Correlated Solutions Inc VIC-3D, 3D - Digital Image Correlation

For Non Contact Full Field Displacement and Strain Measurement

And Modal Analysis.

A Brief Application Note on the Tests Carried out by S. Raviprakash – Pyrodynamics

At Various Organisations in India using VIC-3D, 3D DIC System.

S. Raviprakash
MD & CEO
PYRODYNAMICS
Plot No 272
KIADB Industrial Area Phase 2
Harohalli; Taluka Kanakpura
Dist. Ramanagaram
Bengaluru Rural - 562 112
Karnataka State – India

Tel:- +91 9686428833
Email:- pyrodynamics@gmail.com

Web:- www.pyrodynamics-india.com
Facebook:- Pyrodynamics
DIC Measures Displacements.

Strain is a Derivative of Displacement. Lagrange Strain tensor is used for calculation of Strains

Calculation of strains:

\[ \varepsilon_x = \frac{\partial u}{\partial x}, \quad \varepsilon_y = \frac{\partial v}{\partial y}, \]

\[ \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \]
Two Firewire Camera interfaced to the Fire Wire Ports of the PC.

VIC-3D

Results Obtained from 3D Digital Image Correlation

Contour Co Ordinates: - X, Y and Z ; Displacement: - u, v and w.

Strains: - $\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{xy}$, $\varepsilon_1$, $\varepsilon_2$, Von Mises, Tresca

and Directions of Principal Strains
The VIC-3D Digital Image Correlation Measurement System
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<tr>
<th>Experiment</th>
<th>Fracture Process Zones in Concrete Structures</th>
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Experimental Set up.

Structures Laboratory

Department of Civil Engineering.
Experimental Set up.

- Concrete Coarse Aggregate Size: 20 mm.
- No of Reinforced Bars = 4

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ø (mm)</th>
<th>n</th>
<th>A&lt;sub&gt;s&lt;/sub&gt; (mm²)</th>
<th>S (mm)</th>
<th>L (mm)</th>
<th>W&lt;sub&gt;f&lt;/sub&gt; (mm)</th>
<th>D (mm)</th>
<th>b&lt;sub&gt;rib&lt;/sub&gt; (mm)</th>
<th>d&lt;sub&gt;rib&lt;/sub&gt; (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBF1</td>
<td>20</td>
<td>4</td>
<td>1256</td>
<td>2600</td>
<td>3200</td>
<td>500</td>
<td>560</td>
<td>180</td>
<td>380</td>
</tr>
</tbody>
</table>
Measurement Set Up

- 3D DIC Measurements carried out at the mid span of the beam (1425mm to 1775mm) using VIC-3D-RT, Real Time 3D DIC System.

- AOI: 350 mm x 100 mm in the web and 350 mm X 253 mm in the flange.

- Camera: Two point grey flea2 (1624x 1224 Pixels, 15 fps) firewire 1394b with Schneider 17mm lenses.

- Image Captured every 10 seconds.

- Calibration Grid: 12x9x25 grid with a grid spacing of 25mm

- Subset: 75 X 75 Pixels.

- Electrical Resistance Strain Gage Bonded on the reinforced bar at the mid section of the beam.

- LVDT to measure Displacement mounted at the underside of the mid section of the beam.
The loading protocol was to simulate ambient traffic between simulated test trucks (TT).

In a real-world situation, it is required to collect moving vehicles data for designing the various structural members in a bridge.

A real bridge would have experienced many smaller service loads as well as maybe some isolated unknown higher overloads.

In this present study a series of service-level cycles are applied in between test trucks. These test trucks were chosen to represent the case of structural load testing in the field. TTs were variable in magnitude.

Loading Method: Load Control – 3 Point Bending.

Number of Loading Phases : - 7
Total Number of Load Cycles : - 70
Rate of Loading : - 4kN/sec.
Ultimate Failure Load : - 810 kN.
- Crack observed in the Sixth Phase at peak load of 670 kN.
- Beam Failed at 810 kN.
Image no 552 at the peak Load of phase 7 of the Loading cycle.

Image no 553 - just after the load crossed phase 7 - Specimen cracked at this Load.

Final image – DIC Image No 1230.

