PYRO DYNAMICS

APPLICATION NOTES
CONCRETE STRUCTURES

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 Pyrodynamics

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

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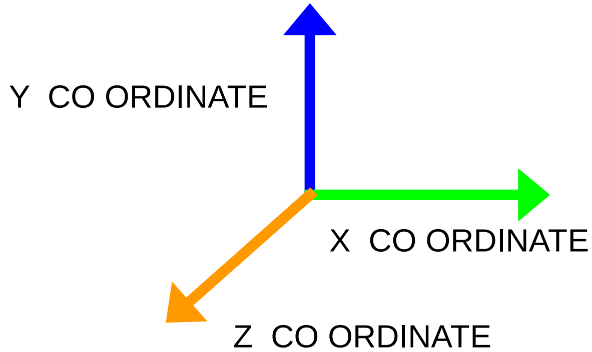
DIC Measures Displacements.

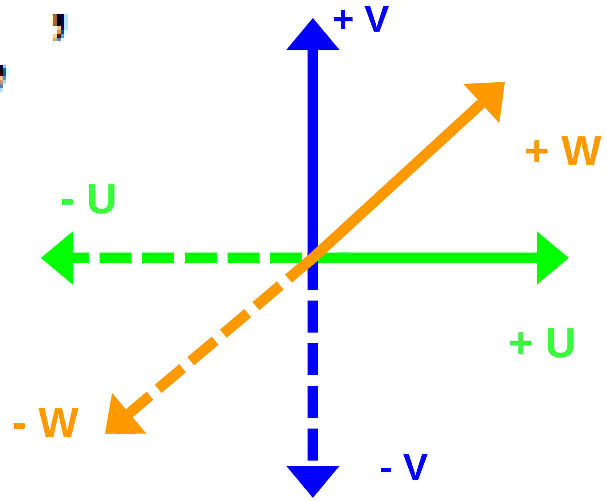
Strain is a Derivative of Displacement. Lagrange Strain tensor is used for calculation of Strains



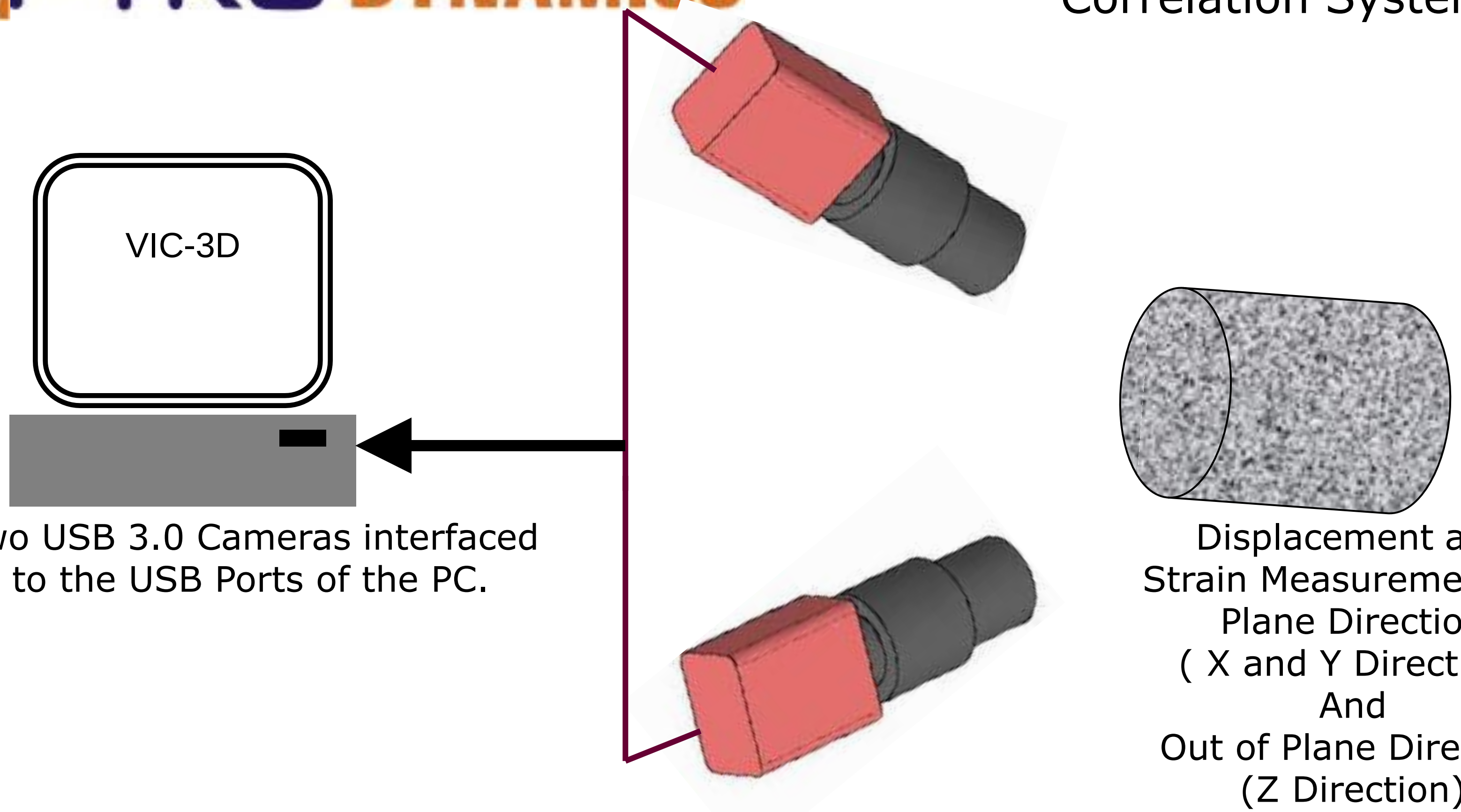
Calculation of strains:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \qquad \varepsilon_y = \frac{\partial v}{\partial y},$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$



VIC- 3D, 3D Digital Image Correlation System.



Results Obtained from 3D Digital Image Correlation

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

Strains:- ε_{xx} , ε_{yy} , ε_{xy} , ε_1 , ε_2 , Von Mises, Tresca

and Directions of Principal Strains

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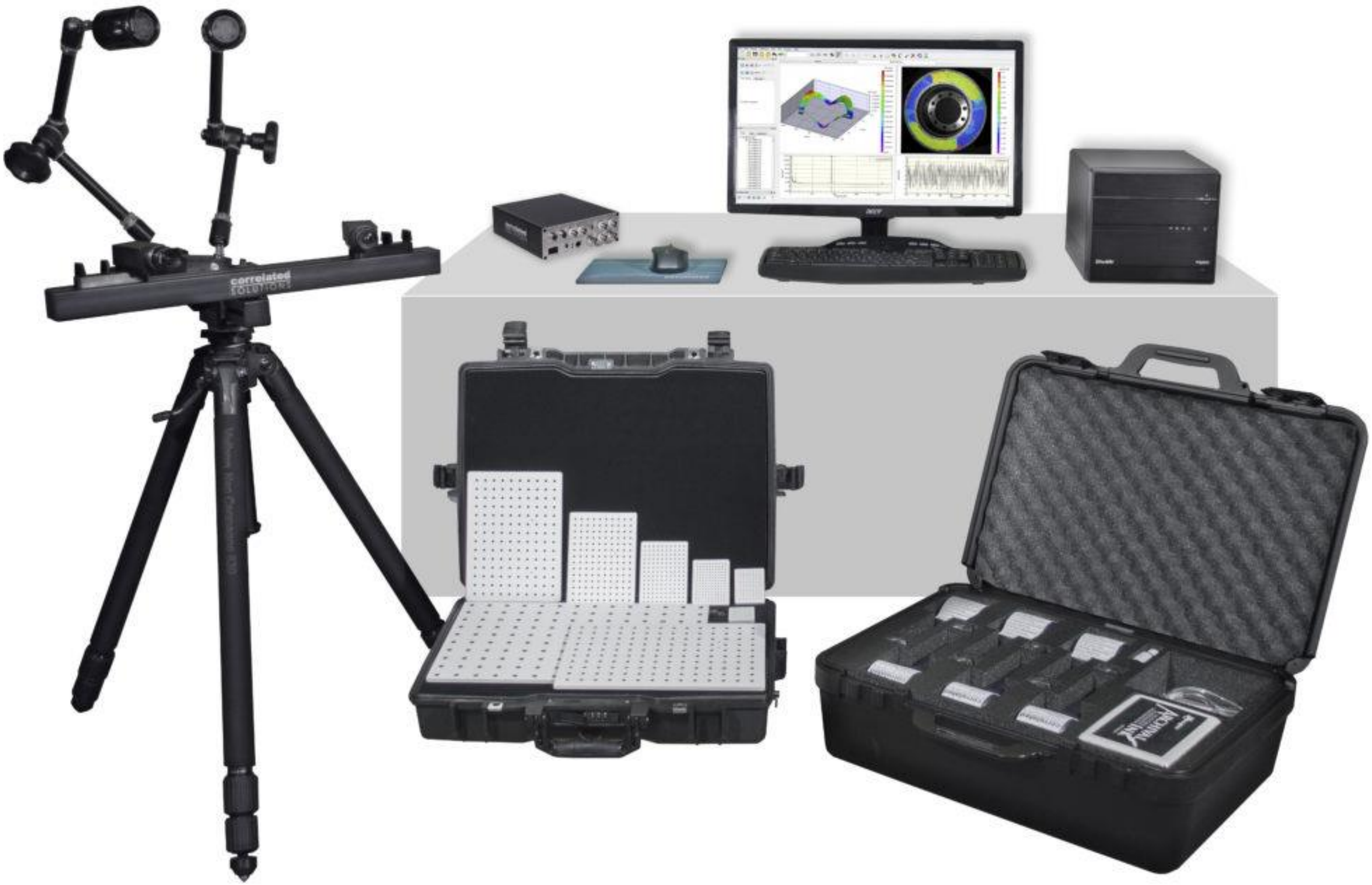
VIC-3D System



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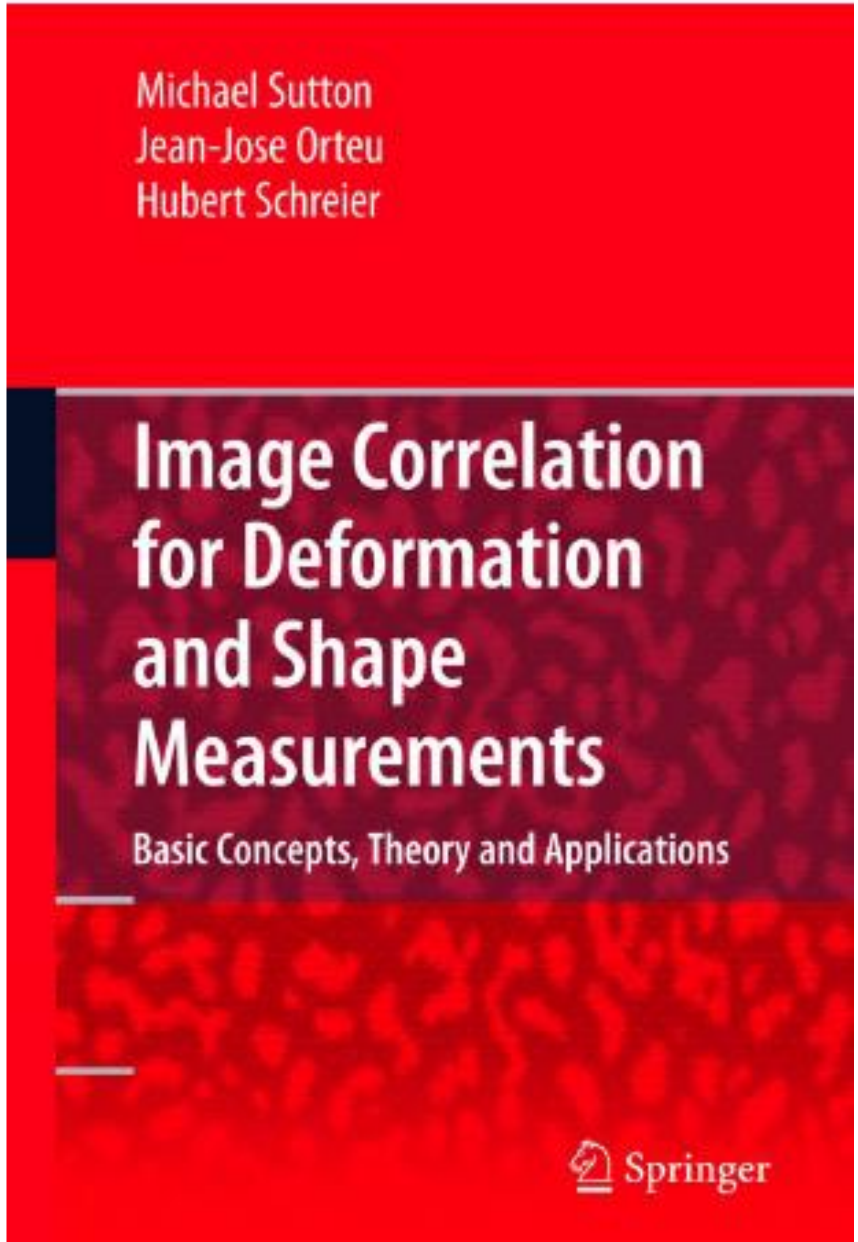

Experiment	Fracture Process Zones in Concrete Structures
System Used	VIC-2D, 2D Digital Image Correlation System.
Loading Conditions	Static Load
Camera Used	Point Grey Research Grasshopper 2MP Camera, 15fps
Image Frame Capture	One Image at every discrete load step.

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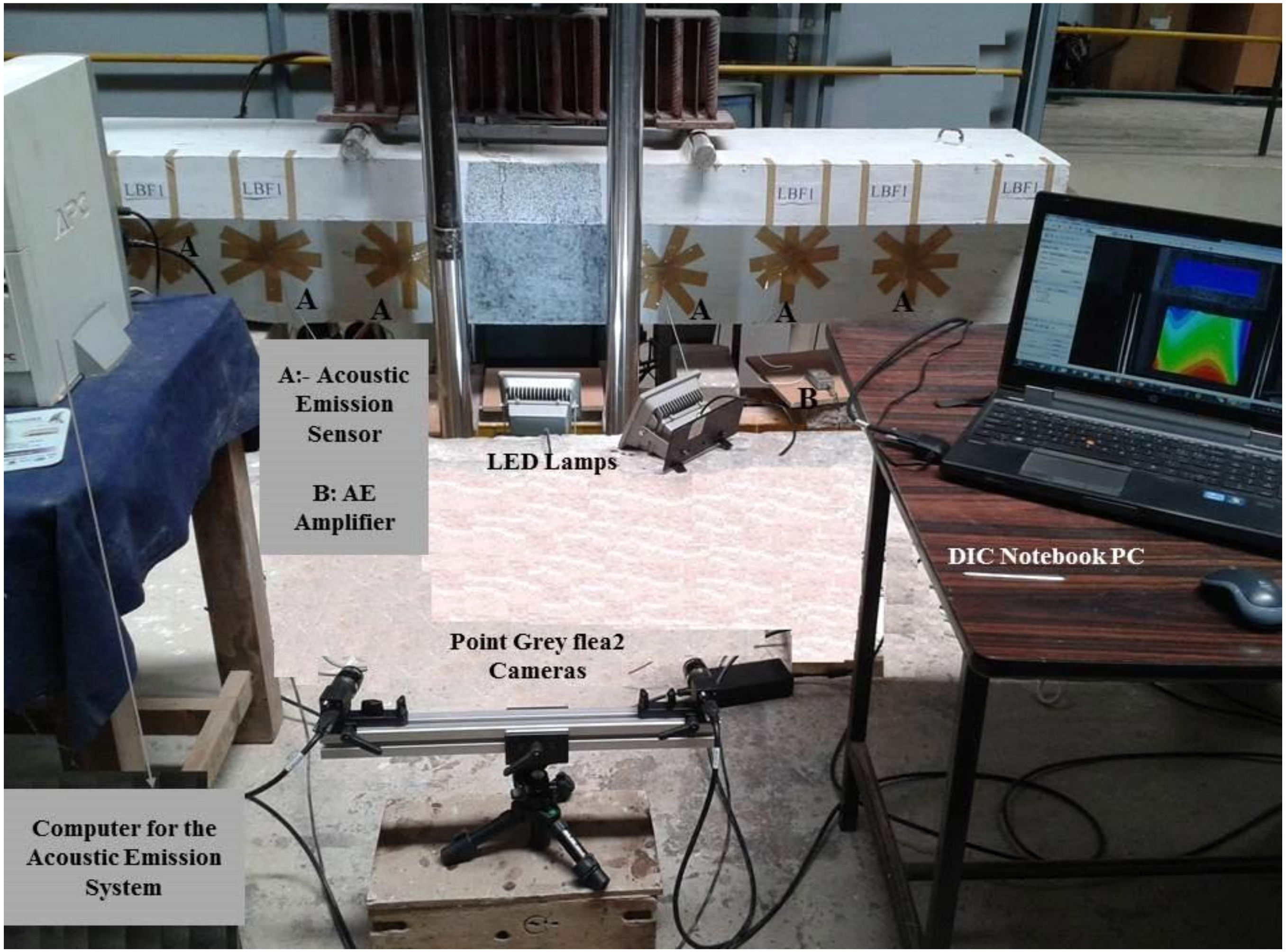
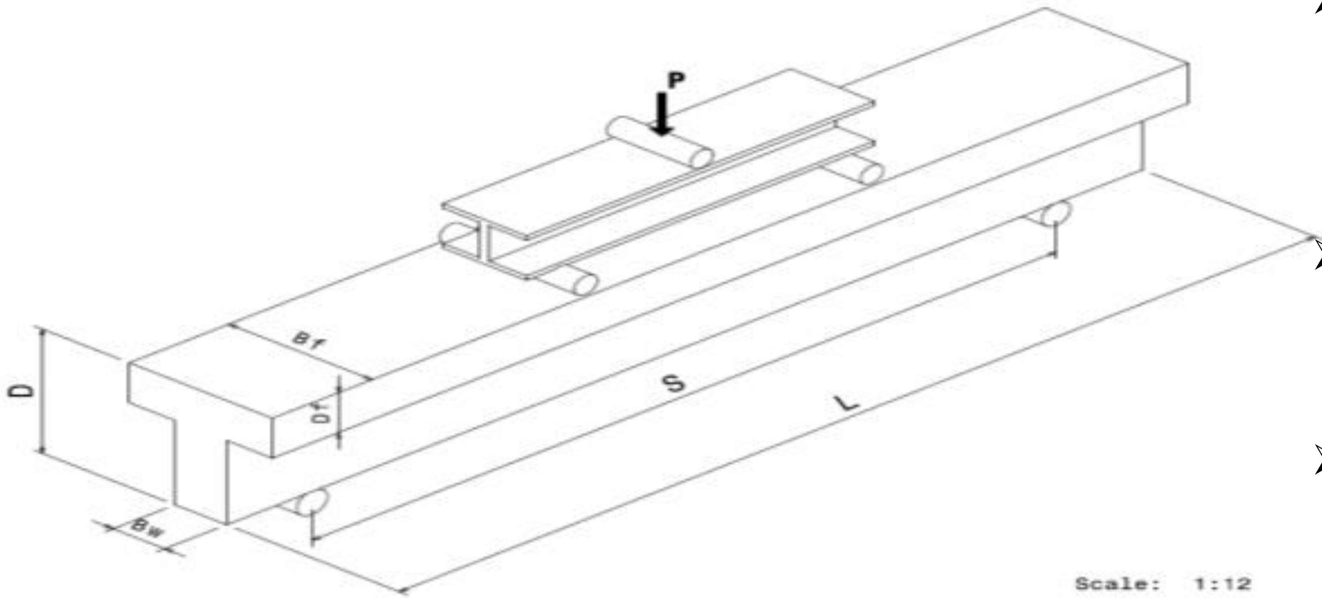
Experimental Set up.

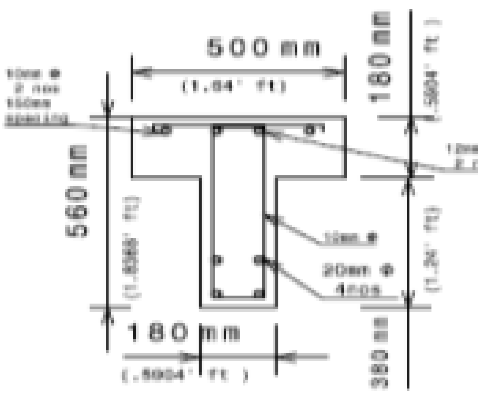
Structures Laboratory

Department of Civil Engineering.



