Structural Engineering Research Group
(SERG)
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Structural Health Monitoring of a Reinforced Concrete Beam Using Finite Element Analysis

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Outline

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

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Introduction

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- **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:**

Sensing technology	Power technology	Communication devices	A monitoring station	Signal processing algorithm	Health evaluation algorithm

- **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

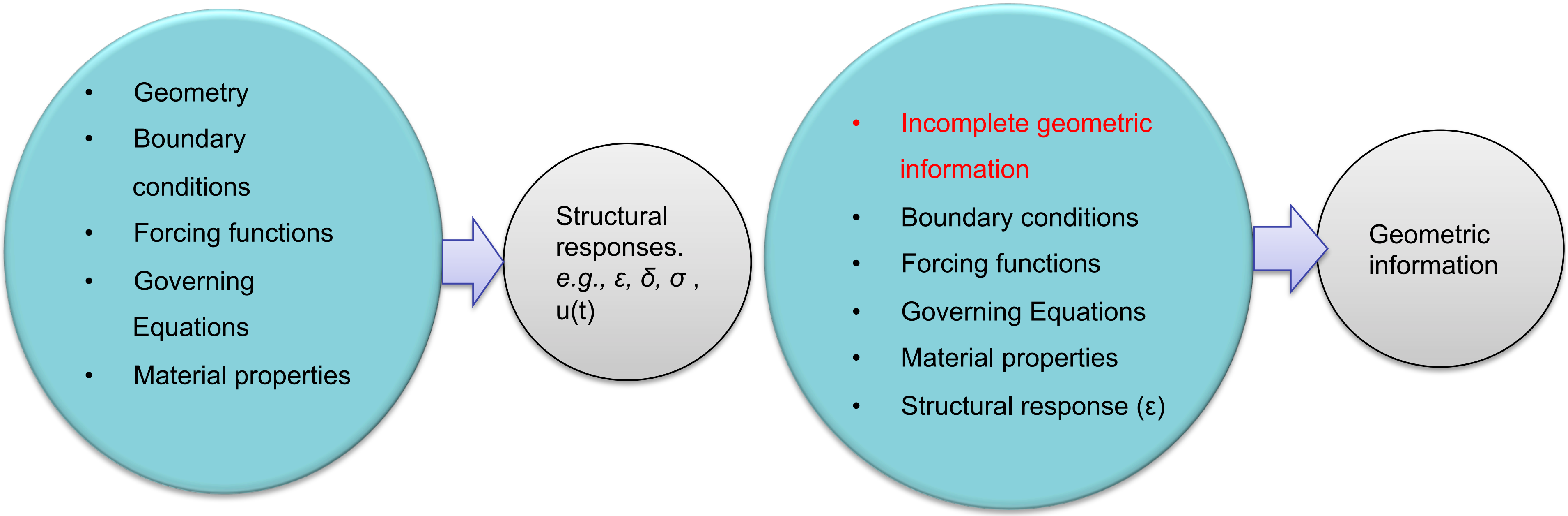
- Applicability of fiber optic sensor (FOS) and digital image correlation (DIC) in strain measurements:

Measurement Technique	Types of surface strain measurement			Subsurface strain measurement
	Points	Lines	Planes	Points / lines
FOS	✓	✓	☒	☒/✓
DIC	✓	✓	✓	☒

- 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
- Inverse problem in this research ★



➢ 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]

Theoretical approach	• Applicable for solving inverse problem using precise local measurements.
Numerical approach	• Can be used in global damage detection • Sensitive-based FE model updating is frequently used in damage detection