- The Flange and web are at a different distance from the cameras. The Flange had a smaller speckle size compared to the web. The camera was focused on the web and since the flange had a smaller speckle it was in focus as well
Phase 1 – 180 kN

Phase 2 – 200 kN
Phase 3 – 300 kN
Phase 4 – 450 kN

Phase 5 – 500 kN
Phase 6 – 570 kN
Phase 7 – 800 kN

$\varepsilon_{xx}$ Plots at Peak Loads of Different Phases of Loading.

No significant strain gradient was observed in the Flange. Hence the Analysis is concentrated in the Web Region.
Time Vs Strain in the High Strain Zone

- 0  DIC virtual strain gauge R0
- 1  DIC virtual strain gauge R1
- 2  DIC virtual strain gauge R2

σ_{xx} (µε)

Image Number

0  100  200  300  400  500
Comparison of DIC and Strain Gage Results - $\varepsilon_{xx}$ At the Mid Section of the Beam
Profile of Strain in the high Strain Zones

Very Good Linearity observed in the strain field at Peak Loads of Different Phases of Loading.
Full field “V” Displacement plot obtained at Peak Load of 800 KN during Phase 7
<table>
<thead>
<tr>
<th>Load Phase</th>
<th>Peak Load (kN)</th>
<th>Development of Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>180</td>
<td>No</td>
</tr>
<tr>
<td>Phase 2</td>
<td>200</td>
<td>No</td>
</tr>
<tr>
<td>Phase 3</td>
<td>300</td>
<td>No</td>
</tr>
<tr>
<td>Phase 4</td>
<td>450</td>
<td>No</td>
</tr>
<tr>
<td>Phase 5</td>
<td>500</td>
<td>No</td>
</tr>
<tr>
<td>Phase 6</td>
<td>570</td>
<td>The growth of existing cracks was seen in sixth phase at 670 kN.</td>
</tr>
<tr>
<td>Phase 7</td>
<td>800</td>
<td>The cracks opened by 1mm width at 765 kN. Multiple cracks were seen in flange. The supports crushed at 765 kN. The spalling of the concrete was seen at the centre of the beam near the top of flange at 800 kN. The beam failed at 810 kN.</td>
</tr>
<tr>
<td>Load Phase</td>
<td>Phase-I</td>
<td>Phase-II</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>Load cycle peak-load (kN)</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>DIC Image Number</td>
<td>36</td>
<td>78</td>
</tr>
<tr>
<td>Strain in Steel. (µε)</td>
<td>655</td>
<td>733</td>
</tr>
<tr>
<td>Strain in Concrete -DIC (µε)</td>
<td>396</td>
<td>347</td>
</tr>
<tr>
<td>Displacement “V” (DIC – mm)</td>
<td>1.78</td>
<td>2.06</td>
</tr>
<tr>
<td>Displacement – LVDT (mm)</td>
<td>1.54</td>
<td>1.69</td>
</tr>
<tr>
<td>Displacement “W” (DIC – mm)</td>
<td>0.63936</td>
<td>0.98617</td>
</tr>
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</table>
Crack Profiling

High Strain Zones indicated by DIC

s1, s2, s3, s5, s6 & s8 are the AE sensor location

Scale: 1:25
Observations

- High Strain Zones were observed during the fifth phase of the loading cycle. The structure fractured precisely at these zones.

- The growth of cracks was observed in sixth phase at 670 kN.

- The cracks opened by nearly 1mm width at 765 kN.

- Multiple cracks were developed in flange & the supports crushed at 765 kN.

- The spalling of the concrete was seen at the center of the beam near the top of flange at 800 kN. The beam failed at 810 kN.

- Crack profiling can be obtained along the entire length of the span using AE technique. Full field strain (or high strain) zones is obtained from DIC technique in the area of measurement which helps in early prediction of the crack that would develop. AE provides global information to identify and confirm the critical locations whereas DIC provides detail local information. A combination of AE technique and DIC techniques is useful in determining the state of damage of large concrete structures in service.
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Experimental Set Up

A speckle pattern was applied on the concrete Beam with a notch under test.

