Structural Health Monitoring of a Reinforced Concrete Beam
Using Finite Element Analysis

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SERG
Outline

- Introduction
- Objective
- Literature Review
- Finite Element Modeling
- Materials Properties
- Experimental Work
- Finite Element Model Validation
- Damage Modeling
- Defect Detection Methodology
- Conclusion
- Future Work
Introduction

- **Structural Health Monitoring (SHM):** The process of implementing a damage identification strategy for civil, mechanical, and aerospace engineering infrastructure is referred to as SHM.

  **Damage:** • Material properties • Geometric properties • Boundary conditions • System connectivity

- **Why SHM?** • Public safety • Economical benefit

- **SHM system:**

<table>
<thead>
<tr>
<th>Sensing technology</th>
<th>Power technology</th>
<th>Communication devices</th>
<th>A monitoring station</th>
<th>Signal processing algorithm</th>
<th>Health evaluation algorithm</th>
</tr>
</thead>
</table>

- **Sensors** can measure (1) **mechanical quantities** (2) thermal quantities (3) electromagnetic/optical quantities and (4) chemical quantities

- Surface strain measuring sensors are widely use in SHM.
## Introduction

- Applicability of fiber optic sensor (FOS) and digital image correlation (DIC) in strain measurements:

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Types of surface strain measurement</th>
<th>Subsurface strain measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Points</td>
<td>Lines</td>
</tr>
<tr>
<td>FOS</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DIC</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- How can surface strain measurement be used to evaluate structural integrity?
- To determine structural health using surface strain measurement is a challenging real-life engineering problem. It is an inverse problem.
- Inverse problem?
Introduction

- Forward problem example
  - Geometry
  - Boundary conditions
  - Forcing functions
  - Governing Equations
  - Material properties

- Inverse problem in this research ★
  - Incomplete geometric information
  - Boundary conditions
  - Forcing functions
  - Governing Equations
  - Material properties
  - Structural response (ε)

➢ Knowledge of forward problem solution can be used to solve the inverse problem.
Objective

- The research objective of this study is to develop a damage detection methodology to relate surface strain measurement to internal conditions (e.g., healthy or damaged) using a singly-reinforced concrete beam as an example.
Literature Review

Internal condition assessment using surface measurements/inverse problem solution techniques for civil infrastructures

Wang et. al. [2010]; Nazmul et. al. [2004, 2007]; Cox et. al. [1991]

<table>
<thead>
<tr>
<th>Theoretical approach</th>
<th>• Applicable for solving inverse problem using precise local measurements.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical approach</td>
<td>• Can be used in <strong>global damage detection</strong></td>
</tr>
<tr>
<td></td>
<td>• Sensitive-based FE model updating is frequently used in damage detection</td>
</tr>
</tbody>
</table>

04/19/2013
FE modeling of RC beam using ABAQUS® can simulate behavior of RC beam.

Sinaei et al. [2012]; Alih et al. [2012]; Wahalatha ntri et. al. [2011]

Meshing

- Meshing element for concrete → C3D8R
- Meshing element for rebars → T3D2
- Suitable mesh size

Material properties

- Complete σ-ε curve of concrete → Hsu and Hsu [1994]
- Perfect elastic plastic model for steel
- Plastic damage of concrete → Hu et. al [2010]

Interaction

- Interaction option → embedded
- Tension stiffening → Nayal and Rasheed [2006]
Literature Review

Surface and subsurface strain measurements

FOS
- Maximum capacity ≤ 4000 µ (Ref. Deng et. al. [2007])
- Good agreement (≤ 5%) with ERSG*
- Applicability: axial compression test, high-stress low-cycle loading test, and bending test
- Subsurface measurement in concrete (Ref. Yang et. al. [2009])
- Measurements have good agreement with FEA

DIC
- Early crack detection and measuring in RC structures
- Measure stain on a plane
- Suitable for in situ damage detection
- Good agreement with FEA
(Ref.: Mulle et. al. [2009], Destrebecq et. al. [2011], Hild et. al. [2006], Kamay et. al. [2011])

* Electrical Resistance Strain Gauge
To develop an internal damage detection methodology using surface strain measurement

Theoretical calculation of structure behaviors

Develop a FE model

Model tuning ($\sigma$-$\epsilon$, $\nu$, mesh size)

FE model validation

Conduct test to measure surface strains of the intact RC structure

Introduce defects to the validated FE model

Simulated response of the damaged RC beam model

Develop relationship between internal defect and surface stress/strain change pattern.

