An experimental testing system for fiber reinforced polymer (FRP) strengthened concrete panels under uniform pressure loads

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<th>Overview of the presentation</th>
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<td>• Motivation for the research</td>
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<td>• Concrete panel and FRP configurations</td>
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<td>• Testing results</td>
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• Determine the design parameters that govern use of fiber reinforced polymer (FRP) strips for external reinforcement of existing concrete structures
Concrete panel specimens

2.1-m x 2.1-m x 64-mm panels
Cylinder strength: 30MPa
9.5-mm coarse rock aggregate

Phase 1
3.42-mm diameter – 75-mm spacing
Yield: 710 MPa
Ultimate: 731 MPa
Elongation: 0.5%

Phase 2
6.35-mm diameter – 150-mm spacing
Yield: 314 MPa
Ultimate: 459 MPa
Elongation: 27.5%
Coated with epoxy bonded sand
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FRP patterns

Phase 1

Phase 2

* Glass fiber strips
Uniform pressure loading

- FRP (tension)
- Steel (tension)
- Concrete (compression)
- Pressure
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Loading system

Maximum pressure = 62 kPa
Distributed load = 278 kN
Loading system

Maximum pressure = 62 kPa
Distributed load = 278 kN
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DIC in two dimensions

CCD camera

PC with digitizer

White light sources

Specimen

90°
Two-dimensional image correlation is based on the ability to accurately match portions from one image to corresponding locations in a second image.

Correspondence can be determined to within 0.02 pixels.
Because the method is computer based we can perform the matching on a large number of points in the image.
Displacement example

Vertical displacements
2.0 pixels/contour

Horizontal displacements
0.5 pixels/contour
The image correlation method can be broken into four segments that answer the following questions:

1. How do you differentiate a positions on the image?
2. How do I get from here to there?
3. How do you work on a scale smaller than a pixel?
4. How do you determine the optimal mapping parameters?
Patterns and grayscales

From an image, how do you know where you are on the surface?
Patterns and grayscales
Constant displacement mapping:

\[ q_x = Q_x + u_c \]
\[ q_y = Q_y + v_c \]
Constant strain mapping:

\[ q_x = Q_x + u_c + (Q_x - C_x) \frac{du_c}{dx} + (Q_y - C_y) \frac{du_c}{dy} \]

\[ q_x = Q_x + v_c + (Q_x - C_x) \frac{dv_c}{dx} + (Q_y - C_y) \frac{dv_c}{dy} \]
Constant strain mapping:

\[
q_x = Q_x + u_c + (Q_x - C_x) \frac{du_c}{dx} + (Q_y - C_y) \frac{du_c}{dy}
\]

\[
q_x = Q_x + v_c + (Q_x - C_x) \frac{dv_c}{dx} + (Q_y - C_y) \frac{dv_c}{dy}
\]
Working at sub-pixel scales
Working at sub-pixel scales

Raw image data

Bi-linear interpolation

Bi-cubic interpolation

Cubic spline interpolation
How do we determine the optimal mapping parameters?
common error functions:

(a) $\sum_i |I'(q_i) - I(Q_i)|$ (magnitude of the intensity differences)

(b) $\sum_i (I'(q_i) - I(Q_i))^2$ (sum of the squares of intensity differences)

(c) $1 - \frac{\sum_i (I'(q_i) I(Q_i))}{(\sum_i (I'(q_i)^2)^{1/2} (\sum_i (I(Q_i)^2)^{1/2})}$ (normalized cross-correlation)

error is minimized using a Newton-Raphson based optimization technique
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Extension into 3D Space

PC with digitizer

Camera 1

Camera 2

Specimen/grid location
Camera parameters

Intrinsic Parameters:
- PhD - Pinhole Distance
- Cx - Hor. Image Center
- Cy - Vert. Image Center
- κ - Lens Distortion Coef.

Extrinsic Parameters:
- α - Rotation about Z Axis
- β - Rotation about Y Axis
- γ - Rotation about X Axis
- Xo - X Axis Offset
- Yo - Y Axis Offset
- Zo - Z Axis Offset
System calibration

Calibrations methods use a combination of known points from standards and correspondence between cameras to determine each camera’s parameters.
Shape Measurement

Camera 1

Surface in space

Camera 0

Undeformed Image Cam 1

Undeformed Image Cam 0
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Displacement Measurement

Camera 1

Undeformed Image Cam 1

Deformed Image Cam 1

Camera 0

Undeformed Image Cam 0

Deformed Image Cam 0

Displaced location

Surface in space

Displacement
Displacements to strains

Strains determined from curve fitting local areas of data

Local areas define a quasi gage-length for the calculations
Strain example

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| Measurement system |
|--------------------|---|
| ![Image of measurement system](image) |
Measurement system
Panel configurations

Control panel  

FRP panel

Local area

Global area

1.98 m

0.30 m
<table>
<thead>
<tr>
<th>Surface patterns</th>
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<tbody>
<tr>
<td>global pattern as imaged from the global cameras</td>
</tr>
<tr>
<td>global and local pattern as imaged from the local cameras</td>
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Center point displacement

![Graph showing center point displacement and pressure relationship for control panel and FRP panel.]

- **Center point displacement (mm)**
- **Pressure (kPa)**

- **Graph legend:**
  - Red squares: control panel
  - Blue diamonds: FRP panel
Control panel displacement

Animation / Video
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Out-of-plane displacements

Control panel

FRP panel
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Strain progression

Animation / Video
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Failure strains

strain map (1st princ. strains)

strains along each FRP strip

\( E_1 \):

Table:

<table>
<thead>
<tr>
<th>Strip</th>
<th>E1 Strain</th>
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<tr>
<td>Y = -150 mm strip</td>
<td>0.0125</td>
</tr>
<tr>
<td>Y = -450 mm strip</td>
<td>0.005</td>
</tr>
<tr>
<td>Y = -750 mm strip</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Graph:

- Red line: Y = -150 mm strip
- Blue line: Y = -450 mm strip
- Green line: Y = -750 mm strip

Graph x-axis: X location (mm)
Graph y-axis: Strip strain
Failure modes

Shear-Flexure Failure – Type 1

Shear-Flexure Failure – Type 2

Shear-Flexure Failure – Type 3

*Glass only
Control phase 1
ultimate = 26.9 kPa
max deflection = 55.6 mm

ultimate pressure/control pressure
displacement in mm
Control phase 1
ultimate = 34.8 kPa
max deflection = 135.1 mm

<table>
<thead>
<tr>
<th>U/C</th>
<th>Disp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>135.1</td>
</tr>
<tr>
<td>0.96</td>
<td>59.6</td>
</tr>
<tr>
<td>1.65</td>
<td>75.5</td>
</tr>
<tr>
<td>0.92</td>
<td>125.8</td>
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</table>
• Determine the design parameters that govern use of fiber reinforced polymer (FRP) strips for external reinforcement of existing concrete structures

  ✓ Develop a method to apply a uniform distributed pressure load to large (7ft x 7ft) panels of steel reinforced concrete

  ✓ Adapt the digital image correlation (DIC) technique to measure full-field displacements and strains in the panels

  ✓ Acquire panel failure data for a variety of FRP reinforcement configurations

  ✓ Analyze the raw image data to obtain full-field displacements, strains and crack patterns

• Use the data to develop design criteria for FRP reinforcement of concrete panels