Dimensions of the concrete beam: 750 mm (L) X 190 mm (H) X 95 mm (D)

The Beam had strain gages and Acoustic Emission Sensor mounted on the back side.

The strain gages were interfaced to SCAD 500 Strain Measurement System.

Load: 3 Point Bending.

The Load increased up to 11.46 KN and began to drop. The concrete beam underwent internal cracking at 11.46 KN and this is clearly seen in the strain plots.
$\varepsilon_{xx}$ Plots at Different Loads after Softening

11.46 KN  9 KN  8 KN  7 KN  6 KN
5 KN  4 KN  3 KN  2 KN  1 KN
Profile of $\varepsilon_{xx}$
Experiment: Fracture Process Zones in Concrete Structures


Loading Conditions: Static Load

Camera Used: Point Grey Research Grasshopper 2MP Camera, 15fps

Image Frame Capture: One Image at every discrete load step.
Under load the crack opens in the X Direction
$\varepsilon_{xx} \ (\mu \varepsilon)$
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A speckle pattern was applied on the concrete Beam under test.

Area of Measurement: 300 mm (L) X 750 mm (H)
The Beam had strain gages and Acoustic Emission Sensor mounted on the back side.

The load was applied in a UTM and images captured at 30KN, 50KN, 70KN, 90KN and in steps of 10 KN from 90 to 200 KN.

The Beam failed at 200 KN.

A LVDT was mounted at the bottom of the beam and the DIC results matched pretty well with the Displacements measured using the LVDT.

Fracture processing zones indicated by AE sensors and DIC matched pretty well.
Since the concrete beam under load has a downward displacement the DIC shows a negative value.

The Red zone shows a lower displacement.

The Blue Zone shows the highest displacement.

The scale does not have any sign change indicating displacement in one direction.
Internal micro cracking of the concrete beam begins at 30KN.

The Strain Plots at all load steps clearly indicates a strain pattern around the crack initialization.
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<tr>
<th>Experiment</th>
<th>Full Field Strain Measurement on Concrete Columns</th>
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<tr>
<td>Camera Used</td>
<td>Point Grey Research Grasshopper 5MP Camera, 7.5fps</td>
</tr>
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</table>
A concrete column – 600mm long, 225mm Diameter was wrapped with a 7mm thick PVC sheet.

A Speckle pattern was applied on the PVC sheet. 

VIC-3D System was used for measurements. 

Camera: Point Grey 5 MP Firewire Cameras. 

Lenses: 17mm Schneider Lens 

Images were captured every 15 seconds. 

Load Applied: Compressive Load 

Maximum Load: 1260 kN
Displacement Vs Load

Compressive Load (kN) vs Displacement (mm)

- Displacement Plot

- Compression Load Range: 0 to 1200 kN
- Displacement Range: 0 to 4 mm

- Color Scale:
  - Red: -4.26 mm
  - Orange: -3.865 mm
  - Yellow: -3.6675 mm
  - Green: -3.47 mm
  - Blue: -3.075 mm
  - Purple: -2.8775 mm
  - Violet: -2.68 mm
  - Gray: -2.285 mm
  - Light Gray: -2.0875 mm
  - Dark Gray: -1.89 mm
  - Light Blue: -1.6925 mm
  - Blue: -1.495 mm
  - Light Cyan: -1.2975 mm
  - Cyan: -1.1 mm
The concrete column had a shear crack and failed at 1260 kN.

The image taken from the back side of the column shows a discoloration of the PVC sheet indicating a shear crack.

Strain Plot just before complete failure
Load Vs Average Strain in the High Strain Zone

Compressive Load (kN) vs Compressive Strain ($\varepsilon_{yy}$) - Compressive Strain ($\mu\varepsilon$)
Compressive Load was applied on a Concrete Column 800 mm Long, 218mm Diameter.

\( \varepsilon_{yy} \) at Peak Load – 1230 kN

\( \varepsilon_{yy} \) just before failure

Strain Plot shows the propagation of the Fracture Process Zone
A concrete column – 800mm long, 75mm Diameter was wrapped with a 3mm thick GI sheet and was subject to a compressive load.

