The feasibility of dynamic full-field earthquake measurements from space: a laboratory study

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Summary

Background

Experimental setup

Experimental Method: Digital Image Correlation

Displacement field – Test1
The importance of filtering data

Displacement field – Test2
COSI-Corr vs. VIC-2D

Strains – Test1

How accurate are our results
Error analysis

High Speed Photography
Preliminary results
Geostationary Space Telescope: A Laboratory Study

White Light source

Specimen

High speed camera system

Analyze images with Digital Image Correlation techniques (e.g. COSI-Corr, VIC-2D)
• Earthquakes are mimicked in the laboratory by the dynamic rupture propagating along an inclined frictional interface formed by two Homalite quadrilateral plates under compression (Xia et al., 2004).
• Dynamic rupture is triggered through the electrical discharge provided by a NiCr wire filament.
Geometry and Loading Configuration

We will discuss two tests:

• $P = 5$ MPa (subRayleigh)
• $P = 15$ MPa (supershear)

Expected rupture speed (from previous experiments)
Digital Image Correlation (DIC) is an optical method to measure the deformation on a specimen surface. DIC technique identifies gray level patterns in small pixel subsets and tracks their motion during deformation. Two methods are used in this study:

- **COSI-Corr** (Leprince et. al, 2007).
- **VIC-2D** (Correlated Solutions Inc.)

**High Speed Camera:**

Cordin 220
767x 574 pixels

**CCD Camera:**

JAI Pulnix/TM4200CL
2048 x 2040 pixels

Before dynamic rupture

After dynamic rupture

Glued interface

Hypocenter

Large: characteristic pattern
Small: high resolution

Subset size: 32x32
Step: 4
Displacement Field - Unfiltered

Test 1, \( P = 5 \) MPa

Correlation parameters

- Subset size: 32
- Step: 4

Profile #1

Profile #2

Horizontal displacement

Vertical displacement

Location along profile

Displacement

Location along profile

Displacement
Displacement Field - *Filtered*

**Test 1, P = 5 MPa**

**Horizontal displacement**
- Profile #1
- Profile #2

**Vertical displacement**
- Profile #1
- Profile #2

Filtering parameters:
- Noise param.: 0.1
- Window size: 51 x 51
- Patch size: 5 x 5

Non local means filter (Buades et al., 2008)
The Non Local Means Filter (NL-Means)
(Buades et al., 2008; Goosens et al. 2008)

- Local smoothing filters give blurred edges
- In contrast the NL-means filter avoids the blurring effect

- It is very useful to accurately reproduce the displacement field of our experiments, which contains sharp edges near the interface and wing cracks.

- In an image, most details occur repeatedly.
- For example, each color box in the image to the left refers to a group of squares which are almost indistinguishable
- The NL-means filter exploits this property of image self-similarity to eliminate noise
- The squares similar to each other are averaged out.

COSI-Corr includes in its tools an implementation of the Non-Local Means algorithm for denoising datasets and images, based on Buades et al., 2008 and Goosens et al., 2008.
Strain Calculation

Before filtering

After filtering

Centered difference formula
Fault parallel and fault normal displacements

Test 1, \( P = 5 \) MPa

Overall the results show that rupture has propagated along the frictional interface, consistent with Rosakis et al. (2007), but has been stopped at the glued boundaries.
Normal and Shear Strains

Test 1, \( P = 5 \text{ MPa} \)

The method allows to determine the complete state of strain (and stress) of virtually any point within the field of view.
COSI-Corr vs. VIC-2D (Test 2, $P = 15$ MPa)

Due to the presence of secondary mode I cracks, VIC-2D correlation fails to converge.

COSI-Corr discards subsets where the correlation does not converge.
Error Analysis
Correlation of two nominally identical images

Gaussian fit to FP PDF
Bias=2.4 µm
Standard deviation= 1.7 µm

Gaussian fit to FN PDF
Bias=2.1 µm
Standard deviation= 1.3 µm
High speed digital image correlation

- **Problem**: Reduce method’s error in μm
- **Solution**: Reduce pixel size by reducing the field of view

Quotes in mm

*Time-series* of displacement fields

Fault parallel displacement (µm)

<table>
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<th>50</th>
<th>100</th>
<th>150</th>
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<td>20</td>
</tr>
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</tr>
<tr>
<td>9</td>
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<td>80</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
</tbody>
</table>

1 pixel ~ 83 µm (Before)