Experimental Set up.





- 28 –Day Compressive Strength of the concrete Mix:- 37MPa.
- Concrete Coarse Aggregate Size:- 20 mm.
- No of Reinforced Bars = 4

Specimen	Ø (mm)	n	A_s (mm^2)	S (mm)	L (mm)	W_f (mm)	D(mm)	b_{rib} (mm)	d_{rib} (mm)
LBF1	20	4	1256	2600	3200	500	560	180	380

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**

Loading Protocol of the RC 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.

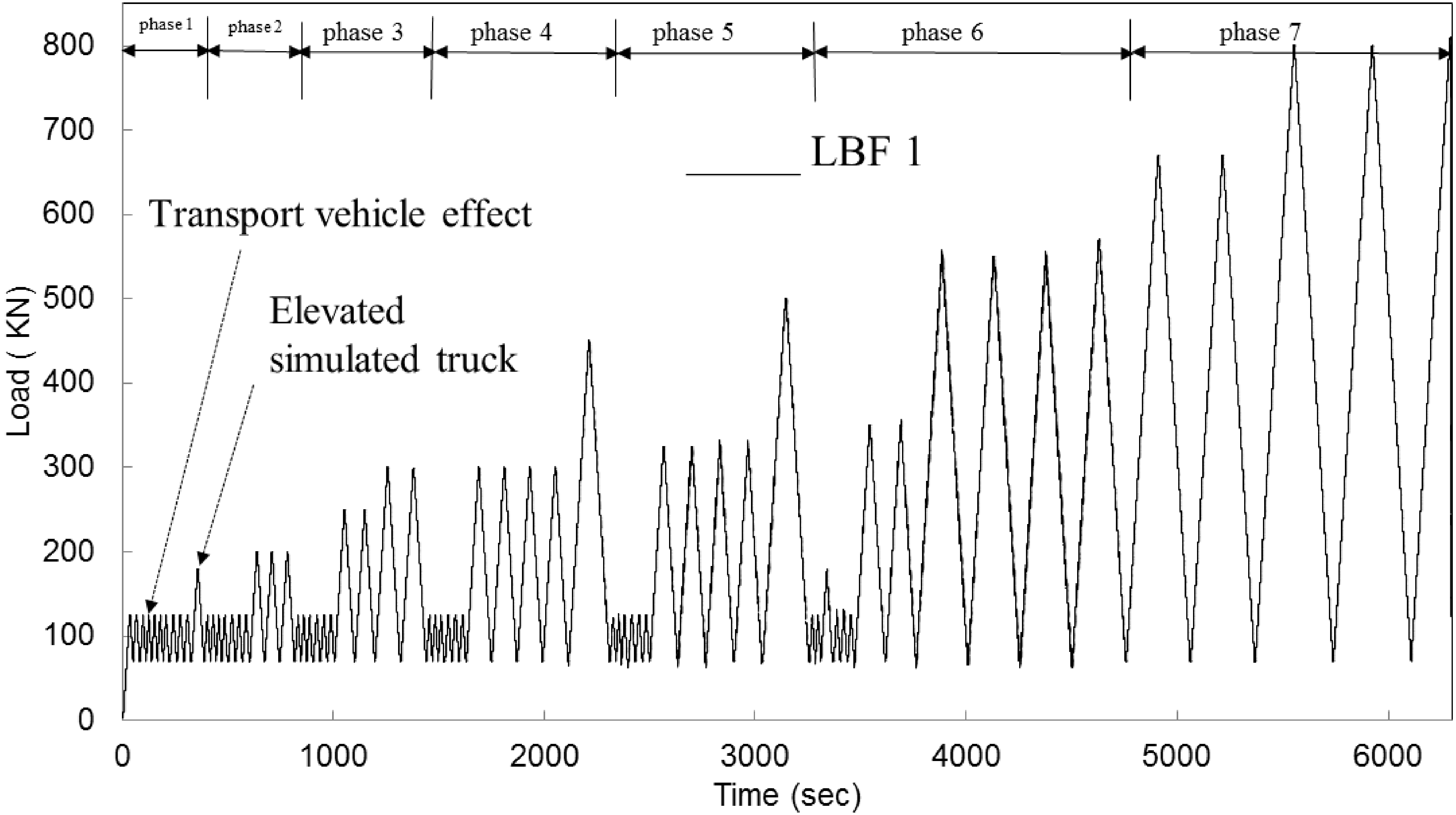
- A real bridge would have experienced many smaller service loads as well as maybe some isolated unknown higher overloads.

- 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.

Loading Protocol of the RC Beam.



- ❑ Crack observed in the Sixth Phase at peak load of 670 kN.
- ❑ Beam Failed at 810 kN.

Speckle Images

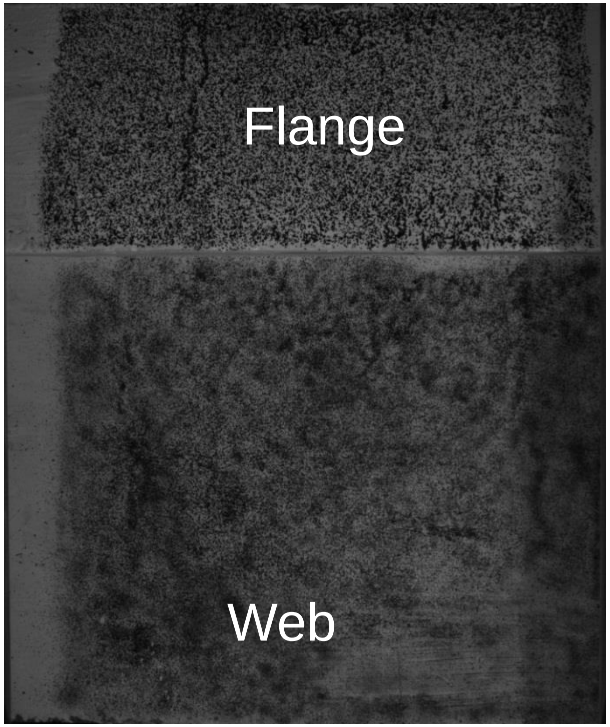


Image no 552 at the peak Load of phase 7 of the Loading cycle.

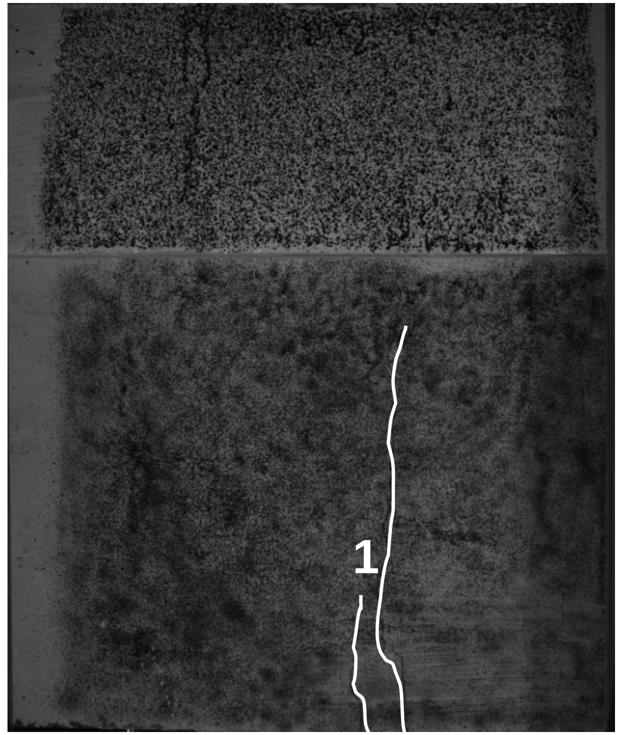
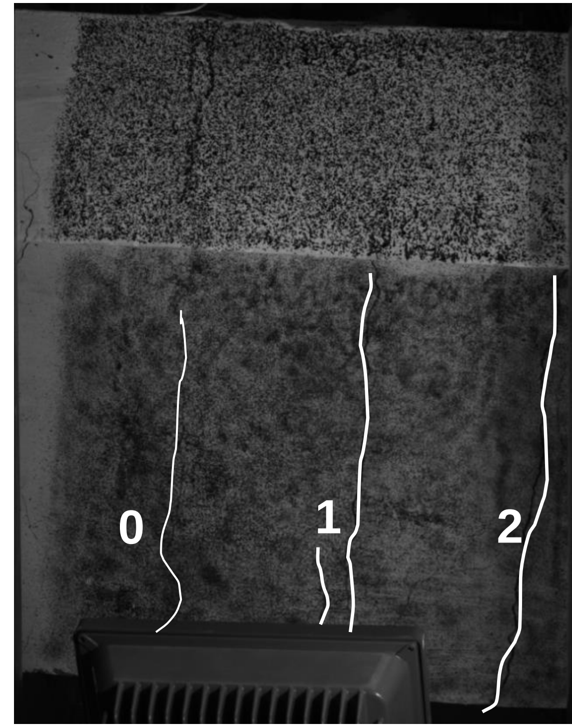


Image no 553 - just after the load crossed phase 7- Specimen cracked at this Load.

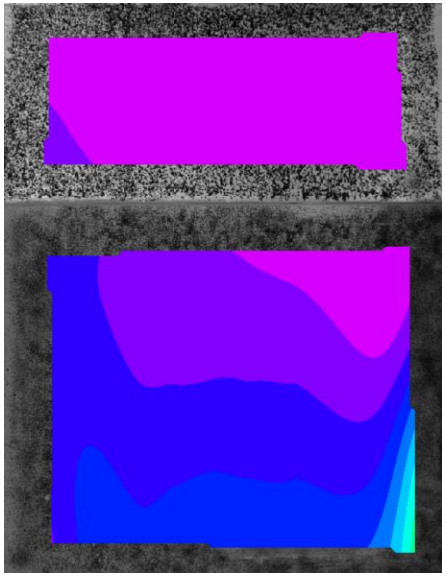


Final image – DIC Image No 1230.

Cracks

- 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

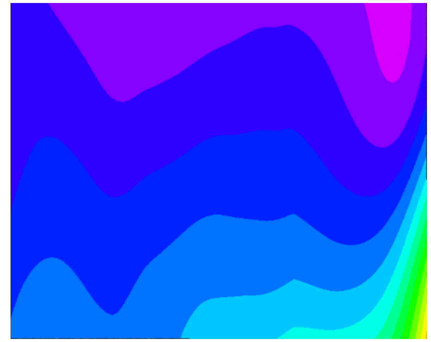
ε_{xx} Plots at Peak Loads of Different Phases of Loading.



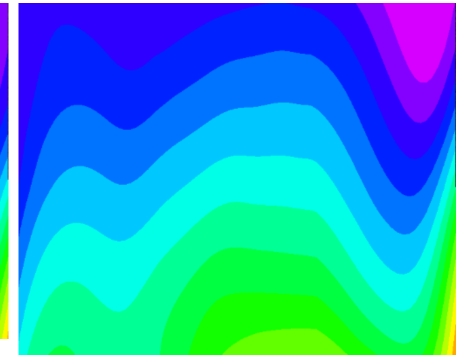
1425 mm 1650mm 1775mm

Phase 1 , 180 kN

Phase 2 – 200 kN

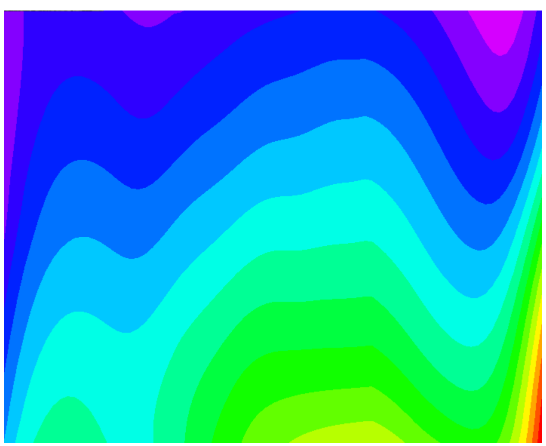


Phase 3 – 300 kN

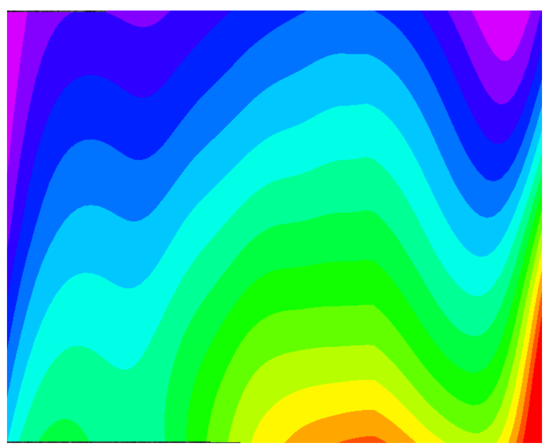


Phase 4 – 450 kN

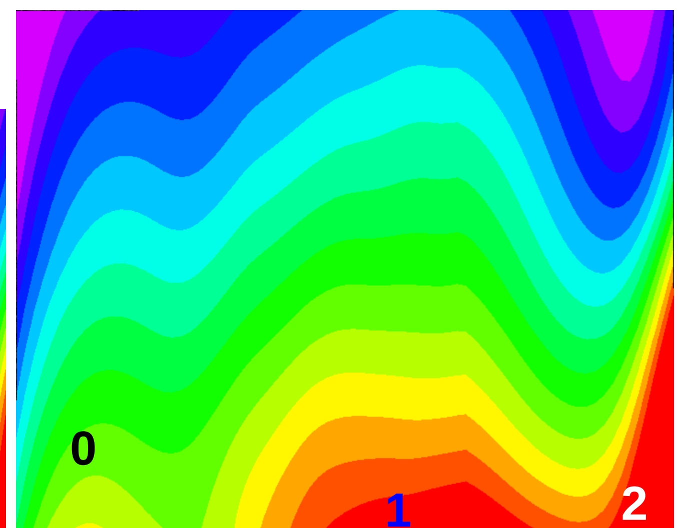
No significant strain gradient was observed in the Flange. Hence the Analysis is concentrated in the Web Region