Develop an internal damage detection procedure using surface strain measurement
FE Modeling

- **Meshing and interaction:**
  - Element to model concrete → C3D20
  - Element to model rebar → C3D8
  - Mesh edge size for concrete → 0.3"
  - Mesh edge size for rebar → 0.25"
  - Total elements in the model → 45,056
  - Total variables → 579,285
  - Interaction between concrete and rebar → embedded

- **Loading and B.C.:**
  - Simply supported
  - Loaded area → 0.125" x 6"
  - Loading level → from 0 to 2.2 kips at four steps
FE Modeling

- Materials properties
  - Elastic properties:
    - \( E_c = 57,000 \sqrt{\sigma_{cu}} \) (ACI 318, units in psi)
    - \( \nu_c = 0.16 \) (Ref. Bonfiglioli et. al. [2003])
    - \( E_s \rightarrow \) Experimentally obtained \( \rightarrow 30 \times 10^6 \) psi
    - \( \nu_s = 0.3 \)
  - Plastic properties and interaction:

<table>
<thead>
<tr>
<th>Model</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hsu and Hsu [1994]</td>
<td>To obtain complete ( \sigma-\varepsilon )</td>
</tr>
<tr>
<td>Perfect elastic-plastic material property</td>
<td>( \sigma-\varepsilon ) behavior of steel</td>
</tr>
<tr>
<td>Nayal and Rasheed model [2006] (Modified by Walhalathantri et. al. [2011])</td>
<td>Simulate interaction between concrete and rebars</td>
</tr>
</tbody>
</table>
Research Roadmap

To develop an internal damage detection methodology using surface strain measurement

Theoretical calculation of structure behaviors

Develop a FE model

Find materials properties

Model tuning (materials $\sigma$-$\epsilon$, $\nu$, mesh size)

FE model validation

Conduct test to measure surface strains of the intact RC structure

Introduce defects to the validated FE model

Simulated response of the damaged RC beam model

Develop relationship between internal defect and surface stress/strain change pattern.

Develop an internal damage detection procedure using surface strain measurement
Materials Properties

- Materials Testing
  - Steel → tension test of rebar
  - Concrete → ASTM standard compression test (C39/C39M)

- Tension Test of rebar
  - Specimen:
    - #4 steel rebar
    - Length → 14”
  - Test result: $f_y \rightarrow 70$ ksi, $E_s = 30 \times 10^6$ psi

- Compression test of concrete
  - ASTM C39/C39M
  - Specimen: Two 4” x 8” cylinders
  - Test result: $\sigma_{cu} = 6,500$ psi
Materials Properties

- **Hsu and Hsu model [1994]**
  
  - A dependent parameter, $\beta = 1/1 + (\sigma_{\text{cu}} / \varepsilon_{\text{o}} E_{\text{o}})$
  
  - Strain at peak stress, $\varepsilon_{\text{o}} = 8.9 \times 10^{-5} \sigma_{\text{cu}} + 3.28312 \times 10^{-3}$
  
  - Peak tangential modulus, $E_{\text{o}} = 1.2431 \times 10^{2} \sigma_{\text{cu}} + 3.28312 \times 10^{3}$
  
  Where,

  - $\sigma_{\text{c}}$ = compressive stress values
  - $\sigma_{\text{cu}}$ = Ultimate compression stress (obtained from standard compression test ASTM C39/C39M)
  - $\varepsilon_{\text{c}}$ = compressive strain (domain)

  - Inelastic strain, $\varepsilon_{\text{c}}^{\text{in}} = \varepsilon_{\text{c}} - \varepsilon_{\text{oc}}^{\text{el}}$
  
  - Damage parameter, $d_{\text{t}} = \varepsilon_{\text{c}}^{\text{in}} / \varepsilon_{\text{c}}$
  
  - Plastic strain, $\varepsilon_{\text{c}}^{\text{pl}} = \varepsilon_{\text{c}}^{\text{in}} - \frac{d_{\text{t}} \sigma_{\text{c}}}{(1 - d_{\text{t}})E_{\text{o}}}$

  \[
  \varepsilon_{\text{oc}}^{\text{el}} = \frac{\sigma_{\text{c}}}{E_{\text{o}}}
  \]