1 pixel ~ 55 µm (Now)
Displacement time series

Fault parallel displacement ($\mu m$) $t=50 \mu s$

Fault parallel displacement ($\mu m$) $t=45 \mu s$

Fault parallel displacement ($\mu m$) $t=40 \mu s$

Fault parallel displacement ($\mu m$) $t=50 \mu s$

Fault parallel displacement ($\mu m$) $t=30 \mu s$

Fault parallel displacement ($\mu m$) $t=35 \mu s$

Fault parallel displacement ($\mu m$) $t=25 \mu s$

Subset: 61 pixels
Step: 4 pixels

NLMeans filter
- Noise par H = 1
- Search area: 21
- Patch size: 5x5

$\Delta u_1$
Fault parallel displacement ($\mu$m)

Subset: 61 pixels
Step: 4 pixels

NLMeans filter
- Noise par H = 1
- Search area: 21
- Patch size: 5x5

- Interface length (shown in frame): $\sim$40 mm
- Rupture goes through interface in $t < 20$ $\mu$s
- Computed rupture speed: $v_r \sim 2.5$ mm/$\mu$s
- Compare to Homalite wave speeds:
  - $c_s = 1.29$ mm/$\mu$s
  - $c_p = 2.61$ mm/$\mu$s
- Mach cone angle is given by:
  \[ \sin \theta = \frac{c_s}{v_r}, \quad \theta \sim 30^\circ \]
- Mach cone will advance $\sim$ 12.5 mm
Displacement time series – Fault parallel

Subset of 61 vs 31 filtered

Displacement field improved… but not good enough to obtain strains yet
Quantifying errors (from gaussian fits)

Effect of subset size

- Correlate two nominally identical images
- The displacement field obtained is taken as a measure of the method’s error
- Increasing the subset size has the effect of reducing the error standard deviation but not the bias
Quantifying errors (from gaussian fits)
Effect of filtering

- Correlate two nominally identical images
- The displacement field obtained is taken as a measure of the method’s error
- Filtering with the NLMeans has the effect of reducing the error standard deviation but not the bias

Standard deviation can be reduced by filtering and increasing subset size, how about the bias?
How can we reduce the bias?

BIAS due to:

- Interpolation
- Noise
- Mismatched shape functions
- Image contamination (e.g. dust on sensor)
- Aliasing -> speckle pattern
- Other causes e.g. lighting change, pattern degradation

Static vs. Dynamic Bias

<table>
<thead>
<tr>
<th>Regime</th>
<th>Static</th>
<th>Dynamic</th>
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</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>83 µm</td>
<td>83 µm</td>
</tr>
<tr>
<td>Bias (µm)</td>
<td>2.4 µm</td>
<td>3.5 µm</td>
</tr>
<tr>
<td>Bias (pixel)</td>
<td>1/35 pixel</td>
<td>1/16 pixel</td>
</tr>
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</table>

Dynamic bias is \( \sim 2.2 \) times larger than static.

How can we do better?

\[ 2.4 \, \mu m \times \frac{1}{83} \, \frac{\text{pixel}}{\mu m} = 0.0289 \]
Troubleshooting...

**Measurement chain involves:**

- **Specimen** → speckle pattern
  
  - fine (3-4 pixels)

- **Plano convex lens** → may introduce distortions

- **Light source** → lighting change from image to image

- **Intensified high speed camera** → will tests two other technologies which
  - may reduce the noise/error but
  - exposure time is worse/larger

  - COSI-Corr more accurate
  - VIC-2D more robust to noise
Conclusions and Future Work

• Successfully characterized full-field static displacements and strain of a dynamic crack with digital image correlation techniques.

• Two DIC software packages have been tested: COSI-Corr outperforms VIC-2D, especially in the presence of opening cracks, such as in Test 2.

• Performed dynamic measurements with high speed camera to capture the time dependent behavior.
Broader goals of the project

- Study the effects of surface roughness and variability, material inhomogeneity, etc.
- Include spontaneous nucleation

High speed Digital Image Correlation

**Time-series** full-field displacement maps

\[ \frac{\partial (.)}{\partial t} \]

Velocity fields

\[ \frac{\partial (.)}{\partial x} \]

Strain fields

+ constitutive properties

Enable stress measurements in the laboratory specimen

Constrain seismic inversions

Characterize ground shaking attenuation away from the fault

Understand nature of frictional law