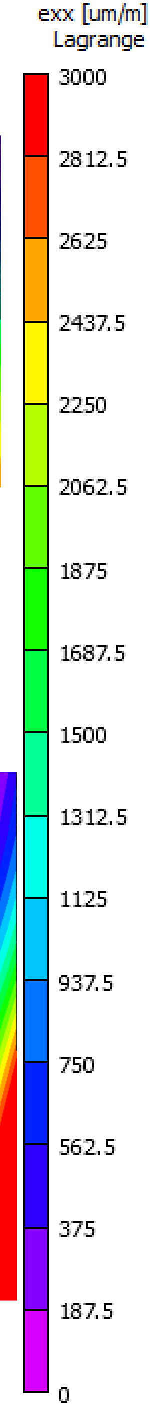
Phase 5 – 500 kN



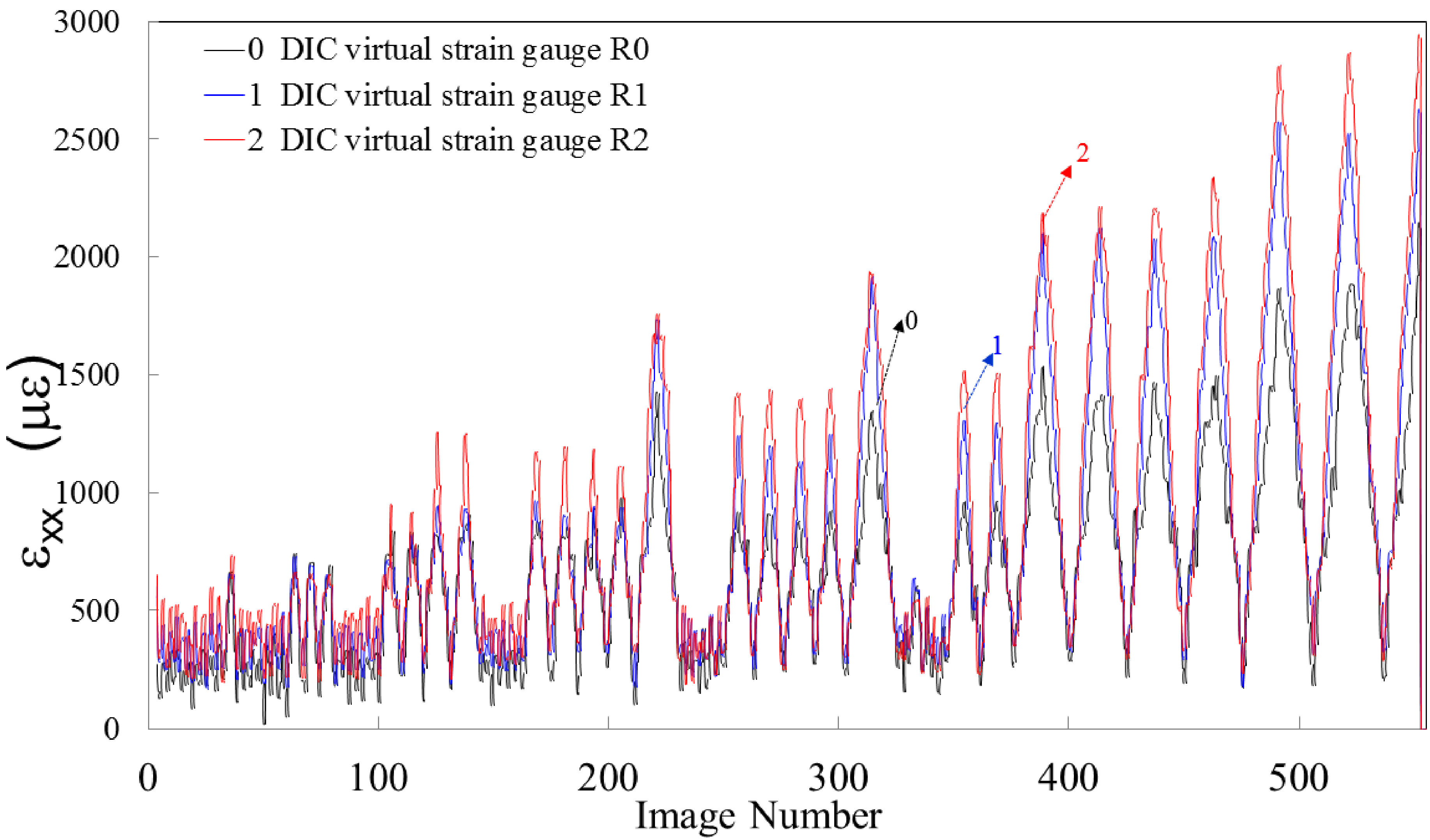
Phase 6 – 570 kN



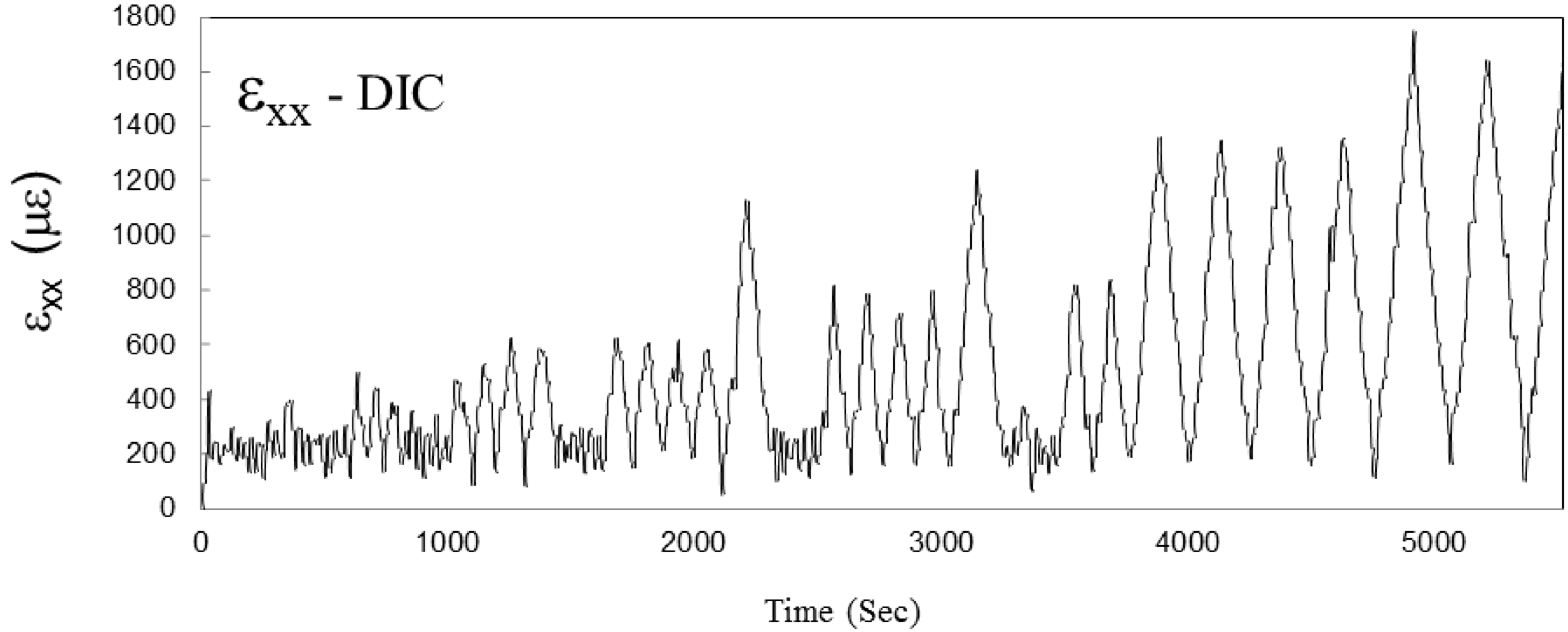
Phase7– 800 kN

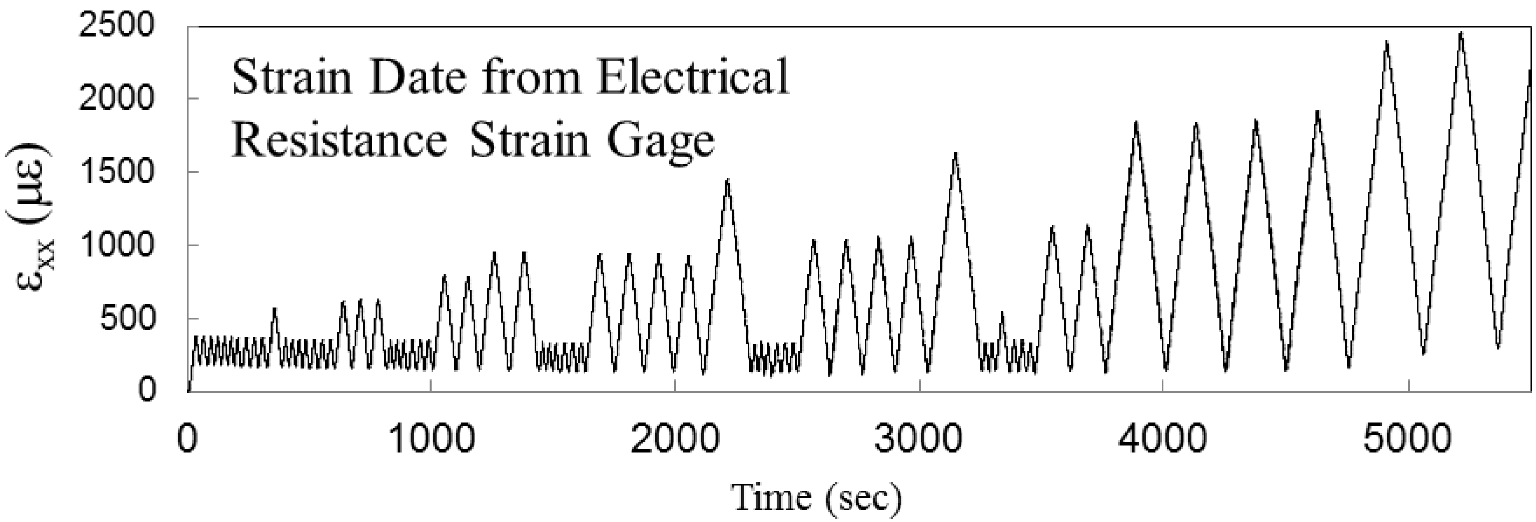


Time Vs Strain in the High Strain Zone

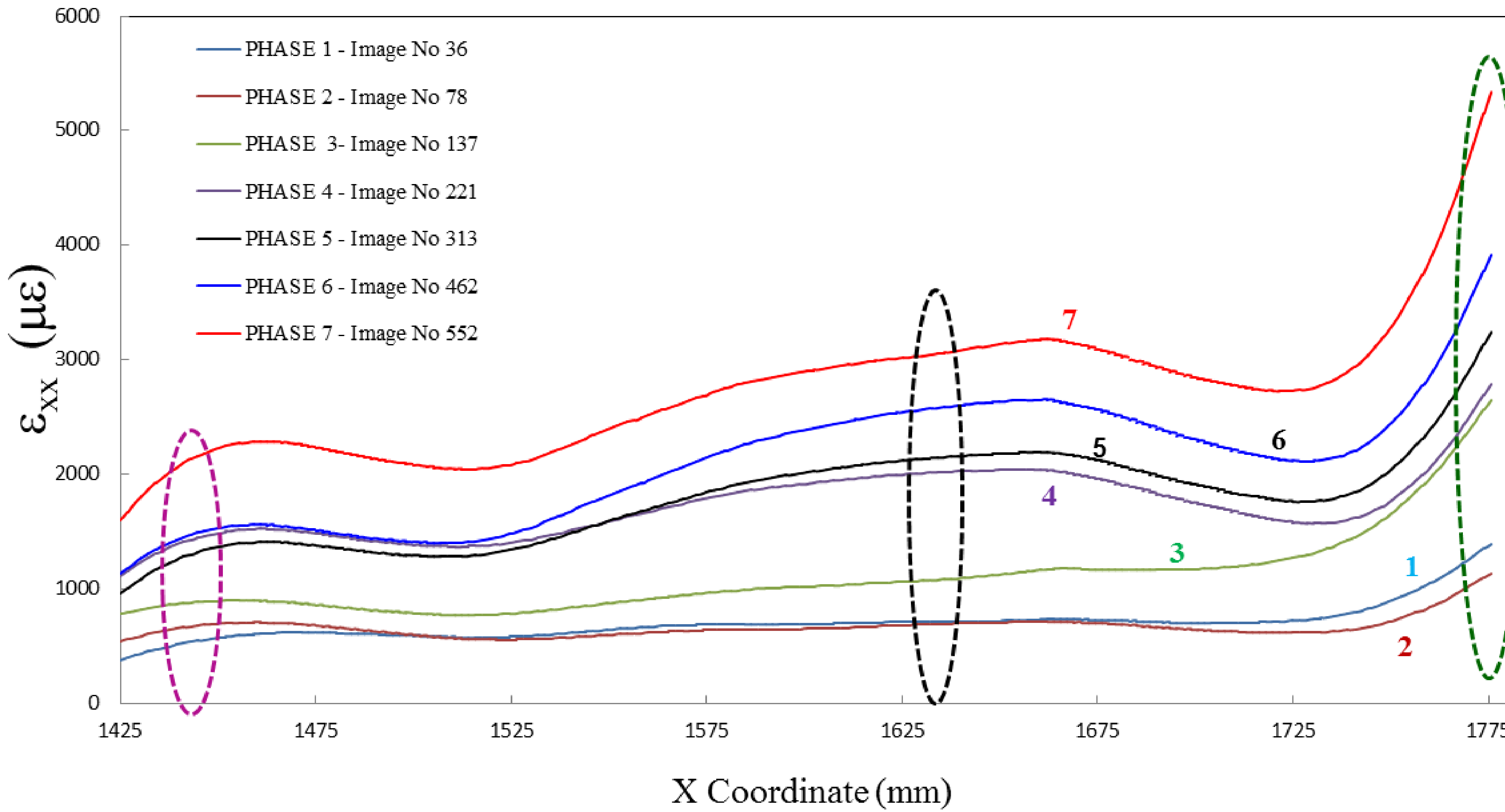


Comparison of DIC and Strain Gage Results - ε_{xx} At the Mid Section of the Beam



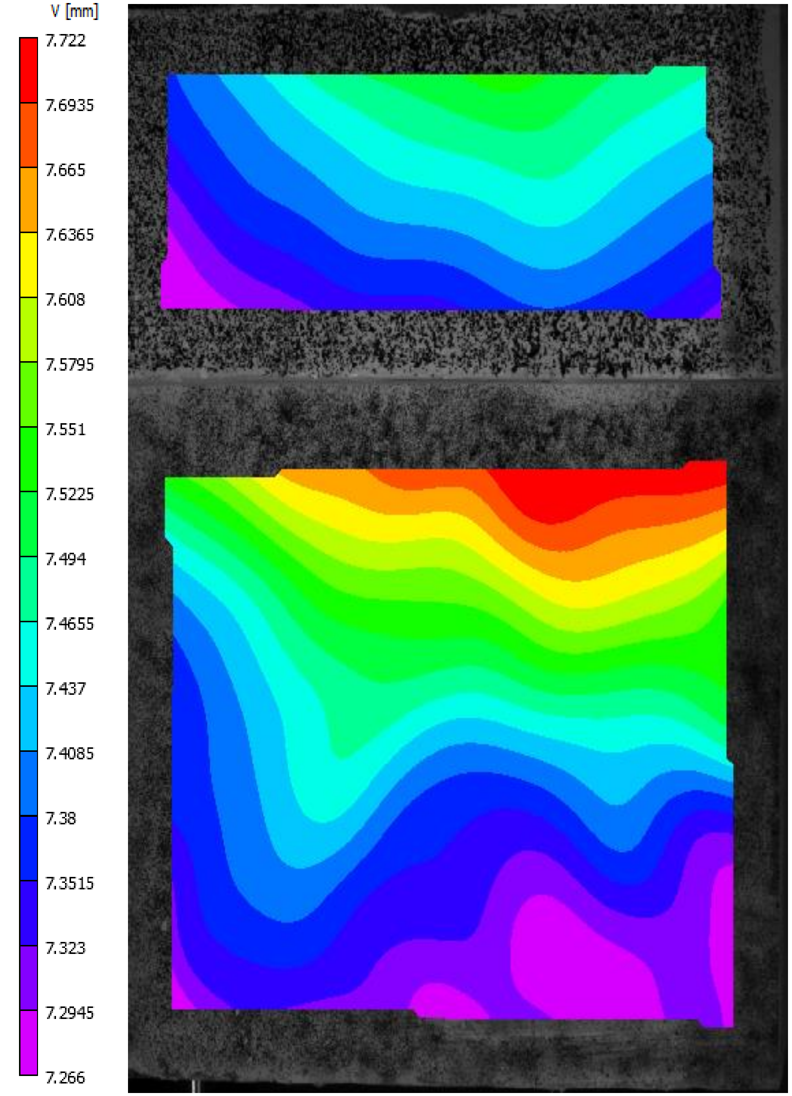


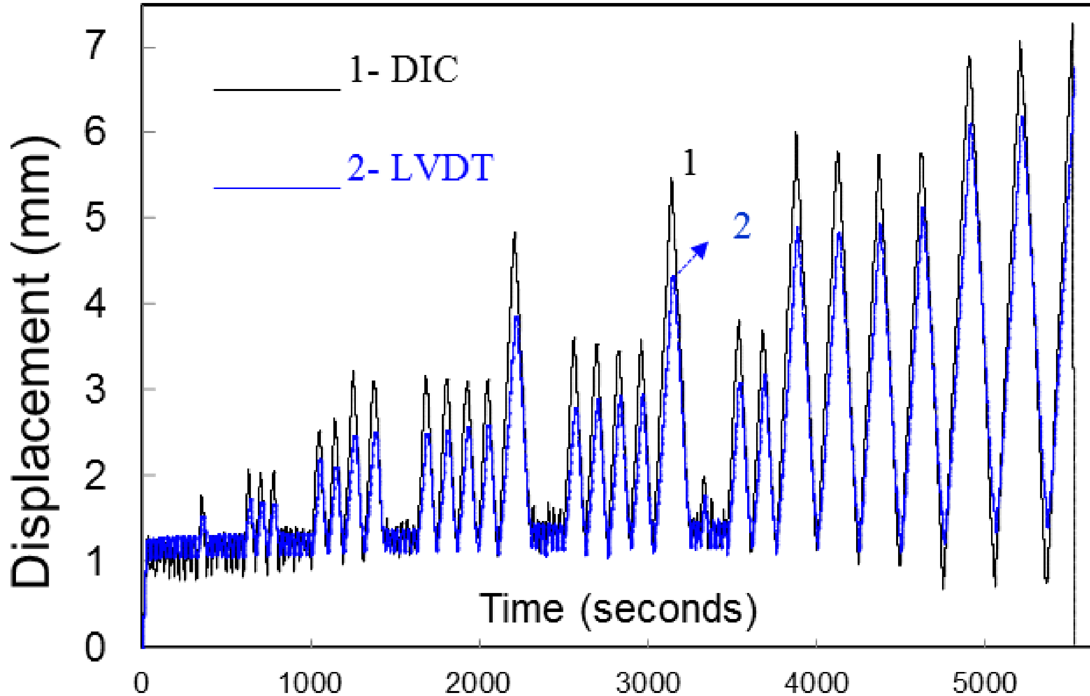
Profile of Strain in the high Strain Zones



Very Good Linearity observed in the strain field at Peak Loads of Different Phases of Loading.

DIC Results – "V" Displacement Plots





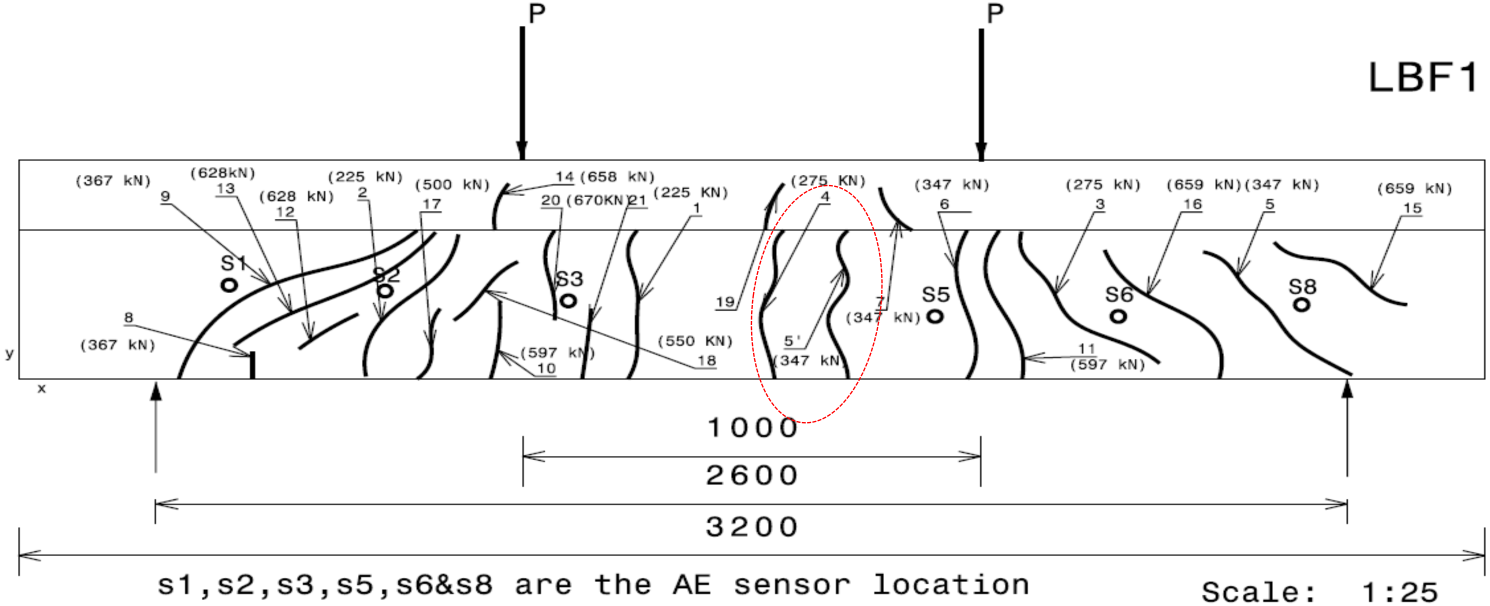
Full field "V" Displacement plot obtained at Peak Load of 800 KN during Phase 7

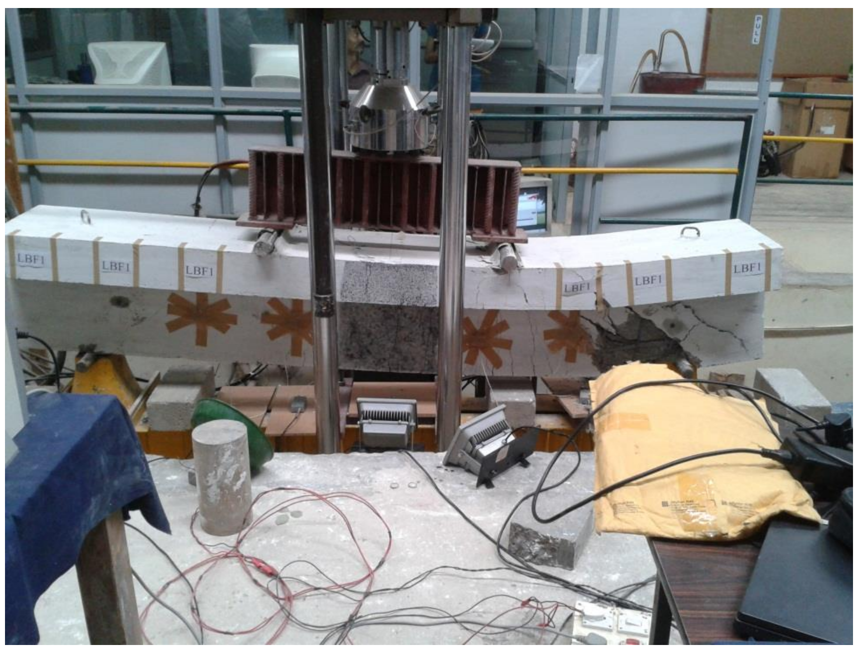
Load Phase	Peak Load (kN)	Development of Cracks
Phase 1	180	No
Phase 2	200	No
Phase 3	300	No
Phase 4	450	No
Phase 5	500	No
Phase 6	570	The growth of existing cracks was seen in sixth phase at 670 kN.
Phase 7	800	The cracks opened by 1mm width at 765 kN. Multiple cracks were seen in flange. The supports crushed at 765 kN. The spalling of the concrete was seen at the center of the beam near the top of flange at 800 kN. The beam failed at 810 kN.

AE parameters and strain at various Loads

Load Phase	Phase-I	Phase-II	Phase-III	Phase-IV	Phase-V	Phase-VI	Phase-VII
Load cycle peak-load (kN)	180	200	300	450	500	570	800
DIC Image Number	36	78	137	221	313	462	552
Strain in Steel. (με)	**655**	**733**	**1111**	**1680**	**1932**	**2289**	**2231**
Strain in Concrete -DIC (με)	**396**	**347**	**591**	**1127**	**1115**	**1349**	**1749**
Displacement "V" (DIC – mm)	1.78	2.06	3.11	4.86	5.40	5.78	7.28
Displacement – LVDT (mm)	1.54	1.69	2.51	3.80	4.31	5.12	5.98
Displacement "W" (DIC – mm)	0.63936	0.98617	1.45246	1.97643	2.19309	2.46631	3.36197

Crack Profiling





High Strain Zones indicated by DIC

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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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Experiment	Fracture Process Zones in Concrete Structures
System Used	VIC-2D, 2D Digital Image Correlation System.
Loading Conditions	Static Load
Camera Used	Point Grey Research Grasshopper 2MP Camera, 15fps
Image Frame Capture	One Image at every discrete load step.

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Experimental Set Up

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

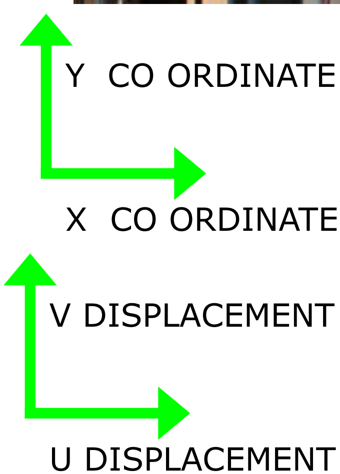
Dimensions of the concrete beam:- 750 mm (L) X190mm (H)X 95 mm (D)

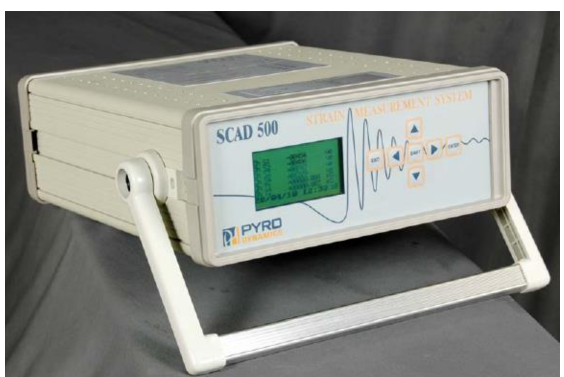
The Beam had strain gages and Acoustic Emission Sensor mounted on the back side.