  Complete $\sigma$-$\varepsilon$ curve of concrete obtained from Hsu & Hsu model

  \[
  \sigma_{\text{c}} = \beta \varepsilon_{\text{c}} / \varepsilon_{\text{o}} / \beta - 1 + (\varepsilon_{\text{c}} / \varepsilon_{\text{o}}) \beta \cdot \sigma_{\text{cu}}
  \]

<table>
<thead>
<tr>
<th>Stress, $\sigma_{\text{c}}$</th>
<th>Damage parameter, $d_{\text{t}}$</th>
<th>Inelastic strain, $\varepsilon_{\text{c}}^{\text{in}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25E+03</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>3.56E+03</td>
<td>8.69E-03</td>
<td>6.20E-05</td>
</tr>
<tr>
<td>3.72E+03</td>
<td>1.01E-02</td>
<td>7.24E-05</td>
</tr>
<tr>
<td>3.88E+03</td>
<td>1.17E-02</td>
<td>8.38E-05</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Materials Properties

- Naylor and Rasheed tension stiffening model [2006] (Modified by Walhalathantri et. al. [2011])
  
  \[ \sigma_{cr} = 7.5 \sqrt{\sigma_{cu}} \]

- Cracking strain, \( \varepsilon_{t}^{ck} = \varepsilon_{c} - \varepsilon_{t}^{el} \)
  \[ \varepsilon_{t}^{el} = \sigma_{t} / E_{o} \]

- Plastic strain, \( \varepsilon_{t}^{pl} = \varepsilon_{c}^{in} - \frac{d_{t} \sigma_{c}}{(1-d_{t})E_{o}} \)

- Damage parameter, \( d_{t} = \frac{\varepsilon_{t}^{in}}{\varepsilon_{c}} \)

### Table

<table>
<thead>
<tr>
<th>Stress, ( \sigma_{c} )</th>
<th>Strain, ( \varepsilon_{t} )</th>
<th>Elastic strain, ( \varepsilon_{el} )</th>
<th>Cracking strain, ( \varepsilon_{ck} )</th>
<th>Damage parameter, ( d_{t} )</th>
<th>Plastic strain, ( \varepsilon_{pl} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>604.66</td>
<td>1.48E-04</td>
<td>1.48E-04</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
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<tr>
<td>465.59</td>
<td>1.85E-04</td>
<td>1.14E-04</td>
<td>7.10E-05</td>
<td>3.84E-01</td>
<td>7.09E-05</td>
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<td>272.10</td>
<td>5.91E-04</td>
<td>6.65E-05</td>
<td>5.25E-04</td>
<td>8.88E-01</td>
<td>5.17E-04</td>
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<td>60.46</td>
<td>1.48E-03</td>
<td>1.48E-05</td>
<td>1.27E-03</td>
<td>9.89E-01</td>
<td>-7.48E+02</td>
</tr>
</tbody>
</table>

Tension stiffening (Ref. Naylor et. al. [2006])
From Euler–Bernoulli beam theory,

- Effective flexural rigidity,

\[ EI = \sum_{i=1}^{N,L} E_i I_i \]

In un-cracked section,

\[ EI = E_c (b h^3 / 12 + bh \cdot e_1 \cdot h^3 + (n-1) A_s \cdot e_2 \cdot h^3) \]

where,

- \( e_1 \) = distance from concrete section c.g. to section c.g.
- \( e_2 \) = distance from equivalent concrete section c.g. to section c.g.

- \( M_{\text{int}} = EI \varepsilon^* / y \)

\[ \varepsilon^* = M_{\text{int}} * y / EI \]
FE Model Response

- **FEA results**
  - $\varepsilon_{zz}$ at loading level 2.2 kips
  - $\varepsilon_{\text{th}} = 131 \mu$ 
  - $129 \mu$

- $n = \frac{E_s}{E_c} = \frac{30}{4.59} = 6.53$

- $n = \frac{E_s \varepsilon}{E_c \varepsilon} = \frac{\sigma_s}{\sigma_c}$

- $\sigma_c = 2330 / 357 = 6.53$
Rebar stress from FEA results:

