pattern with reference image and determining the displacements of the ‘subsets’. The software eliminates rigid rotations of the subset before determining the strain field.

This technique was originally designed for large-strain measurements and as such, it works very well when large strains are present, but when determining small strain fields, especially in combination with large (rigid body) deformations or large strain gradients, this technique becomes a lot more sensitive to the boundary conditions of the experimental setup and the speckle pattern [1].

In this paper, studies done on capturing strains during various types of strain measurement viz. strain gradients, large strains etc are presented. Efforts made in implementation of proper speckle pattern (speckle size, density) for accurate measurement. Issues involved in picking up Strain gradient around holes, cut-outs were studied.

Specifically the following case studies have been presented:

- Accurate measurement of surface strains due to Static loading to visualize strain distribution at selected small areas of CFRP cylinder due to Static loading on static test rig.
- CFRP honeycomb sandwich coupon variations absorbed in honeycomb cell walls and cell centre.
- DIC measurement was made on Aluminum Interface ring.
• CFRP and Aluminum Honeycomb sandwich coupons with circular cut-out are static loaded and results were presented. An attempt is made to establish correlation between Strain gauge Data and strain measured by DIC system.
• DIC measurement was made on propellant tank, while Proof pressure loading.

2. Large Strain Gradient Measurements

2.1 Short Cylinder under Compression loading

Any new design of CFRP layup of the cylinder involves a static load qualification. Prior to fabrication of full size thrust cylinder, a cylinder of shorter height but identical diameter and layups is fabricated and loaded on a test rig. During such a test, the test article is instrumented with many strain gauges, displacement transducers to study behavior of the cylinder.

2.2 Experimental results

The images were acquired using a digital camera having a resolution of 5 Mega pixels. Continuous illumination was provided using LED lamps ensuring a reasonably uniform illumination without any heating of test specimen. Fig.1 shows DIC experimental setup used on the short cylinder. Camera was placed at a distance of half a meter from the specimen and images were recorded continuously. The images were later analyzed using digital image correlation software, VIC-3D to obtain strain fields. An important advantage of the method is the whole field nature of the measurement data, providing quantitative evidence of important features such as strain localization during the loading process.

Fig 1: shows DIC experimental setup used on the short cylinder

Fig 2: Strain field (eyy, loading direction strain) in composite cylinder

Since the composite cylinder is black in colour, random white colour speckle pattern was applied on the component. Compression load 50 ton was applied on the composite cylinder.
Loading sequence was 0-25-50-25-0 ton. DIC Measurement image on Composite Cylinder at 50 ton compressive load was shown in Fig. 2.

2.3 Honeycomb sandwich coupon

Random speckle pattern was applied on Honeycomb sandwich coupon and strain gauge also mounted on it. A small load of 25 Kg of compression was applied on the coupon. DIC measurement and Strain gauge monitoring was done simultaneously. Variation in the strain gradients was absorbed in the cell centre and edges, which is shown in Fig. 3a. A strain gradient along the vertical line drawn on the coupon is shown in Fig. 3b. Maximum Strain measured in Strain gauges was -245 micro strains and corresponding DIC measurement was -250 micro strains. The measured strain reading shows a good correlation between the Strain gauge and DIC measurements.

2.4 DIC measurement was made on Aluminum Interface ring.

DIC measurement was made on Aluminum Interface ring. First white paint was coated on the interface ring; later black random speckles were sprayed over it. Compression load 50 ton was applied on the Interface Ring. Loading sequence was 0-25-50-25-0 ton. DIC measurement Image is shown in Fig. 4. Strain values at top, middle and bottom locations are shown in Table 1. The DIC measured strain reading shows a good agreement with FEM analysis results.
2.5 **Honey comb sandwich plate with a circular cut-out.**

A CFRP sandwich panel with aluminum honeycomb core with a hole is prepared. This coupon is tested with 500 Kgf load for getting strain gradient around the Circular cut-out. For getting strain gradient different optics and speckle pattern has been tried. Images were recorded and analyzed.

<table>
<thead>
<tr>
<th>Load in Ton</th>
<th>Strain Y-Top</th>
<th>Strain Y-Middle</th>
<th>Strain Y-Bottom</th>
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<tr>
<td>0</td>
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<td>-129</td>
<td>-29</td>
</tr>
</tbody>
</table>

Table 1: Strain values at top, middle and bottom locations on Interface Ring.