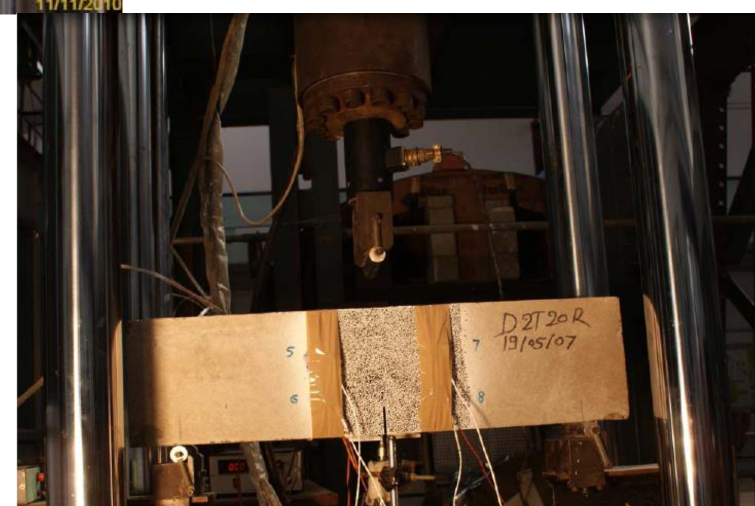
The strain gages were interfaced to SCAD 500 Strain Measurement System

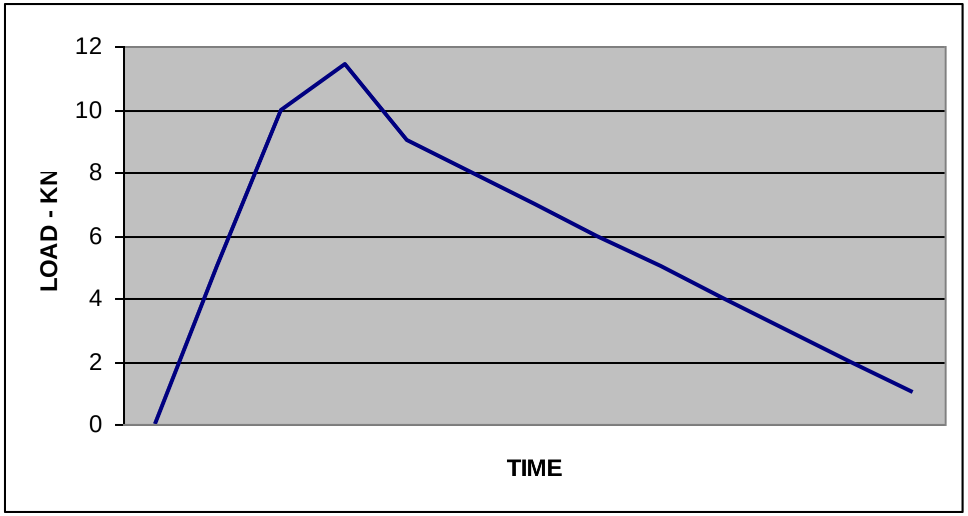
Load:- 3 Point Bending.

The Load increased upto 11.46KN and began to drop. The concrete beam underwent internal cracking at 11.46 KN and this is clearly seen in the strain plots.

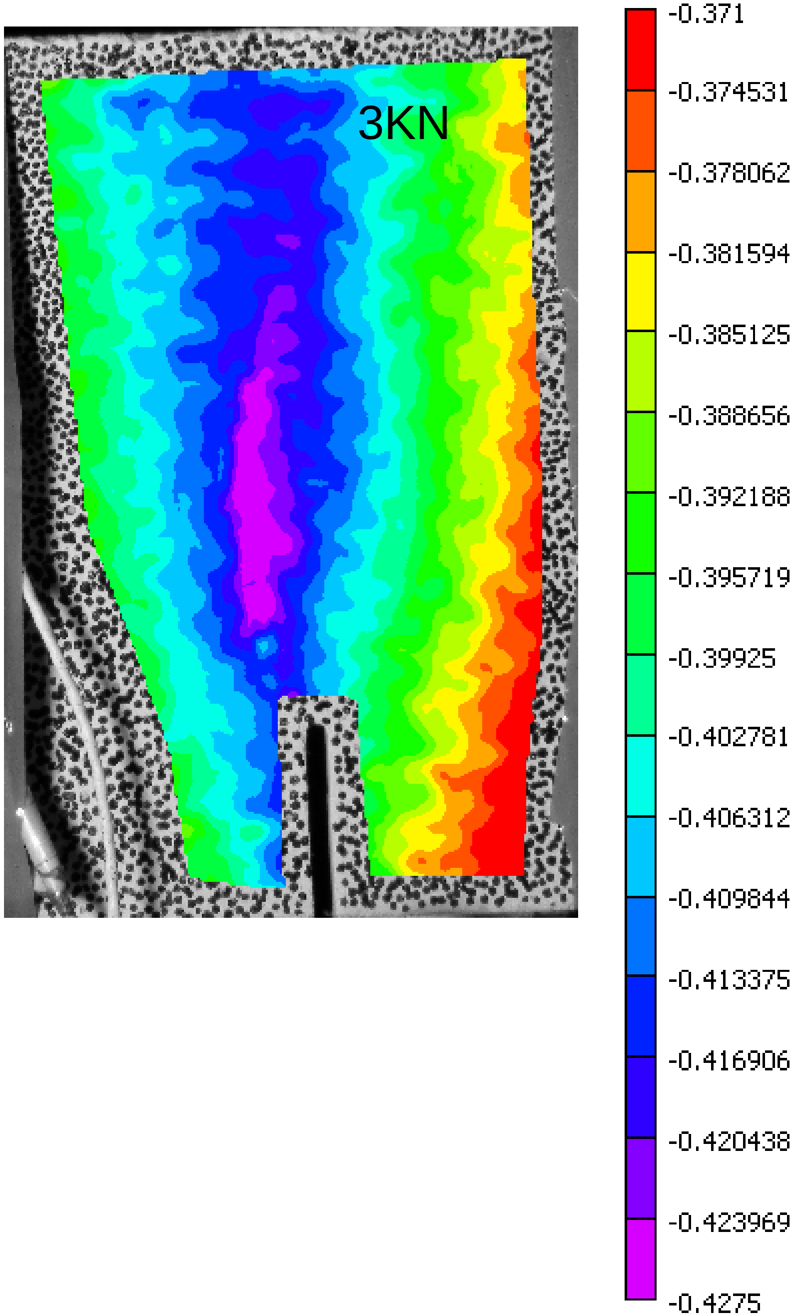








"V" Displacement



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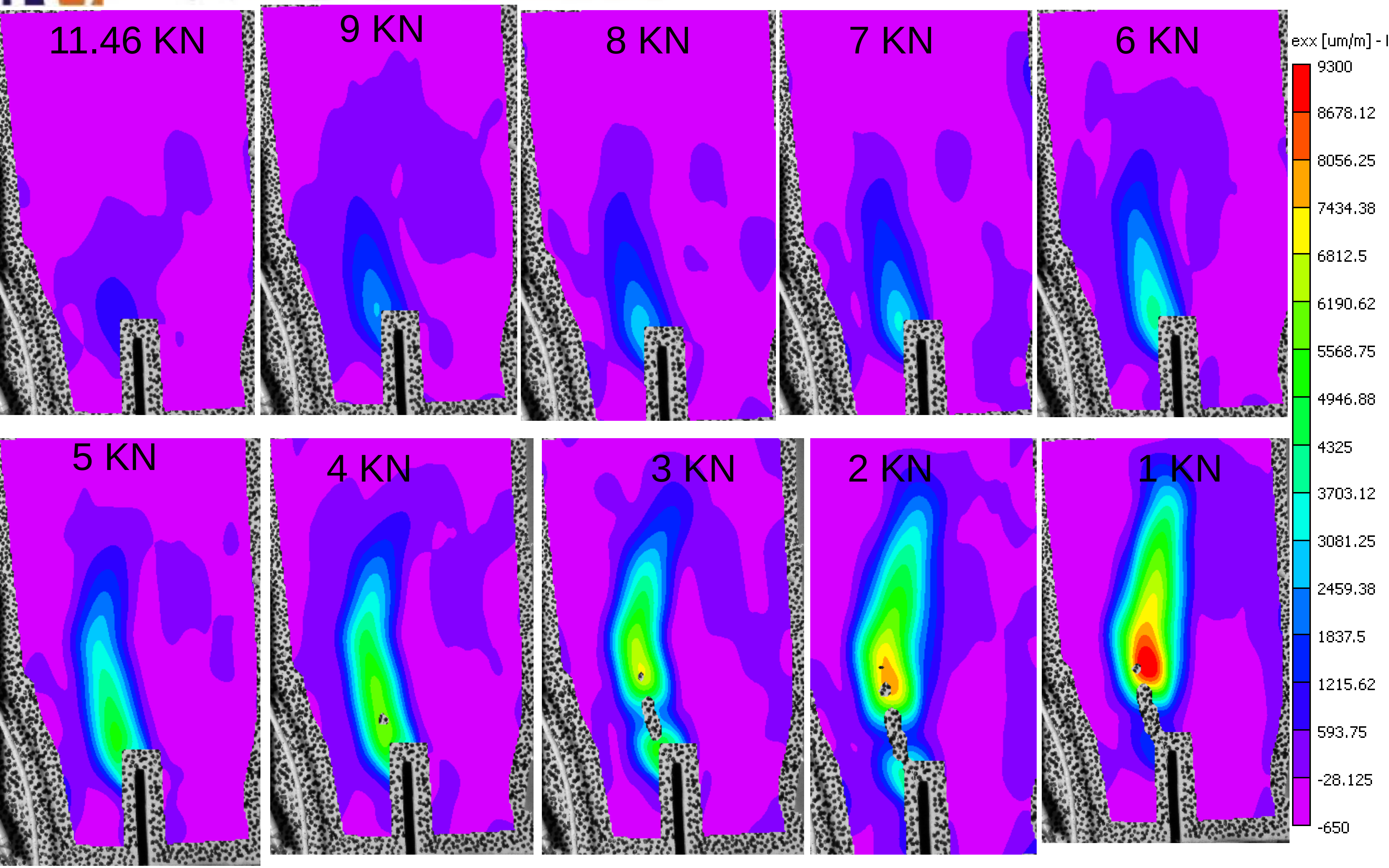
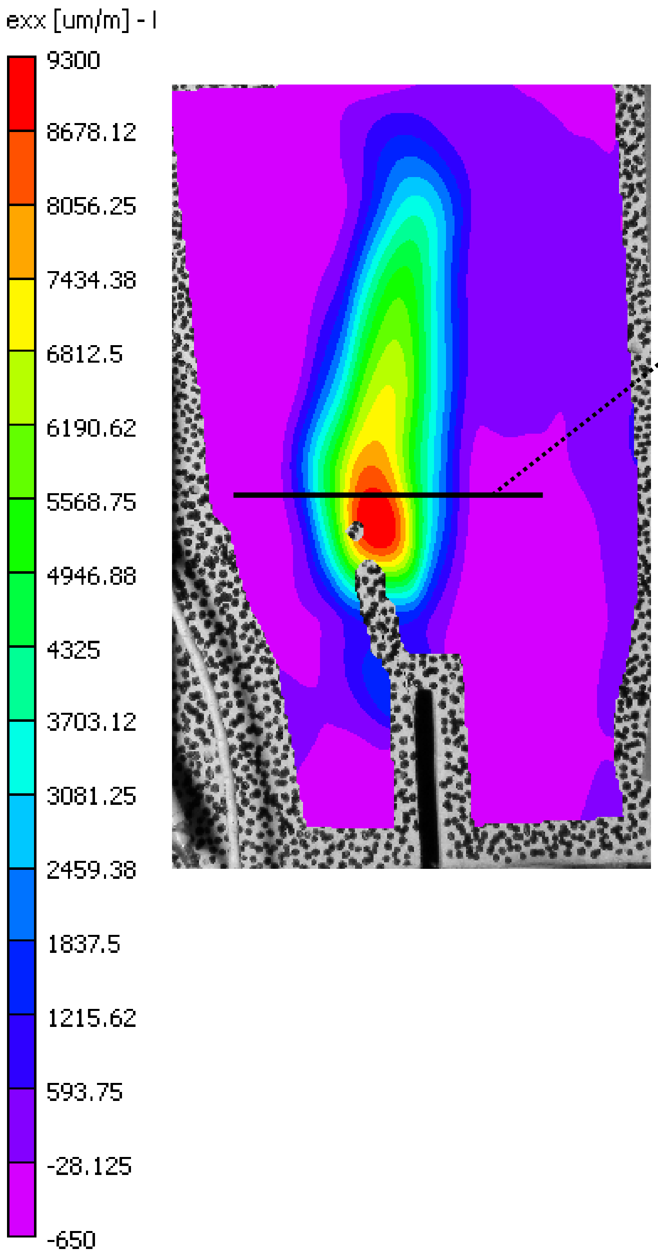
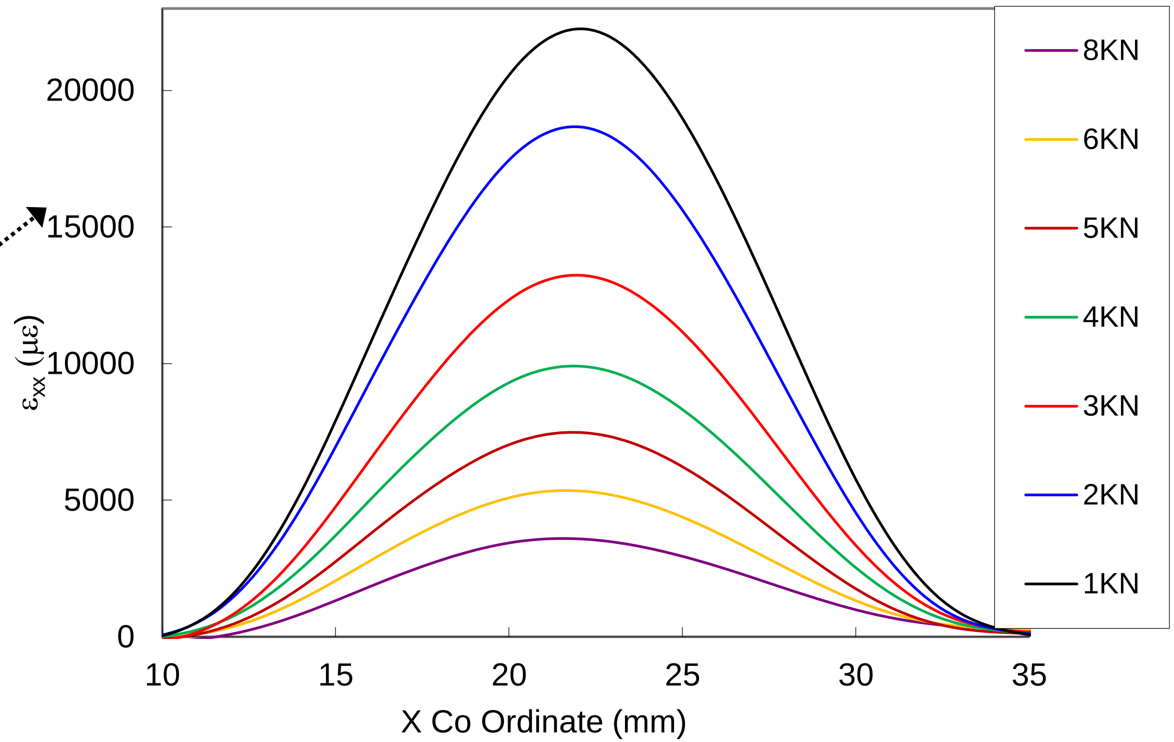
ε_{xx} Plots at Different Loads after Smoothening



Profile of ε_{xx}





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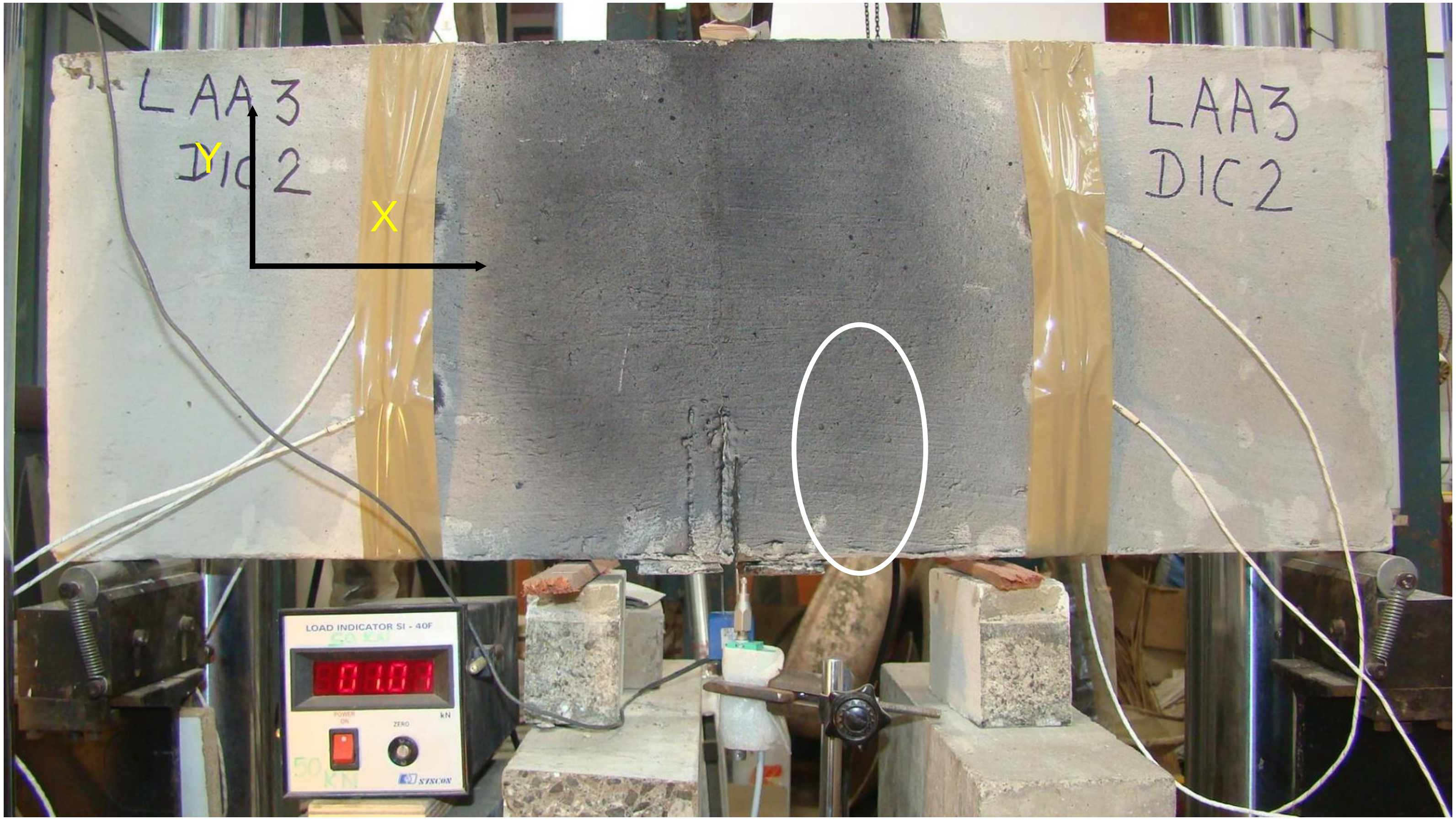
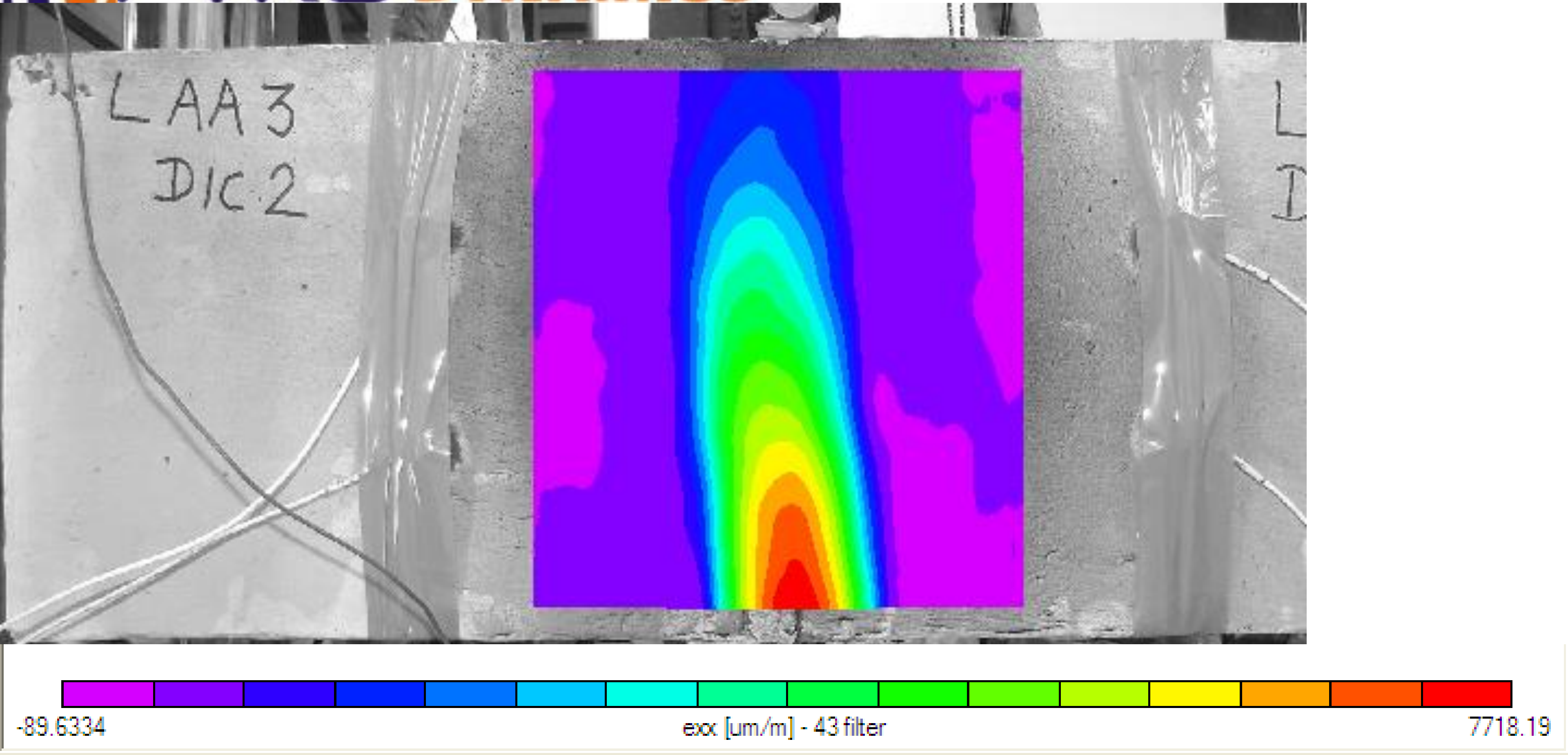
Experiment	Fracture Process Zones in Concrete Structures
System Used	VIC-2D, 2D Digital Image Correlation System.
Loading Conditions	Static Load
Camera Used	Point Grey Research Grasshopper 2MP Camera, 15fps
Image Frame Capture	One Image at every discrete load step.