$\varepsilon_{yy}$ Plot
Average $\varepsilon_{yy}$ in the High Strain Zone Vs Load
List of End Users of VIC-3D/2D Systems In India.

- Indian Institute of Technology – Roorkee – Department of Civil Engineering.
- Indian Institute of Technology – Chennai – Department of Applied Mechanics.
- Indian Institute of Technology – Mumbai – Department of Mechanical Engineering.
- Indian Institute of Technology – Kanpur – 4i Laboratory
- Tata Steel Limited – Tatanagar.
- MRF Tyres Limited - Chennai
- National Aerospace Laboratories – Bengaluru.
- Indian Institute of Technology – Chennai – Department of Aerospace Engineering.
- General Motors Technical Centre – India.
- Indian Institute of Technology – New Delhi – Department of Applied Mechanics.
- GEITC – John Welch Technology Centre – Bengaluru.
- Central Glass and Ceramic Research Institute – Kolkata.
- Indian Institute of Technology – Chennai – Department of Engineering Design.
- Indian Institute of Technology – Hyderabad – Department of Civil Engineering.
- Vikram Sarabhai Space Centre – Thiruvananthapuram.
- Central Glass and Ceramic Research Institute – Kolkata.
- Indian Institute of Science – Bengaluru – Department of Aerospace Engineering.
- Indian Institute of Technology – Hyderabad – Department of Mechanical Engineering.
- GEITC – John Welch Technology Centre – Bengaluru.
- Indian Institute of Technology – Kharagpur - Department of Mechanical Engineering.
- Indian Institute of Technology – Chennai – Department of Applied Mechanics.
- Indian Institute of Science – Bengaluru – Department of Materials Engineering.
- Indian Institute of Technology – Kharagpur – Tribology Laboratory.
- Indian Institute of Technology – Kanpur – Department of Mechanical Engineering.
- Indira Gandhi Centre For Atomic Research – Kalpakkam.
Advantages of Digital Image Correlation

✓ Non Contact and Full Field.

✓ Setup time is less.

✓ Easy to use.

✓ Provides Full Field Displacement & Strain Fields.

✓ Full Field Modal analysis and Full Field Acceleration Measurement.

✓ Strain Resolution of 25 to 50 με or better.

✓ Displacement Resolution: A few Microns to Sub Microns depending on the Field of View.

In Plane Displacement Resolution = 1/100000 of the Field of View.

Out of Plane Displacement Resolution = 1/50000 of the Field of View.

Field of View is defined as the Diagonal Distance of the Area of Interest.
DIC Measurements can be made on any material: Concrete, Metal, Plastics, Composites, Rubber, Human Skin… etc.

Validation of FEM Data can be done easily.

Direct interface to Matlab to Compare DIC and FEM Data.

High Speed DIC and Modal Analysis.

Area of Measurement: mm² to a few m²

Strain Range: Upto 100’s of % Strain.

High Strain Zones easily identified.

Generally 5MP Fire wire or GigE cameras with 5 to 15 fps are used for DIC Measurements.

However the recent trend is to use Cameras with a resolution of 14 to 29 Mega Pixels to carry out Strain Measurements on Large Structures Like Wind Turbine Blades, Wing of Air Craft, Space Craft Shells… etc. This way DIC Measurements are carried out with a good displacement and strain resolutions.
Limitations of DIC

× Optical Access of The Test Object is a must.

✓ Cameras with 2 MP Resolution and frame rates ranging from 60 to 300 fps are Available for Dynamic Measurements.

✓ Recent Trend is to use High Speed Cameras (10,000 fps upwards with 1 MP Resolution) to carry out High Strain Rate, Impact Measurements, Shock Tube Applications, Hopkinson Bar Tests…etc

✓ Recent Trend is that DIC has been successfully used for Non Contact Full Field Modal Analysis

✓ Recent Trend is DIC has been successfully used for measurements of Microscopic Images (In AFM or SEM), MEMS…etc.

✓ The future is to use Volumetric Digital Image Correlation. VDIC has the promise and capability to carry out DIC Measurements insitu of the structure (Something that was carried out so far only through Fiber Optic Sensors).

This technique is still in the University Research and will be commercially available soon.
For More Detailed Information / Demonstration, Please contact us at

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