**Fig 6a:** Strain measurement using VIC 2D

**Fig 6b:** Data correlation along cutout with fill boundary extrapolation

**Fig 5a:** strain \((e_{yy})\) variation along cutout

**Fig 5b:** Comparison of strain with FEM data

**Fig 4:** DIC Image on the Aluminum Interface Ring

**Fig 5:** Table 1: Strain values at top, middle and bottom locations on Interface Ring

**Fig 6:** Strain measurement using VIC 2D
The fabricated test coupons are tested in a UTM to study the strain distribution with DIC. Speckle pattern on the surface of test coupons is done by using Acrylic paints for Digital image correlation. Test coupons with speckle pattern are mounted to the UTM with the help of loading fixtures and the test is conducted by applying tensile load. The images are taken at regular intervals while loading and post processing of the images is done.

The graphs are plotted for strain distribution at cut-out section for results obtained from both FEM and DIC technique. While comparing it is found fairly good agreement between FEM and DIC technique results (Fig 5a & b). Selection of subset size affects the data correlation. Smaller the subset better is the spatial resolution but decorrelation chances are more. So a trade off is required. Hence to have data correlation and strain value near cut-out edge many subset sizes were tried and shown in Fig. 7 iteratively with a starting value as suggested by the DIC software itself. In the range of 29 x29 to 75 x 75, it was found smaller subset resulted in some of the area not being correlated, while with higher subset area near cut-out edge was not correlated. To overcome this situation different optics and different patterns have been tried. The lack of measurement at edge of holes or cut outs was recognized. For 2D measurements, the data is extrapolated up to edge of holes /cut-outs (Fig 6a & b).

![Various subset sizes for correlation at the edge of the cut-out](image)

Fig 7 Various subset sizes for correlation at the edge of the cut-out

### 2.6 Large strain monitoring during Proof pressure testing on RLV tank.

Propellant tanks are by design thin walled structures meant for carrying pressures in the order of 35 bars. During handling of the tank, a small strain concentration zone had developed and a need for pressurisation test arose. DIC technique was used to monitor in real time the strain build-up around the local area of interest (AOI) is shown in the Fig.8. Proof pressure test was conducted on the tank and Strain monitoring during multiple pressure cycles was done on the
Mounting of strain gauge was not possible in that area. The AOI was painted with white paint and random black speckles pattern was sprayed over the white paint area. 15 cycles of pressurization was done on the propellant tank. The highest strain noticed was around 7600 micro strains and DIC images for 1st cycle was shown in Fig. 9. Strain measurements were correlated with FE analysis. Both test and analysis strain data showed similar strain distribution.

Fig 8: Strain monitoring on RLV tank proof pressure testing (35 bars MEOP)

Figure 9: DIC image pattern of the Propellant tank at 35 bar

3. Results & Discussion

The case studies have provided valuable inputs for future measurements and have exposed some of the limitations in the DIC technique. The finite size of the subset prevents measurement of the strain value at the highest stress concentration points. An estimator for linearly extrapolating the values is required in 3D measurements. The speckle size and density of the pattern need to be so chosen as to be able to select a small subset without encountering de-correlation problem. To some extent proper choice of optical lens with a larger focal length and larger aperture number helps in zooming on to smaller region on the component[2]. A good Variations of Strain across honeycomb cell walls and cell centre was captured. Large strain measurements of the order of 7600 micro strains as encountered in the propellant tank case called for a speckle pattern of lower
density and larger speckle size. Issues arising during measurement of large strain gradients, large strains, are handled by speckle pattern.

4. Conclusions

During the course of implementation of DIC for structural components the following objectives have been achieved.

- Gradients around Stress concentration zone.
  - Circular cut-out in a sandwich plate
- Large strain monitoring.
  - Proof pressure testing on RLV tank.
- During the implementation effect on uncertainty:
  - Pattern speckle size and density
  - Selection of subset size and step size for image processing.

The DIC technique has been used in a variety of situations presenting unique measurement challenges. The curvature of short cylinder was addressed by limiting the field of view to overcome depth-of-field problems of optics. In situations of picking up strain gradients around structural cut-outs, need for selecting subset size and optics was addressed. The lack of measurement at edge of holes or cut outs was recognized. For 2D measurements, the data is extrapolated up to edge of holes /cut-outs. Speckle size and density of pattern used for large strains as in the case of propellant tanks was adequate to capture the strain field reliably.

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6. References.

[1] Image correlation for shape, motion, and deformation measurement : Basic concept, theory and applications by Michael A Sutton, Jean-Jose Orteu & Hubert W. Schreier