EXPERIMENTAL SET UP



Under load the crack opens in the X Direction



ε_{xx} ($\mu\varepsilon$)

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Experiment	Fracture Process Zones in Concrete Structures
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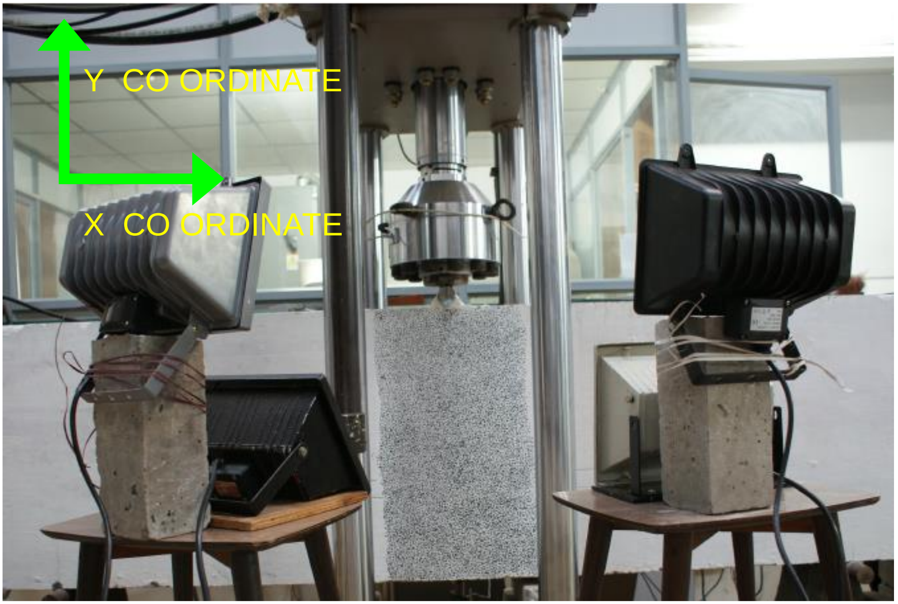
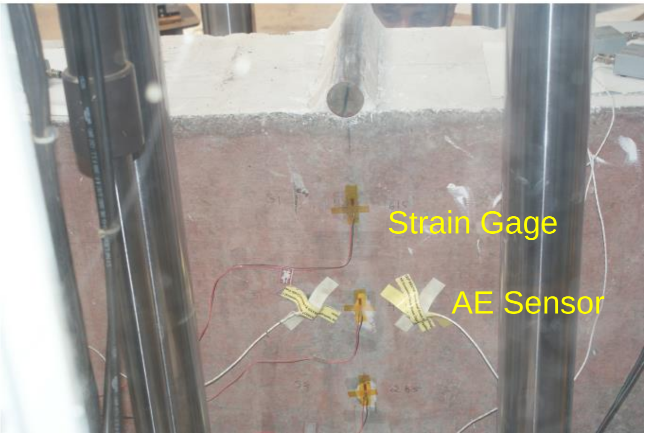
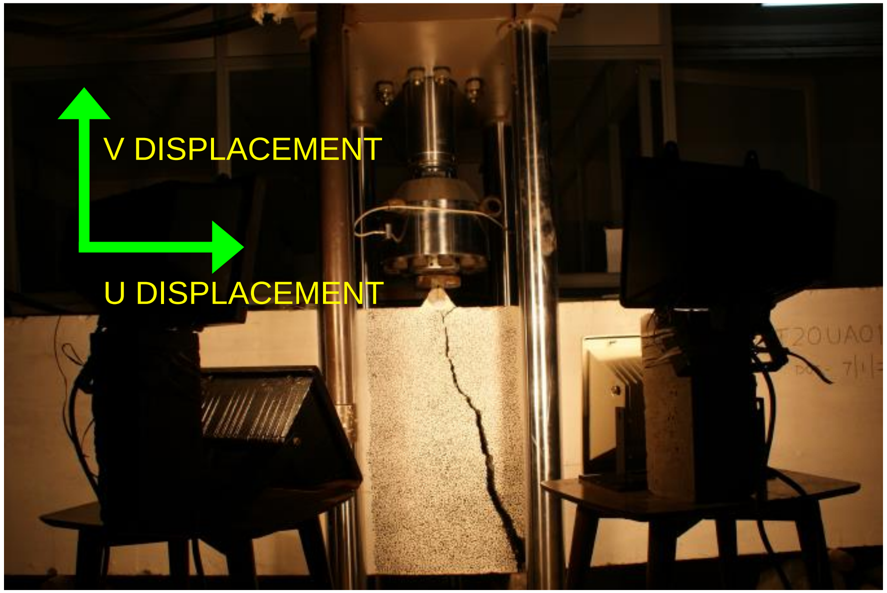
Experimental Set Up







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.

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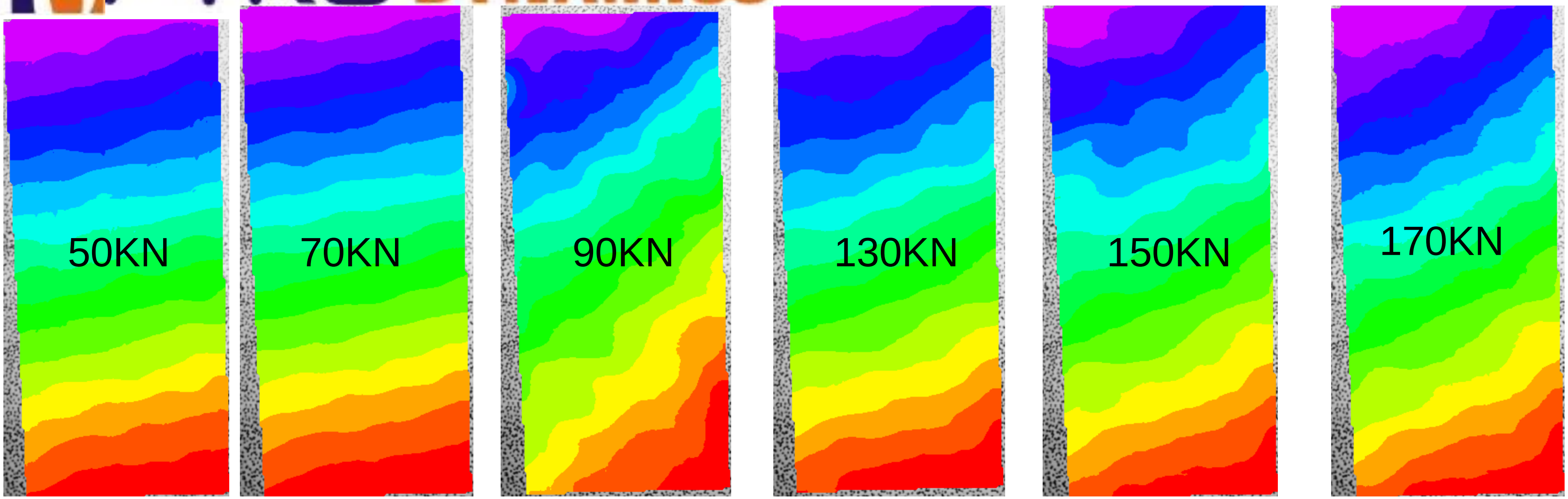
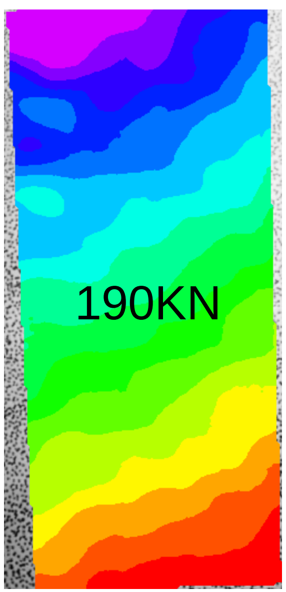
“V” Displacement



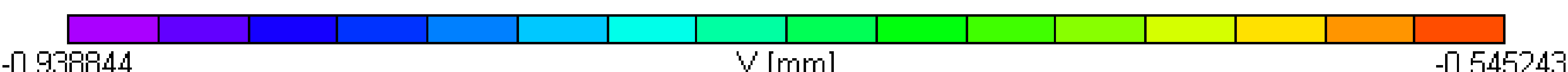


Since the concrete beam under load has a downward displacement the DIC shows a negative value.

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.



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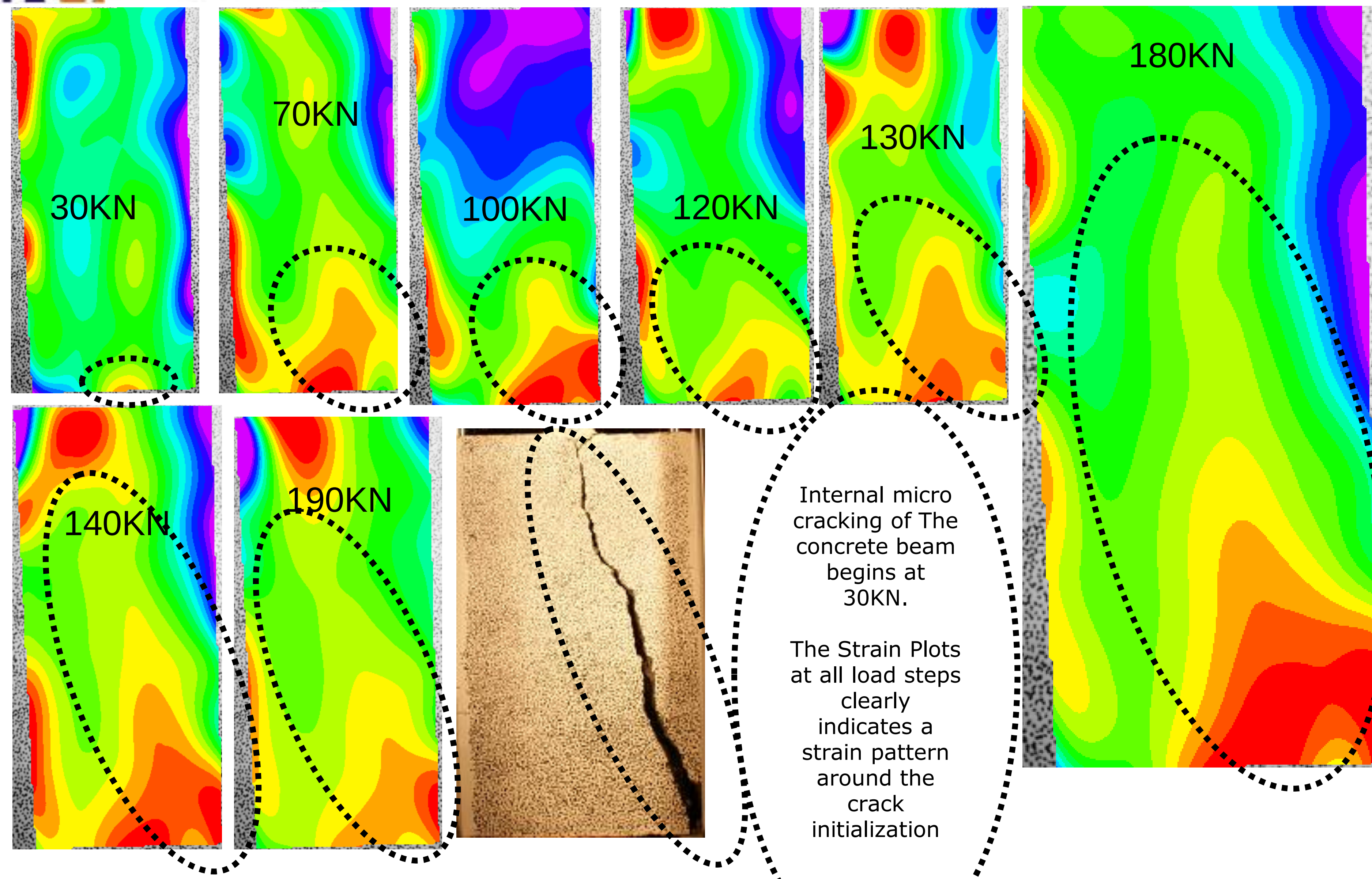
ε_{xx} Plot at Different Loads



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

Experiment	Retrofitted CFRP Wrapped Concrete Bare Frame
System Used	VIC-3D, 3D Digital Image Correlation System.
Loading Conditions	Quasi-Static Load
Camera Used	Basler 8.9Mp, 43 fps, USB 3.0 CMOS Cameras.
Image Frame Capture	Two Images per second.

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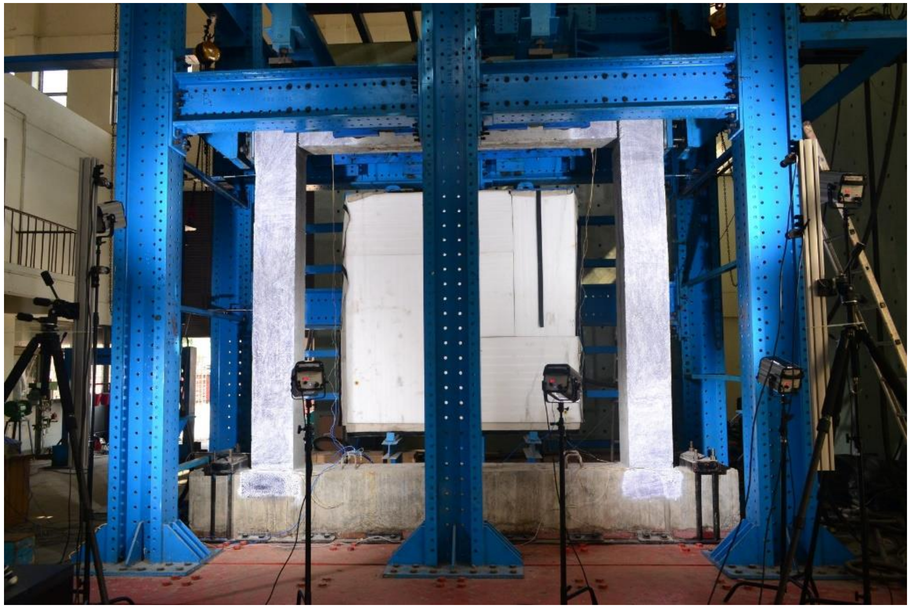
Retrofitted CFRP Wrapped Concrete Bare Frame Test



Structure Details :-

Concrete Column Bare Frame.

Height = 3.15m ; Width = 400mm ; Thickness = 400mm

VIC-3D, 3D DIC System Set Up.

Cameras :- USB3.0 CMOS – 8.9 MP;43 fps with Schneider 10 mm Lenses – 2 Systems Connected to the Same Computer.

Image Capture:- 2 fps.

All cameras triggered simultaneously.