- $\sigma_{zz}$ at loading level 2.2 kips

- $\sigma_{num} = 2613$ psi
- $\sigma_{thr} = 2676$ psi

$\frac{\sigma_{thr} - \sigma_{num}}{\sigma_{thr}} \times 100 = 2.35\%$
To develop an internal damage detection methodology using surface strain measurement

1. Theoretical calculation of structure behaviors
2. Develop a FE model
3. Find materials properties
4. Model tuning
   - (σ-ε, ν, mesh size)
5. Conduct test to measure surface strains of the intact RC structure
6. Introduce defects to the validated FE model
7. Simulated response of the damaged RC beam model
8. Develop relationship between internal defect and surface stress/strain change pattern.
9. Develop an internal damage detection procedure using surface strain measurement
Experimental Work

- **Specimen:**
  - 6” x 6” x 35” RC beam
  - 2-#4 steel rebars in the tension zone
  - Mix proportion of concrete (by volume) = 1:1.5:3 (cement: sand: gravel)
  - Water to cement ratio = 0.5 (by weight)
Experimental Work

- Maximum load and loading levels:
  - $\sigma_{cr} = 7.5 \sqrt{\sigma_{cu}} = 604.66$ psi
  - $M_{cr} = \sigma_{cr} I g / y t = 24.11$ k-in
  - $P_{\text{max}} = M_{cr} / l = 2.29$ kips

- Loading level steps: 2.2 kips, 2.0 kips, 1.5 kips, 1.0 kip, and 0.5 kip
Experimental Work

- **Test schedule**

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Loading levels and cycles</th>
<th>Date</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k</td>
<td>Aug. 1, 2012</td>
<td>DIC, FOS, and radar</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k</td>
<td>Sep. 27, 2012</td>
<td>FOS and radar</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k</td>
<td>Oct. 05, 2012</td>
<td>FOS and radar</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>3 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k</td>
<td>Jan. 25, 2013</td>
<td>FOS and radar</td>
</tr>
</tbody>
</table>

- **Equipment:**
  - **Load cell:**
    - Model Name: Lebow 3175
    - Maximum capacity → 50,000 lb.
  - **FOS:**
    - Model name: os3110
    - Maximum capacity → +/- 2500 µε
  - **DIC:**
    - Resolution → 4096 x 3072
Experimental Work

- FOS measurement:

![Graph showing FOS response and filtered data over time.](image)
Theoretical and FEA comparison

Validation using experimental measurements

\[ \varepsilon^* = \frac{M_{int} \cdot y}{EI} \]
To develop an internal damage detection methodology using surface strain measurement

Theoretical calculation of structure behaviors

Develop a FE model

Model tuning

\( (\sigma-\epsilon, \nu, \text{mesh size}) \)

FE model validation

Conduct test to measure surface strains of the intact RC structure

Introduce defects to the validated FE model

Simulated response of the damaged RC beam model

Develop relationship between internal defect and surface strain/stress change pattern.

Develop an internal damage detection methodology using surface strain measurement
**Damage Modeling**

- **Definition of damage:**
  - Reduction of steel rebar cross section/volume
  - To simulate rebar corrosion
  - Cross sectional reduction, \( \Delta A_s = A_{so} - A_{sr} \)
    \[ \frac{A_{so}}{} * 100 \]
  - Volume reduction, \( \Delta V_s = V_{so} - V_{sr} / V_{so} \)
    \[ *100 \]

<table>
<thead>
<tr>
<th>( \Delta A_s(%) )</th>
<th>( V_{so} - V_{sr}(in^3) )</th>
<th>( \Delta V_s ) (1-in defect)</th>
<th>( \Delta V_s ) (5-in defect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.013</td>
<td>6.633</td>
<td>5.736</td>
</tr>
<tr>
<td>15</td>
<td>0.020</td>
<td>10.204</td>
<td>8.768</td>
</tr>
<tr>
<td>20</td>
<td>0.026</td>
<td>13.265</td>
<td>11.402</td>
</tr>
<tr>
<td>25</td>
<td>0.033</td>
<td>16.837</td>
<td>14.419</td>
</tr>
<tr>
<td>30</td>
<td>0.040</td>
<td>20.408</td>
<td>17.836</td>
</tr>
<tr>
<td>36</td>
<td>0.048</td>
<td>24.48</td>
<td>21.635</td>
</tr>
</tbody>
</table>
Damage Modeling

- Artificial damage scenarios:
  (i) Type I
  (ii) Type II
  (iii) Type III
  (iv) Type IV