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Literature Review

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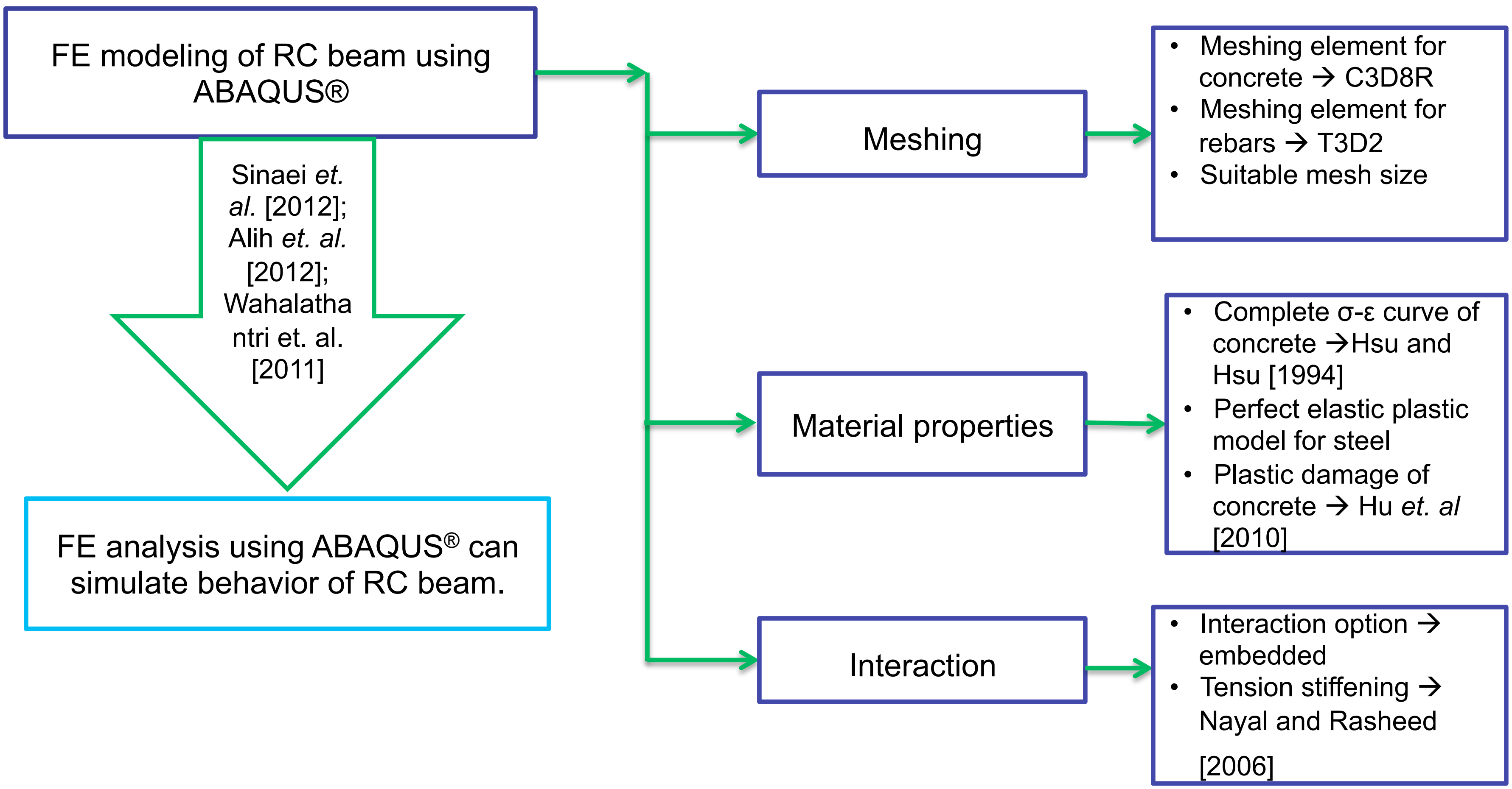