Image Correlation:-

- **Subset Size:- 45 Pixels. Step size:- 11.**
- **Strain Filter Size:- 29 Pixels.**

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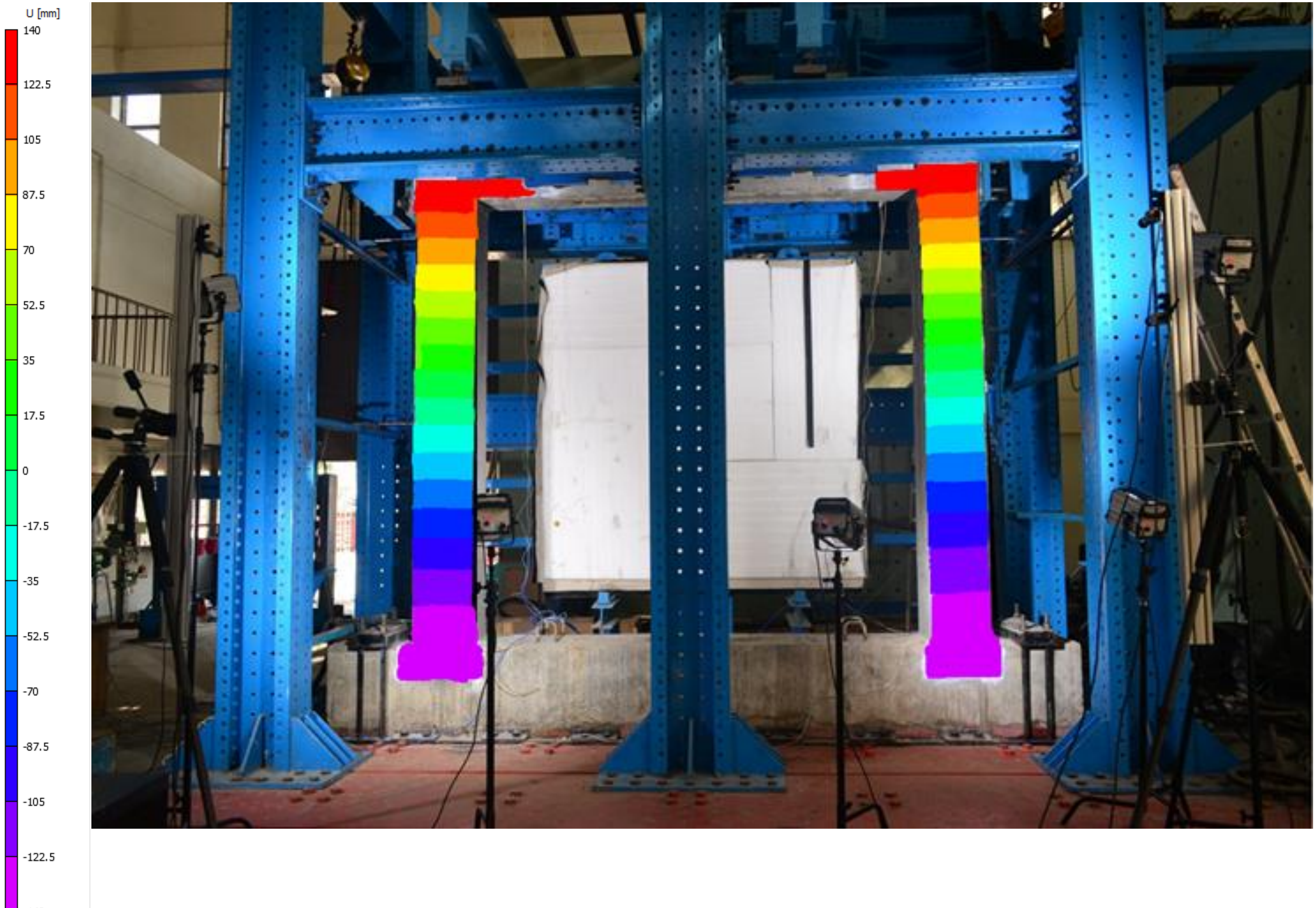
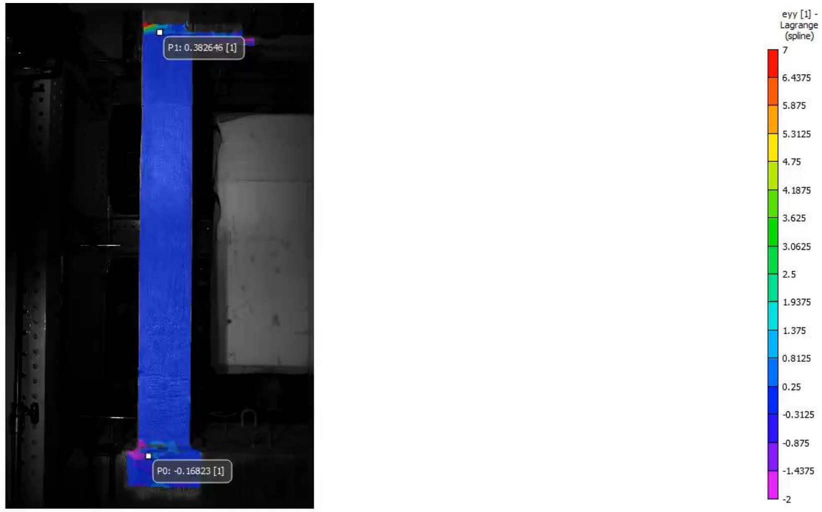
Displacement Plot – U mm

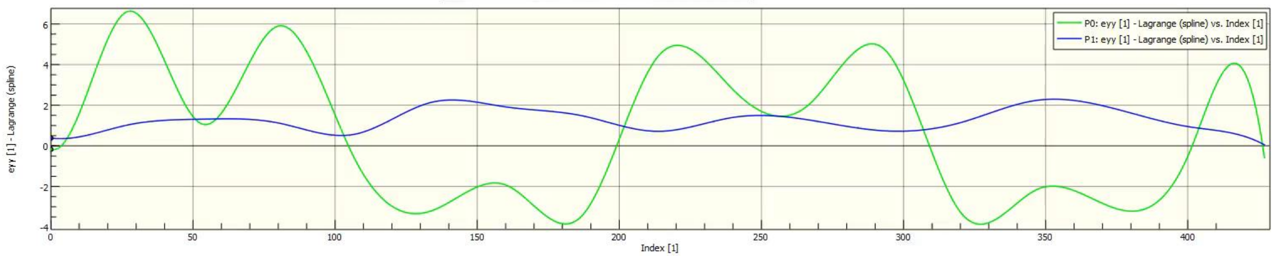


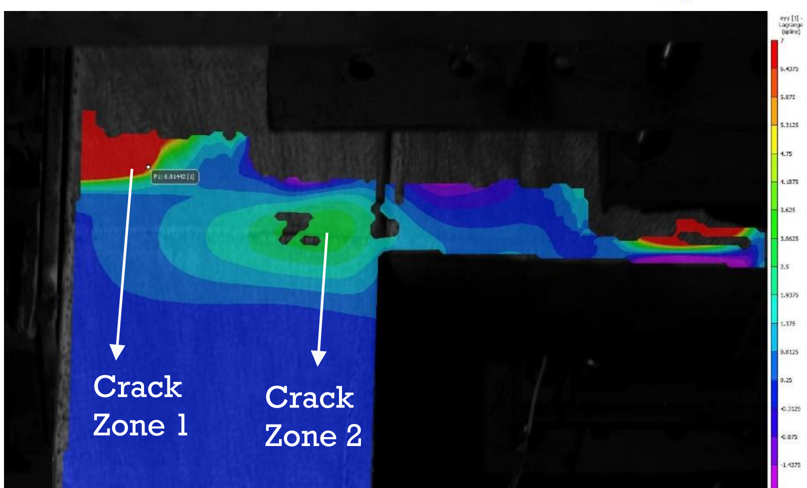
Strain Plot – ε_{yy} (%Strain)

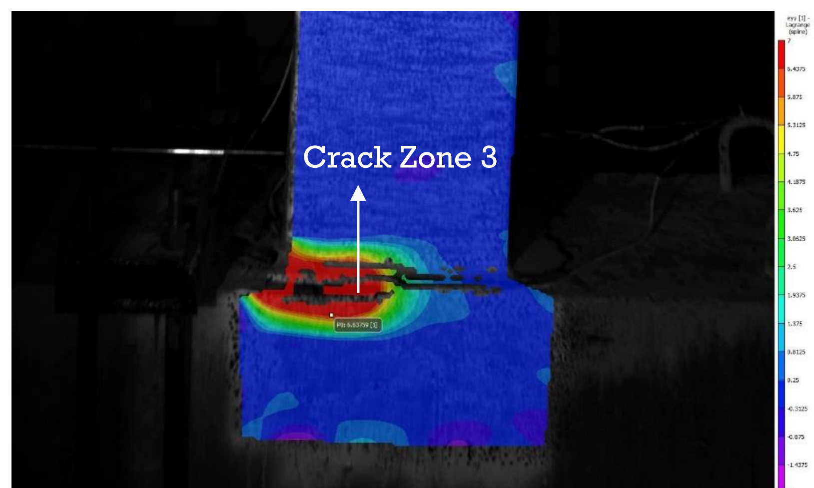


The Maximum Strain zones and the cracks were observed on the Top and Bottom Junctions of the Left Column during loading.

Other than the junctions no significant cracks were observed at the Left column





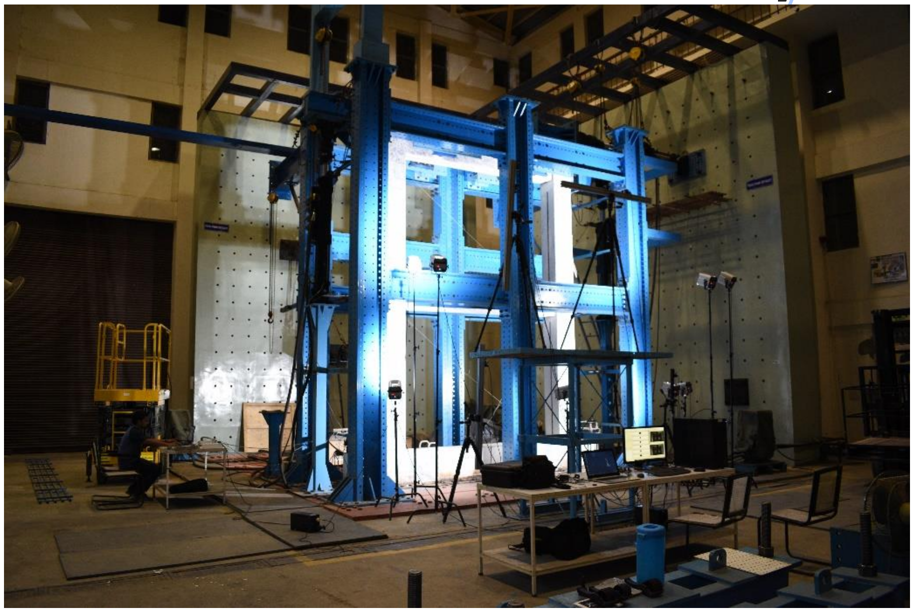


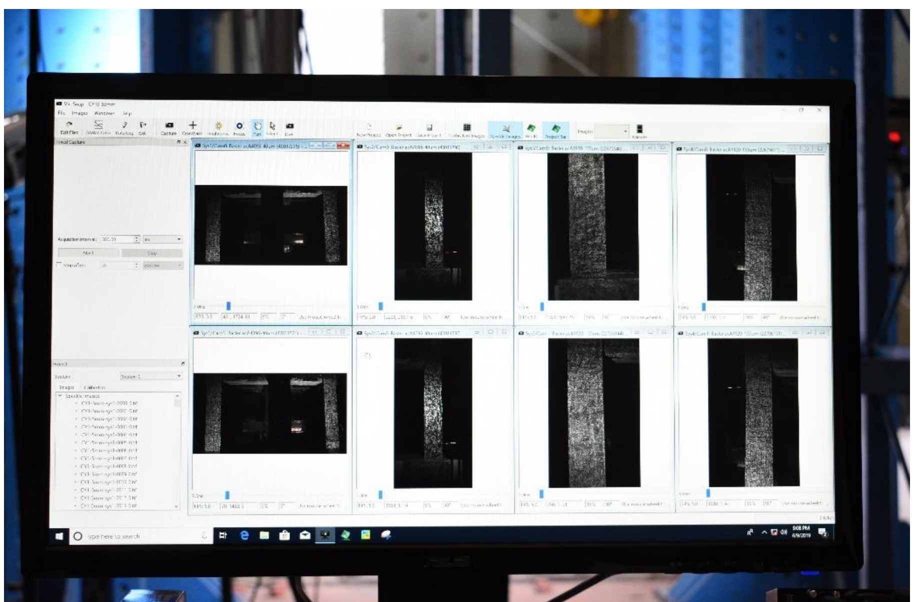
PYRO DYNAMICS

Experiment	Double Storied Concrete Bare Frame
System Used	VIC-3D, 3D Digital Image Correlation System.
Loading Conditions	Quasi-Static Load
Camera Used	Basler 8.9Mp, 43 fps, USB 3.0 CMOS Cameras.
Image Frame Capture	Two Images per second.

PYRO DYNAMICS

Double Storeyed Concrete Bare Frame Test





Structure Details :-

Two Storeyed Concrete Column Bare Frame.

Height = 6m ;
Width of Each Column = 400mm ;
Thickness = 400mm

VIC-3D, 3D DIC System Set Up.

Cameras :- USB3.0 CMOS – 8.9 MP;43 fps with Schneider 10 mm Lenses – 4 Systems Used.

Image Capture:- 2 fps.

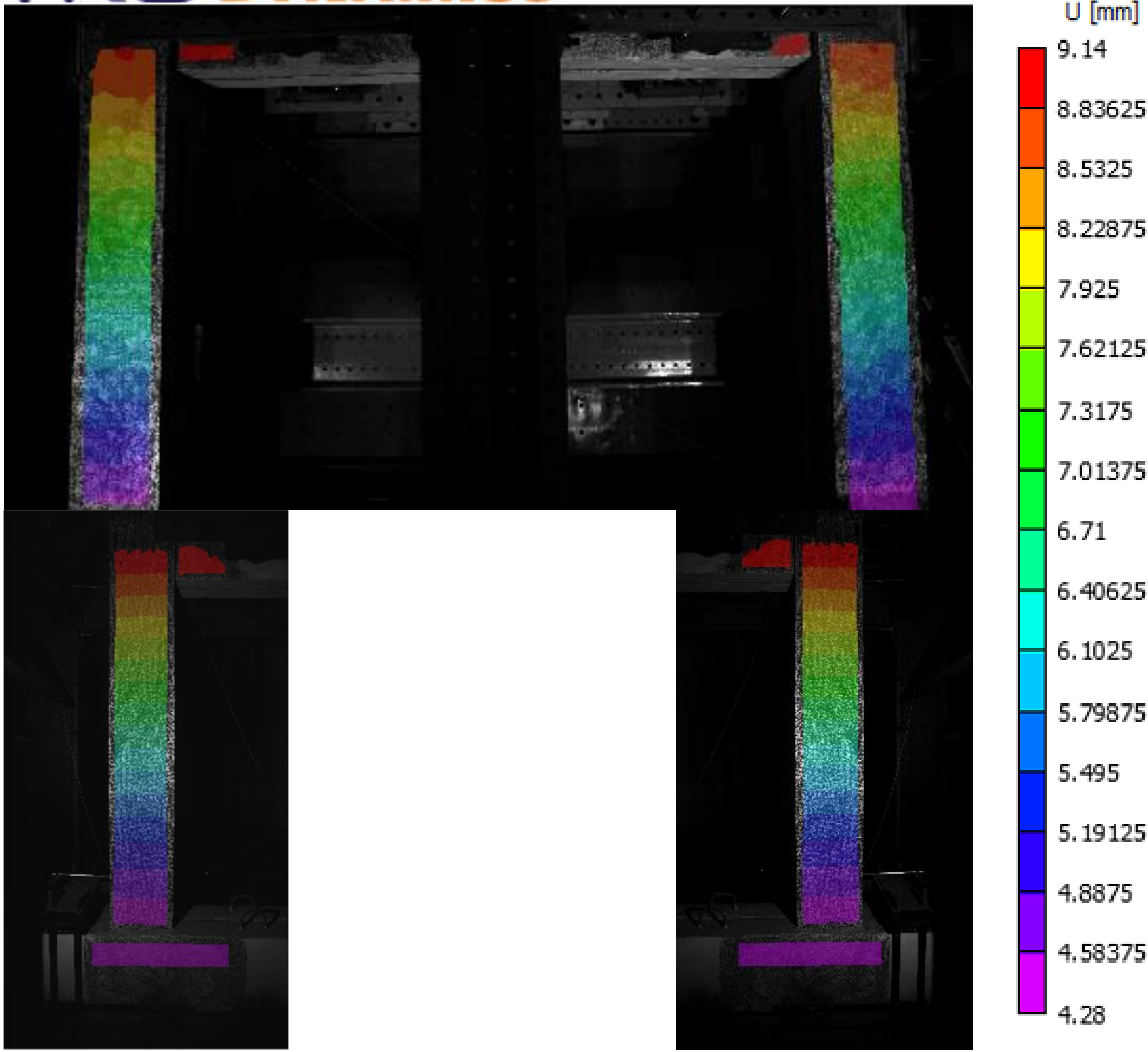
All cameras triggered simultaneously.

Image Correlation:-

- **Subset Size:- 45 Pixels.**
- **Step size:- 11.**
- **Strain Filter Size:- 29 Pixels.**

PYRO DYNAMICS

Displacement Plot – U mm



Experiment	Shock Table Impact Test
System Used	VIC-3D, 3D Digital Image Correlation System.
Loading Conditions	Impact Load
Camera Used	Basler 8.9Mp, 43 fps, USB 3.0 CMOS Cameras.
Image Frame Capture	33 frames per second.

PYRO DYNAMICS

CASE STUDY 8

Shock Table Impact Test

Structure Details :-

Grouted Concrete Structure placed on a Shock Table.

Height = 1.5m ; Width = 3m

VIC-3D, 3D DIC System Set Up.

Cameras :- 2 Systems Used

Cameras:- USB3.0 CMOS – 8.9 MP;

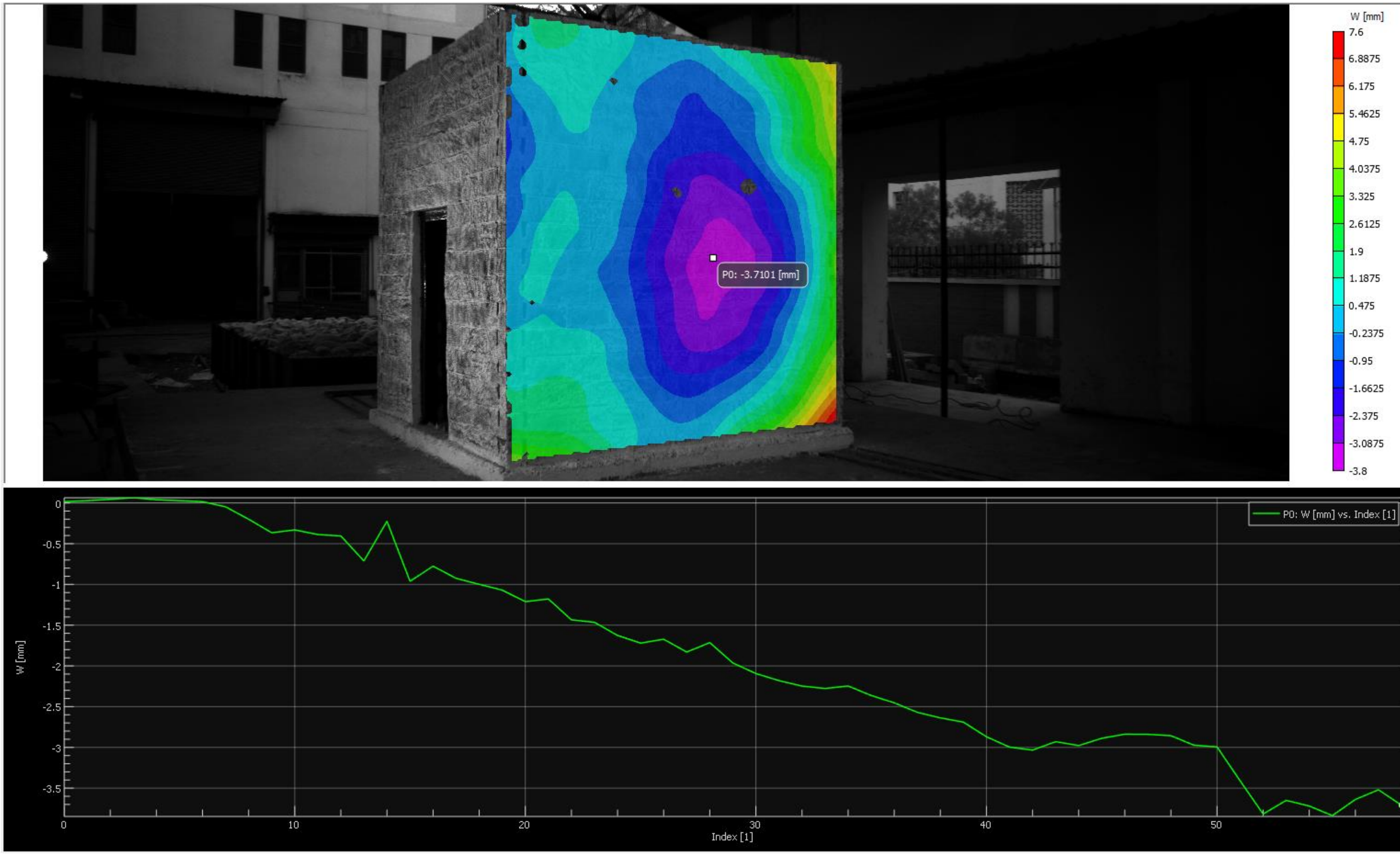
43 fps with Schneider 10 mm Lenses

All cameras triggered simultaneously using Hardware Trigger.