- Damage intensity, $\Delta A_s \rightarrow 36\%, 30\%, 25\%, 20\%, 15\%$, and $10\%$
• Subcategories of Type I are
  (a) Type I-I (Symmetric) and
  (b) Type I-II (Nonsymmetrical)
• Damage intensity, $\Delta A_s \rightarrow 36\%, 30\%, 25\%, 20\%, 15\%, \text{ and } 10\%$
Damage Modeling

- Subcategories of Type II are
  - (a) Type II-I (Symmetric)
  - (b) Type II-II (Nonsymmetrical)
- Damage intensity, $\Delta A_s \rightarrow 36\%, 30\%, 25\%, 20\%, 15\%$, and $10\%$
• Type III does NOT have any subcategory.
• Damage intensity, $\Delta A_s \rightarrow 36\%, 30\%, 25\%,$
  $20\%, 15\%,$ and $10\%$
Damage Modeling

- Subcategories of Type IV are
  (a) Type IV-I (Symmetric) and
  (b) Type IV-II (Nonsymmetrical)
- Damage intensity, $\Delta A_s \rightarrow 36\%, 30\%, 25\%, 20\%, 15\%, \text{ and } 10\%$
To develop an internal damage detection methodology using surface strain measurement

- Theoretical calculation of structure behaviors
- Develop a FE model
  - Model tuning
    - \((\sigma, \epsilon, \nu, \text{mesh size})\)
  - FE model validation
- Find materials properties
  - Conduct test to measure surface strains of the intact RC structure
- Introduce defects to the validated FE model
- Simulated response of the damaged RC beam model
  - Develop relationship between internal defect and surface strain/stress change pattern.
- Develop an internal damage detection methodology using surface strain measurement
Surface Strain Change and Damage

- Surface stress change of Type I damage:

\[ \Delta_j \tilde{\sigma}_{33} = \tilde{\sigma}_{33}^j - \tilde{\sigma}_{33}^o \]

<table>
<thead>
<tr>
<th>( \Delta A_s (%) )</th>
<th>( \Delta V_s (%) )</th>
<th>( A_{\Delta \sigma} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.632653</td>
<td>3.139</td>
</tr>
<tr>
<td>15</td>
<td>10.20408</td>
<td>4.834</td>
</tr>
<tr>
<td>20</td>
<td>13.26531</td>
<td>6.085</td>
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<td>25</td>
<td>16.83673</td>
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<td>30</td>
<td>20.40816</td>
<td>8.461</td>
</tr>
<tr>
<td>36</td>
<td>24.4898</td>
<td>9.72</td>
</tr>
</tbody>
</table>
Surface Strain Change and Damage

- Relationships between $\Delta \sigma_{\text{max}}$ and $\Delta V_s$ of Type I damage:
  
  $\rightarrow$ Difference of $\Delta \sigma_{\text{max}}$ between side A$_1$ and A$_2$

Type I-I

$\Delta \sigma_{\text{max},1} \approx \Delta \sigma_{\text{max},2}$

Type I-II

$\Delta \sigma_{\text{max},1} \gg \Delta \sigma_{\text{max},2}$
Surface Strain Change and Damage

- Relationships between $A_{\Delta \sigma}$ and $\Delta V_s$ of Type I damage:
  - Difference of $A_{\Delta \sigma}$ between side $A_1$ and $A_2$

![Graphs showing relationships between $A_{\Delta \sigma}$ and $\Delta V_s$ for Type I and Type II damage](image_url)

- Type I-I
  - $A_{\Delta \sigma}$
  - $\Delta \sigma$

- Type I-II
  - $A_{\Delta \sigma}^1 
  - $A_{\Delta \sigma}^2$

- Type II
  - $A_{\Delta \sigma}^1 
  - $A_{\Delta \sigma}^2 
  - $A_{\Delta \sigma}^2 \rightarrow 0$
Surface Strain Change and Damage

- Relationship between $A_{\Delta \sigma}$ and $\Delta V_s$ of Type I damage:
  $\rightarrow$ Relationships for $A_1$ side

\[
\Delta V_s = 0.00963 A_{\Delta \sigma}^3 - 0.05696 A_{\Delta \sigma}^2 + 2.169 A_{\Delta \sigma} + 0.01394
\]

- Data points Sym.
- Data points Non-sym.
- poly3
- Linear

Type I-I

Type I-II
Surface Strain Change and Damage

- Relationships between $\Delta \sigma_{\text{max}}$ and $\Delta V_s$ of Type I damage:
  - $\rightarrow$ Relationships for $A_1$ side

Type I-I

$$\Delta V_s = -0.0394\Delta \sigma_{\text{max}}^2 + 3.442\Delta \sigma_{\text{max}} + 0.04076$$

Type I-II

$$\Delta V_s = -0.03449\Delta \sigma_{\text{max}}^2 + 3.37\Delta \sigma_{\text{max}} + 0.04028$$
Surface Strain Change and Damage

- Relationship among $A_{\Delta \sigma}$, $\Delta \sigma_{\text{max}}$, and $\Delta V_s$ of Type II damage:
  - Difference of $A_{\Delta \sigma}$ between side $A_1$ and $A_2$

Type II-I:

\[ \Delta \sigma_{\text{max}1} \approx \Delta \sigma_{\text{max}2} \]

Type II-II:

\[ \Delta \sigma_{\text{max}1} \gg \Delta \sigma_{\text{max}2} \]

\[ \Delta \sigma_{\text{max}1} \rightarrow 0 \]

\[ \Delta \sigma_{\text{max}2} \rightarrow 0 \]
Surface Strain Change and Damage

- Relationships between $A_{\Delta \sigma}$ and $\Delta V_s$ of Type II defect:
  → Relationships for $A_1$ side

  $\Delta V_s = 0.02307 A_{\Delta \sigma}^3 - 0.2155 A_{\Delta \sigma}^2 + 3.069 A_{\Delta \sigma} + 0.05642$

  Type II-I

  $\Delta V_s = 2.316 A_{\Delta \sigma} + 0.4188$

  Type II-II
Surface Strain Change and Damage

- Surface stress change of defect Type III:
  - Relationships among $A_{\Delta \sigma}$, $\Delta \sigma_{\text{max}}$, and $\Delta V_s$ in Type III follow relationships of Type II-I
Surface Strain Change and Damage

- Relationships between $\Delta \sigma_{\text{max}}$ and $\Delta V_s$ of Type IV defect:

  $\rightarrow$ Difference of $\Delta \sigma_{\text{max}}$ between side $A_1$ and $A_2$

Type IV-I

$\Delta \sigma_{\text{max}}^{\uparrow 1} \approx \Delta \sigma_{\text{max}}^{\uparrow 2}$

Type IV-II

$\Delta \sigma_{\text{max}}^{\uparrow 1} \gg \Delta \sigma_{\downarrow n}$
Surface Strain Change and Damage

- Relationship between $A_{\Delta \sigma}$ and $\Delta V_s$ of Type IV defect:
  - Type IV–I, $\Delta V_s = 0.002 A_{\Delta \sigma}^3 - 0.0416 A_{\Delta \sigma}^2 + 0.5687 A_{\Delta \sigma} - 0.002163$
  - Type IV–II, $\Delta V_s = 0.008 A_{\Delta \sigma}^2 + 0.18 A_{\Delta \sigma} + 0.1344$

![Graph showing the relationship between contour area and rebar volume reduction](graph.png)
Surface Strain Change and Damage

- Relationships among $\Delta V_s$, $A_{\Delta \sigma}$, and $\Delta \sigma_{\text{max}}$

$$\Delta V_s = p A_{\Delta \sigma}^3 + q A_{\Delta \sigma}^2 + r A_{\Delta \sigma} + C1$$

<table>
<thead>
<tr>
<th>Co-efficient</th>
<th>p</th>
<th>q</th>
<th>r</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I-I</td>
<td>0.00963</td>
<td>-0.0569</td>
<td>2.1690</td>
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<td>0.06134</td>
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<tr>
<td>Type III</td>
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<td>0.06134</td>
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<tr>
<td>Type IV-I</td>
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<td>Type IV-II</td>
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<td>0.00622</td>
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</table>

- Relationships can be used to determine the internal defect intensity.