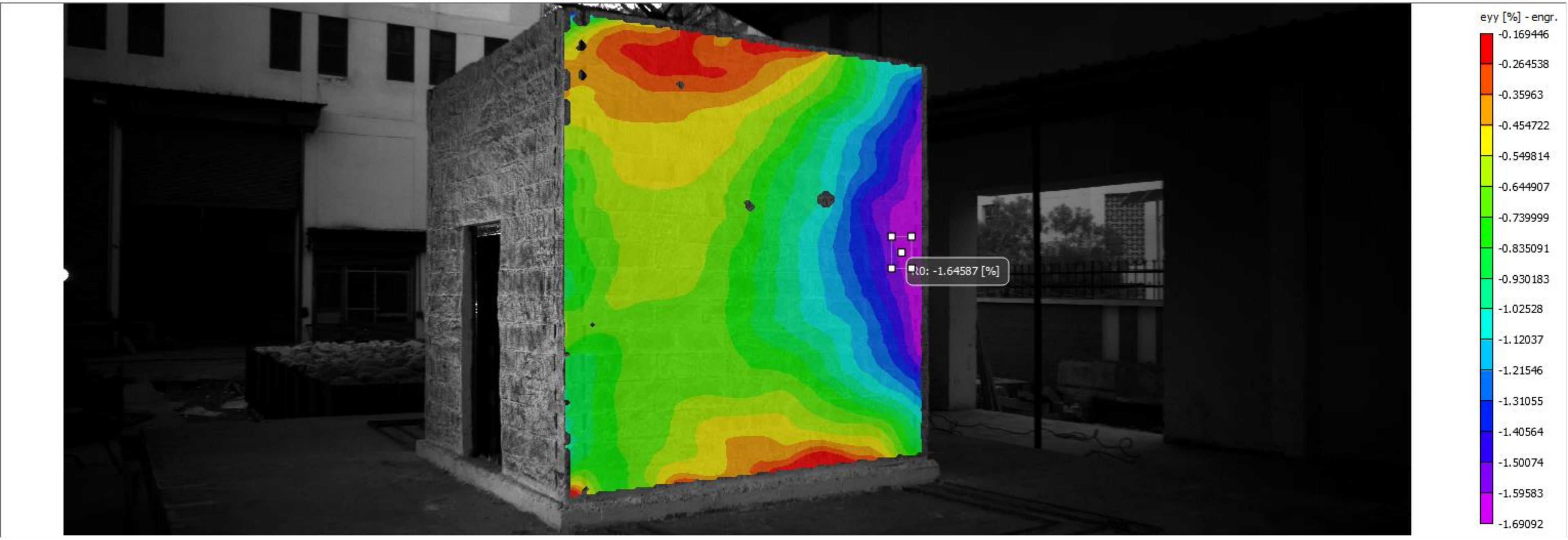
Image Correlation:-

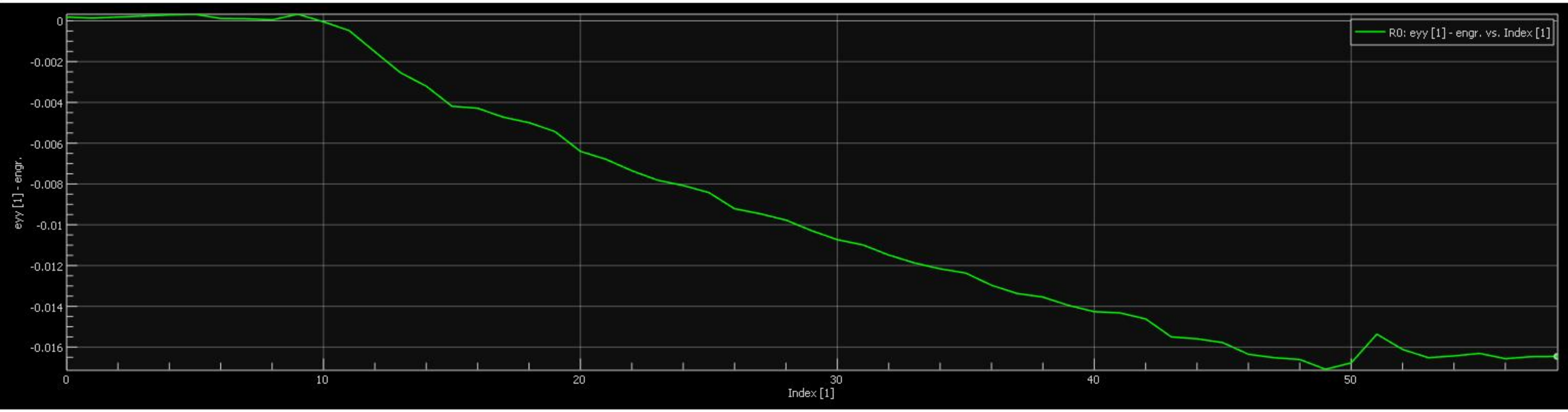
- **Subset Size:- 45 Pixels.**
- **Step size:- 11.**
- **Strain Filter Size:- 29 Pixels.**

Displacement Plot – W mm

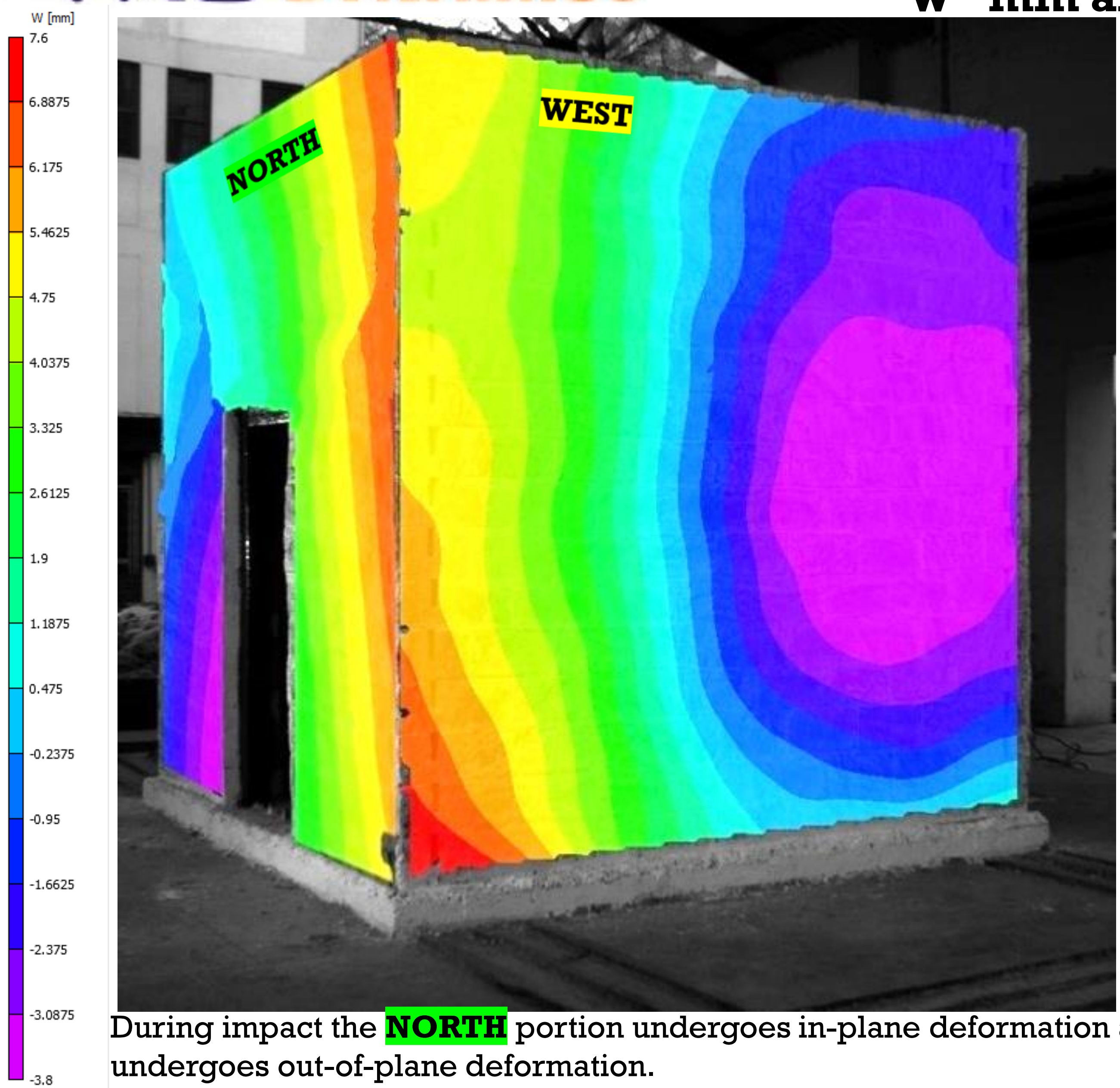


Strain Plot – ε_{yy} % Strain





Out of Plane Displacement "W" mm after impact.



During impact the **NORTH** portion undergoes in-plane deformation and **WEST** portion undergoes out-of-plane deformation.

Experiment	Full Field Strain Measurement on Concrete Columns
System Used	VIC-3D, 3D Digital Image Correlation System.
Loading Conditions	Static Load
Camera Used	Point Grey Research Grasshopper 5MP Camera, 7.5fps
Image Frame Capture	One Image at every discrete load step.

Concrete Column wrapped with PVC Sheet

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.

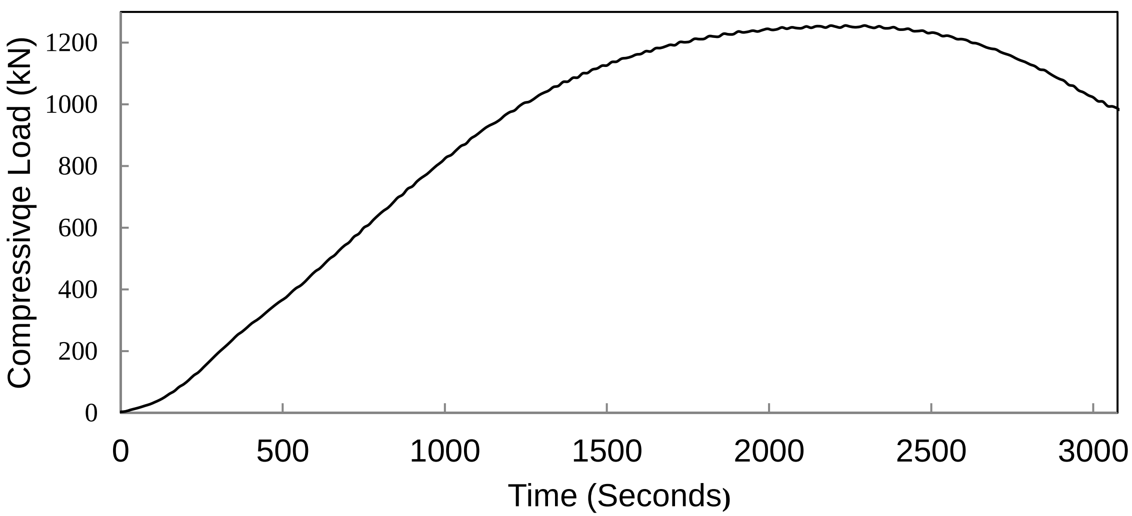
Camera:- Point Grey 5 MP Firewire Cameras.

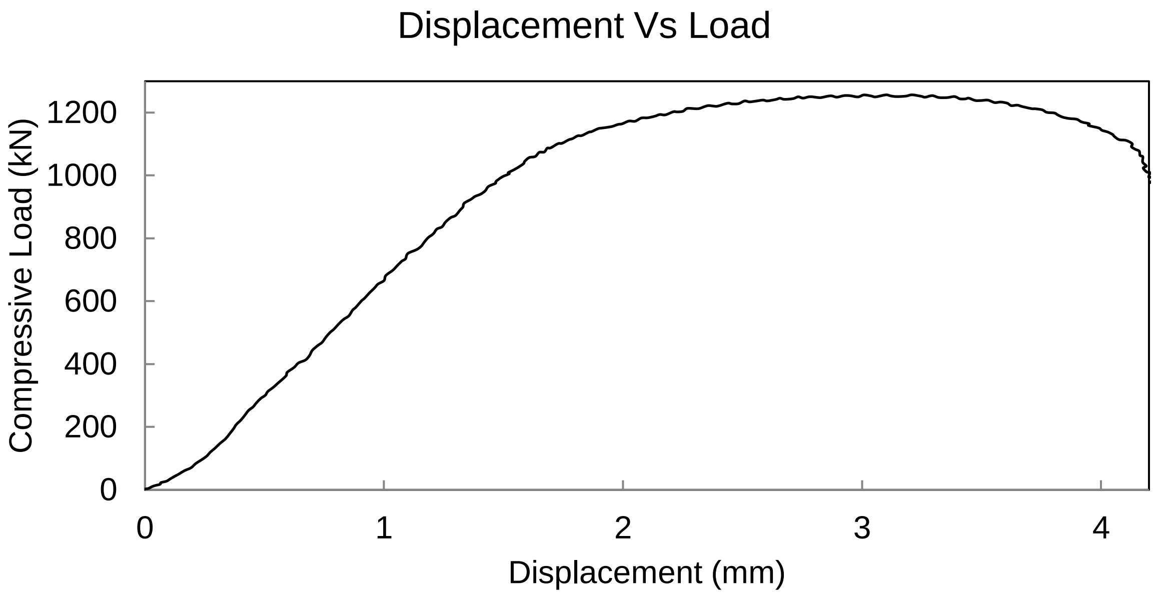
Lenses:- 17mm Schneider Lens

Images were captured every 15 seconds.

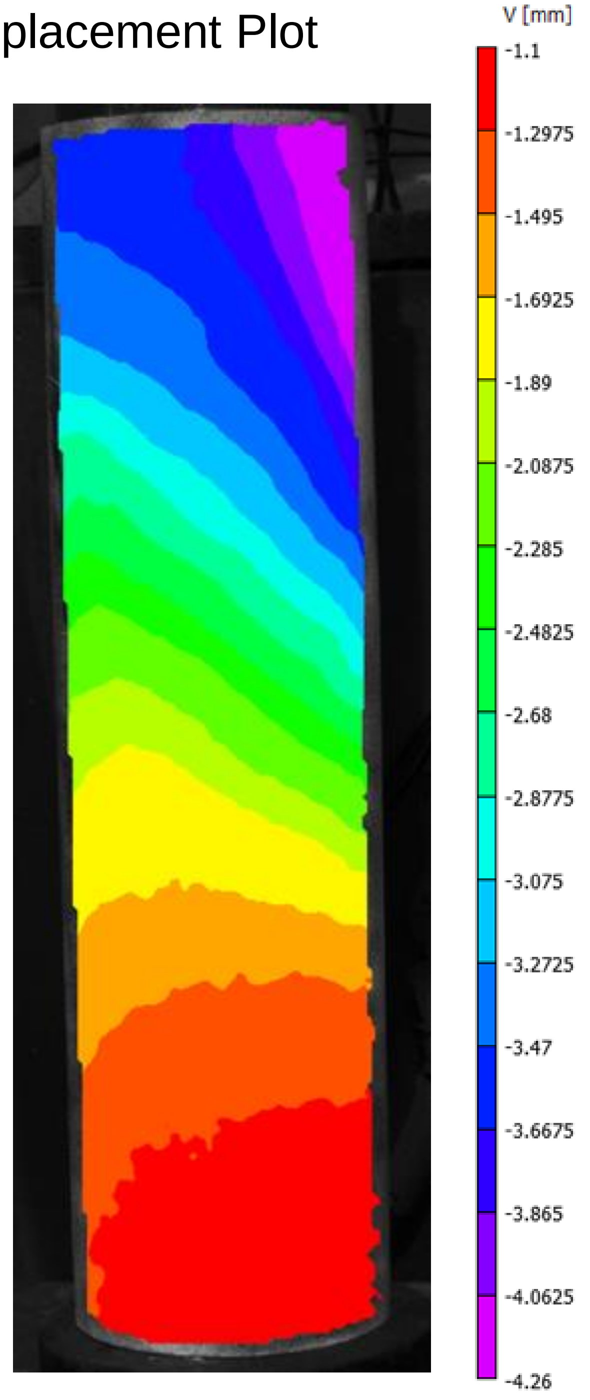
Load Applied:- Compressive Load

Maximum Load:- 1260 kN



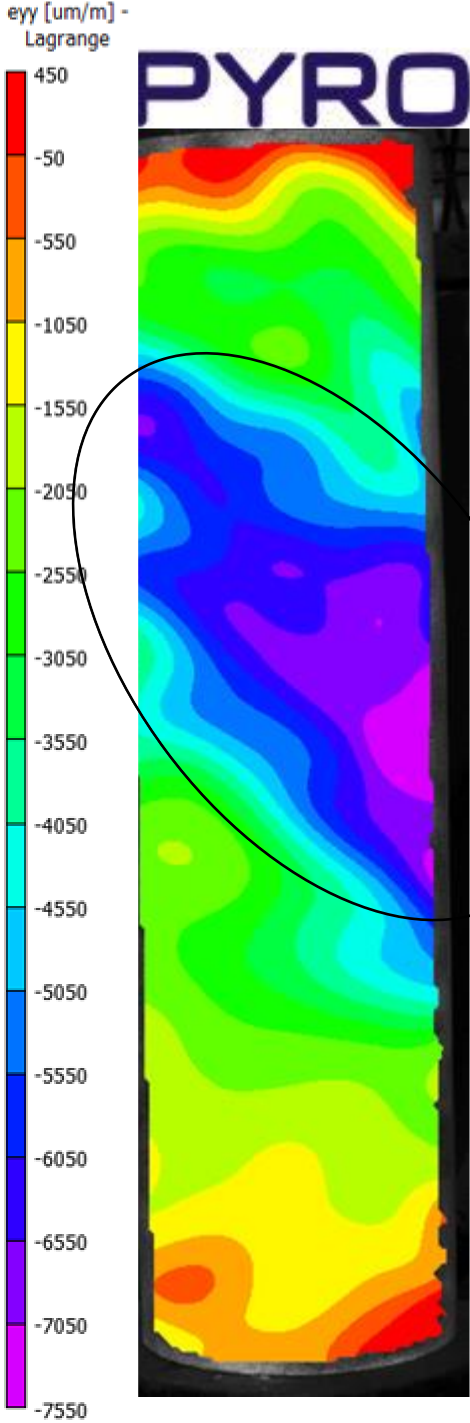


Displacement Plot



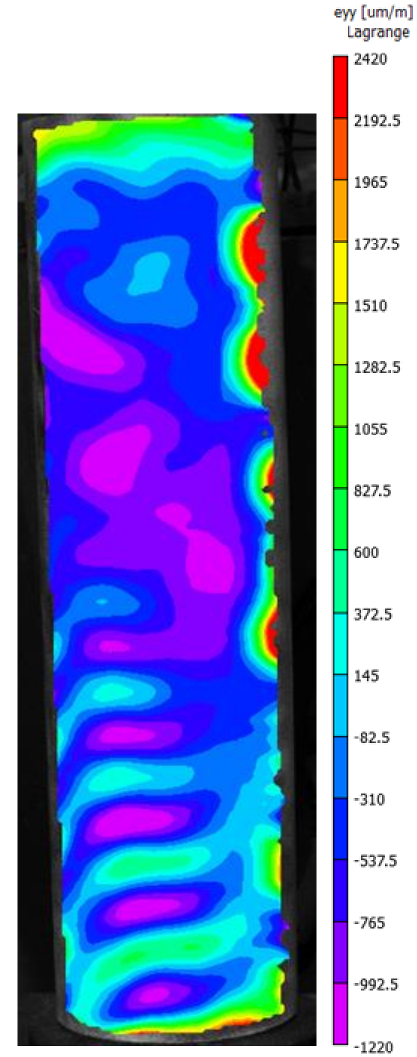
ε_{yy} Plot at 1260 kN

PYRO DYNAMICS



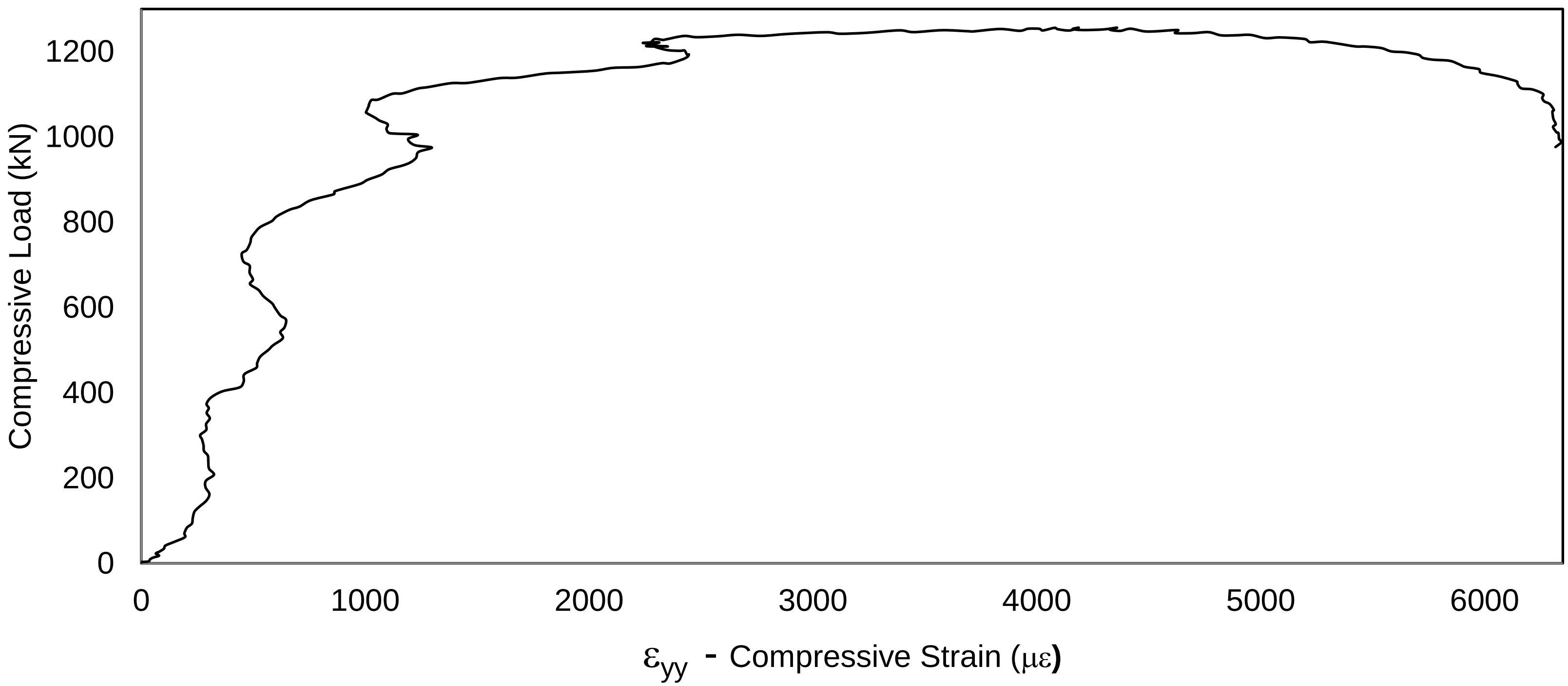
The concrete column had a shear crack and failed at 1260 kN.