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Surface Strain Change and Damage

- Relationships among $A_{\Delta \sigma}$ and $V_{\Delta \sigma}$ of Type I-I damage

$$A_{\Delta \sigma} = -0.002891(V_{\Delta \sigma})^2 + 0.2977(V_{\Delta \sigma}) + 2.156$$

- This relationship can be used to find volume loss in rebar using the volume of surface stress change.
Research Roadmap

To develop an internal damage detection methodology using surface strain measurement

Theoretical calculation of structure behaviors

Develop a FE model

Find materials properties

Model tuning

(\(\sigma\), \(\epsilon\), \(\nu\), mesh size)

Conduct test to measure surface strains of the intact RC structure

FE model validation

Simulated response of the damaged RC beam model

Introduce defects to the validated FE model

Develop relationship between internal defect and surface strain/stress change pattern.

Develop an internal damage detection procedure using surface strain measurement
Proposed Damage Detection Procedure

- This damage detection procedure can help experimental sensing systems (e.g., DIC, FOS) used for the subsurface damage detection of RC structures by improving the data interpretation algorithm.
- With this methodology, damage detection procedures for other types of defect (e.g., concrete deterioration, bound slippage between concrete and rebar) can be developed.

\[
\Delta \sigma_{\text{max}} \quad \text{and} \quad A_{\Delta \sigma}
\]

\[
\Delta_j \tilde{\sigma}_k = \tilde{\sigma}_k^j - \tilde{\sigma}_k^0
\]

\[
\Delta_j \tilde{\sigma}_k^j \quad \text{Contour mapping} \quad A_k^{\Delta \sigma}
\]
Proposed Damage Detection Procedure

\[
\Delta_l \sigma_{\text{max}}^k \rightarrow 0 \\
\text{&} \\
A_{\Delta\sigma}^k \rightarrow 0 
\]

No

\[
\Delta_l \sigma_{\text{max}}^1 \approx \Delta_l \sigma_{\text{max}}^2 \\
\text{&} \\
A_{\Delta\sigma}^1 \approx A_{\Delta\sigma}^2 
\]

Sym. defects

Yes

Intact

Yes

No

Type I-I or IV-I

Sym. defects

No

Non-sym. defects

Type II-I or III

Shape recognition algorithm

Type II-I

Type IV-II

Type I-II or IV-II

Type II-II
Structural Health Monitoring Strategy

Process 1

1. Start
2. Create a FE model
3. Fine tune the FE model
4. Validate the FE model:
   \[ \varepsilon_{\text{exp}} \approx \varepsilon_{\text{FE}} \]
   \[ \Delta_{\text{exp}} \approx \Delta_{\text{FE}} \]

Process 2

1. Introduce different types of defect in FE model
2. Surface stress difference shape vs. the defect types data base
3. Relationships between \( A_{\Delta\sigma} \) and \( \Delta V_s \)
4. Start monitoring the structure
5. Take measurement. Find the surface strain (stress) difference.
6. Identify defect type
7. Find defect intensity

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Conclusions

• Surface strain of a RC beam can be simulated using FE package ABAQUS®.
• FOS provides consistent measurements of surface strain during four point bending tests.
• Simulated RC beam model response revealed that surface stress/strain field of the RC beam changes due to internal defect.
• Defect introduced in the rebar embedded in a RC beam model can be accurately located using surface stress difference.
• Relationships developed between surface stress-field change and internal defect intensity for four damage scenarios can be used to predict defect intensity.
• Nonsymmetrical damages yield more contour area of stress change than the symmetric damages (in Type I, Type II, and Type IV).
• Maximum stress changes both in symmetric and nonsymmetrical damages are quite identical (1~5%).
Contributions

• A damage detection procedure and methodology are proposed to identify internal defect using surface strain measurements.

• Relationships established between internal defect intensity and surface stress difference ($A_{\Delta \sigma}$ and $\Delta \sigma_{\text{max}}$) can be used to predict artificial internal defect intensity.

• Applied FE modeling technique to simulate artificial internal defect for modeling corrosion in RC structures.
Future Work

• Conduct experiment to confirm the surface strain change pattern.
• Develop a pattern recognition algorithm to recognize the pattern from the experimental works and FE simulations.
• Introduce more defect types (e.g., honey comb in concrete and intolerable slippage between concrete and rebars).
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Thank you!
Questions?
• Assumptions:
  1. Applicable for given geometric configurations and material properties
  2. Singly reinforced beam (no shear reinforcement)
  3. Lost rebar volume is filled up by concrete
  4. Loading level $\rightarrow$ elastic
  5. No cracking in the section of the beam