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



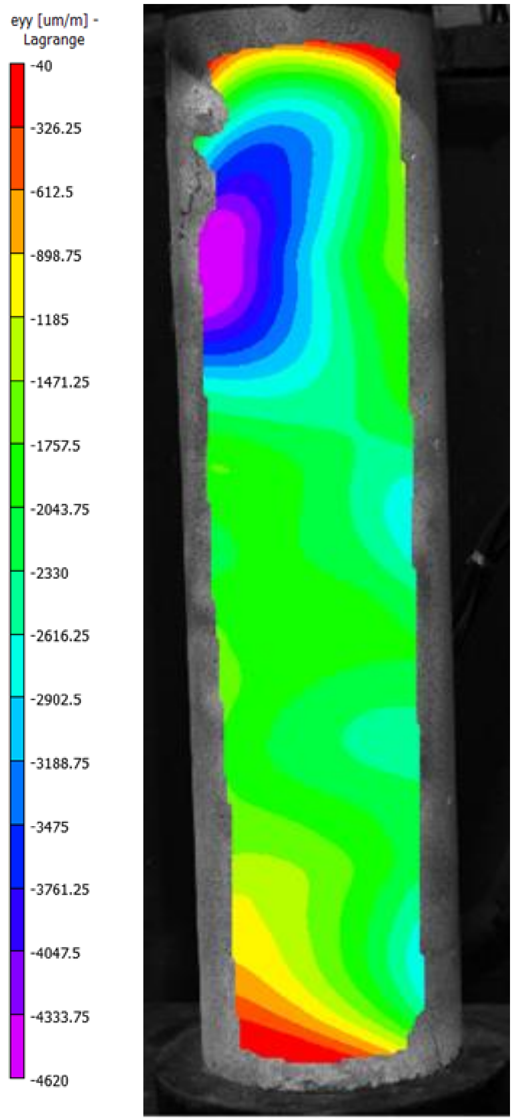
Strain Plot just before complete failure

Load Vs Average Strain in the High Strain Zone



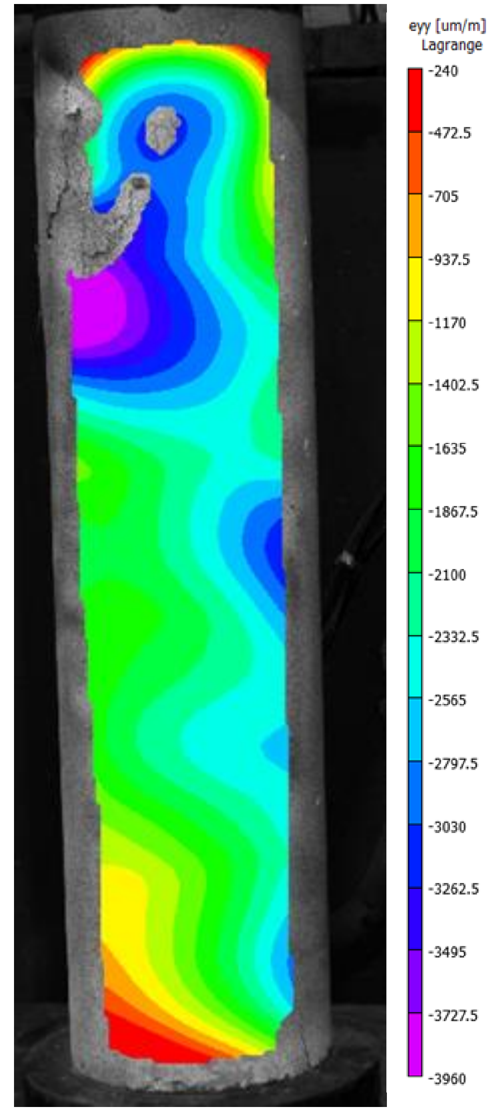
Strain Measurement on a Concrete Column

Compressive Load was applied on a Concrete Column 800 mm Long , 218mm Diameter.



ε_{yy} at Peak Load – 1230 kN

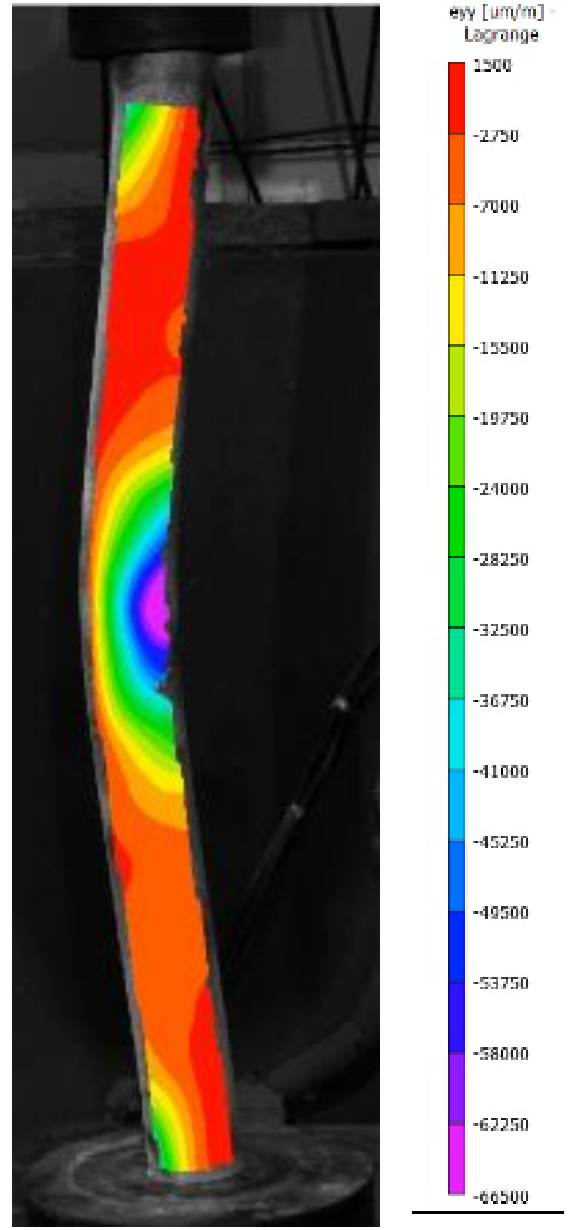
Strain Plot shows the propagation of the Fracture Process Zone



ε_{yy} just before failure

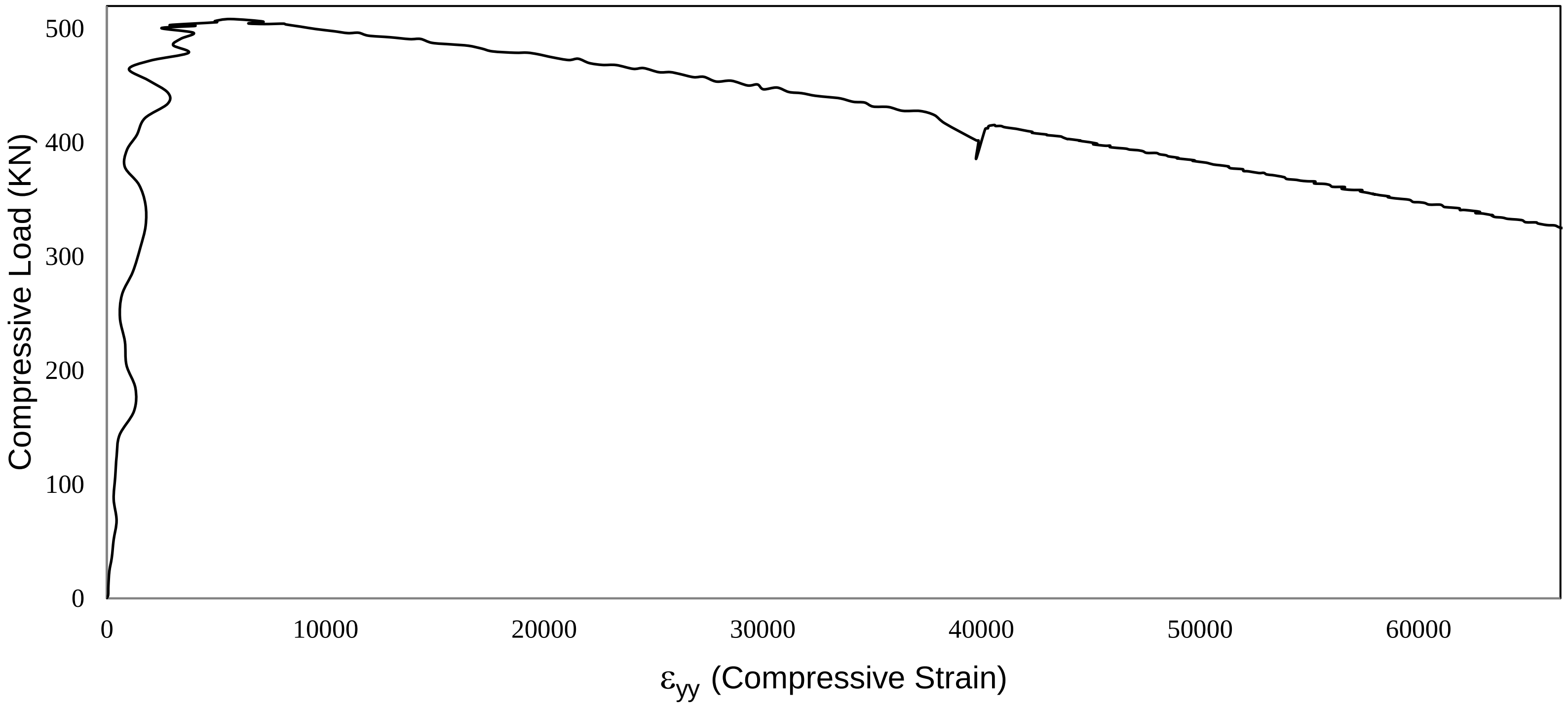
Concrete Column wrapped with Galvanised Iron Sheet

A concrete column – 800mm long, 75mm Diameter was wrapped with a 3mm thick GI sheet and was subject to a compressive load



ε_{yy} Plot

Average ε_{yy} in the High Strain Zone Vs Load



List of End Users of VIC-3D/2D Systems In India & UAE.

- Indian Institute of Technology – Kharagpur – Department of Civil Engineering.
- Indian Institute of Technology – Kanpur – Department of Materials Science and Engineering.
- Indian Institute of Technology – Roorkee– Department of Civil Engineering.
- Indian Institute of Technology – Hyderabad – Department of Civil Engineering.
- National Aerospace Laboratories – Bengaluru.
- Indian Institute of Technology – Chennai – Department of Aerospace Engineering.
- India Science Lab – General Motors Technical Centre – India.
- Indian Institute of Technology – New Delhi – Department of Applied Mechanics.
- 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 – Kolkatta.
- Indian Institute of Science – Bengaluru – Department of Aerospace Engineering.
- Indian Institute of Technology – Hyderabad – Department of Mechanical Engineering.
- 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.
- Tata Steel – Tatanagar.
- GEITC – John Welch Technology Centre – Bengaluru.
- Masdar Institute of Technology – Abu Dhabi.
- KAUST – Saudi Arabia.

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 $\mu\varepsilon$ 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:- mm^2 to a few m^2
- ✓ Strain Range:- Upto 100's of % Strain.
- ✓ High Strain Zones easily identified.
- ✓ Generally 5MP USB cameras with 75fps are used for DIC Measurements.
- ✓ However the recent trend is to use Cameras with a resolution of 8.9 to 12.3 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.

✓ Cameras with 2 MP Resolution and frame rates of 162 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.

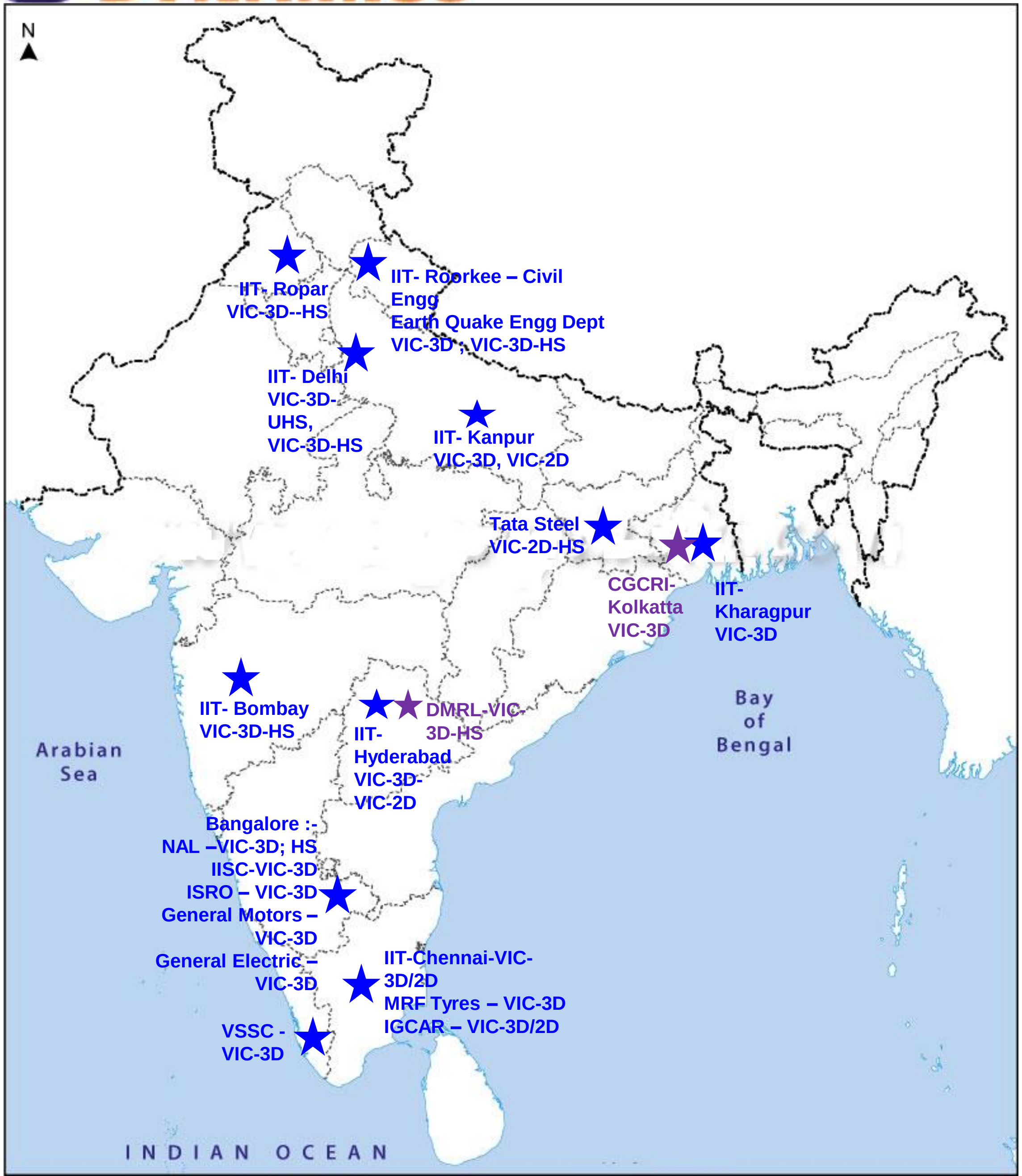
✓ The future is to use Volumetric Digital Image Correlation. VDIC has the promise and capability to carry out DIC Measurements insitu of the structure (Something that was carried out so far only through Fiber Optic Sensors).

This technique is still in the University Research and will be commercially available soon.

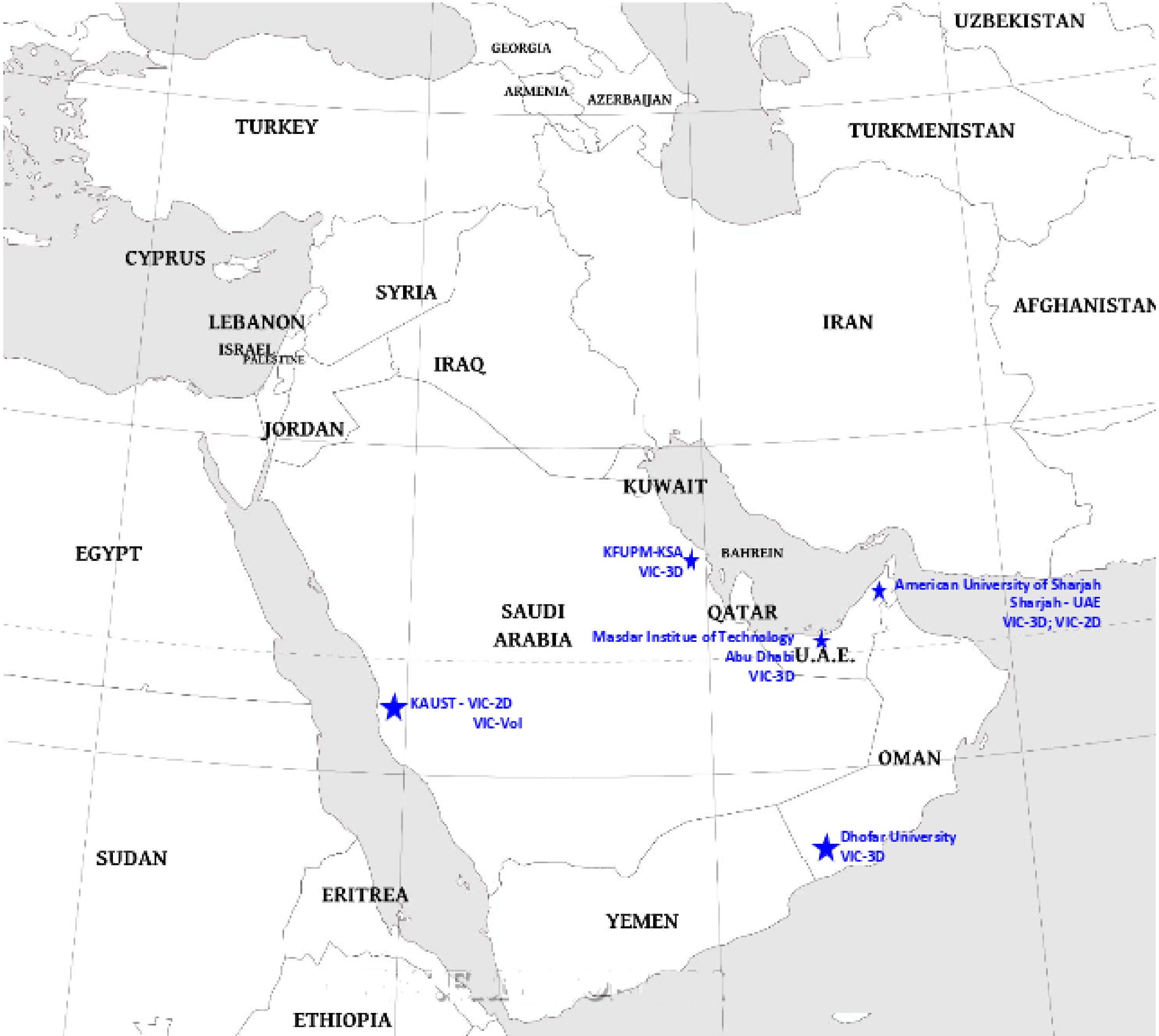
Limitations of DIC

× Optical Access of The Test Object is a must.

VIC-3D User Map - India.



VIC-3D User Map – UAE & Gulf



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Lets Think Collectively

Thank You

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