Literature Review

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

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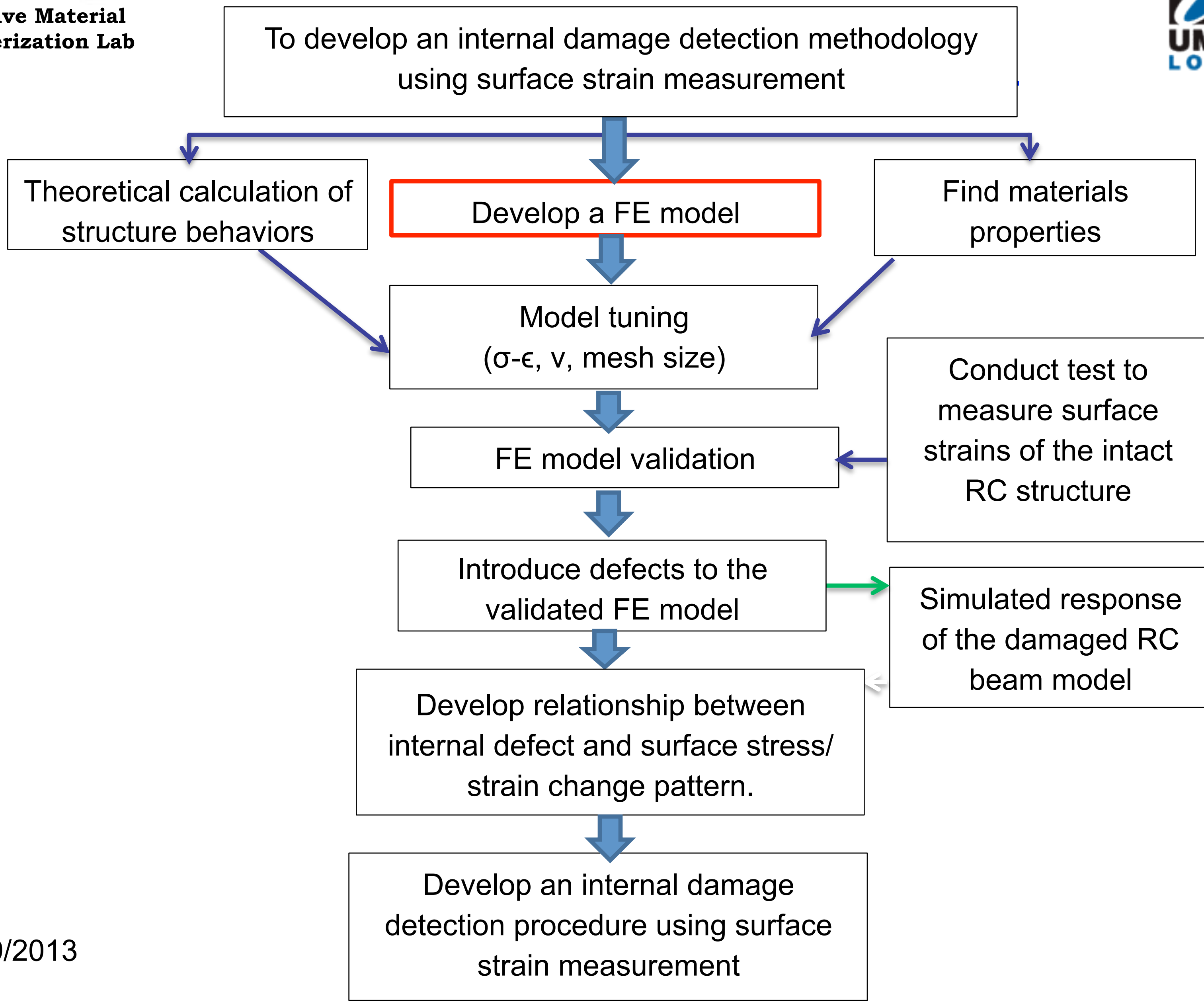
Research Roadmap



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FE Modeling

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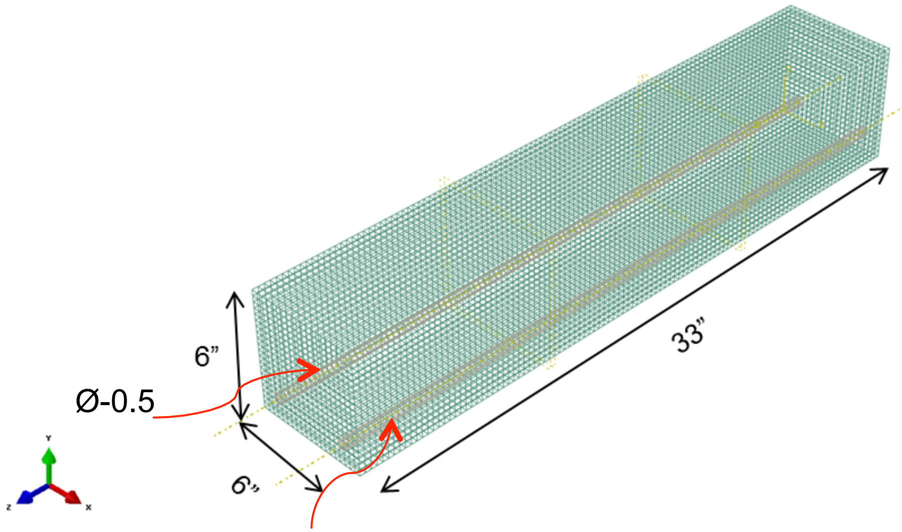
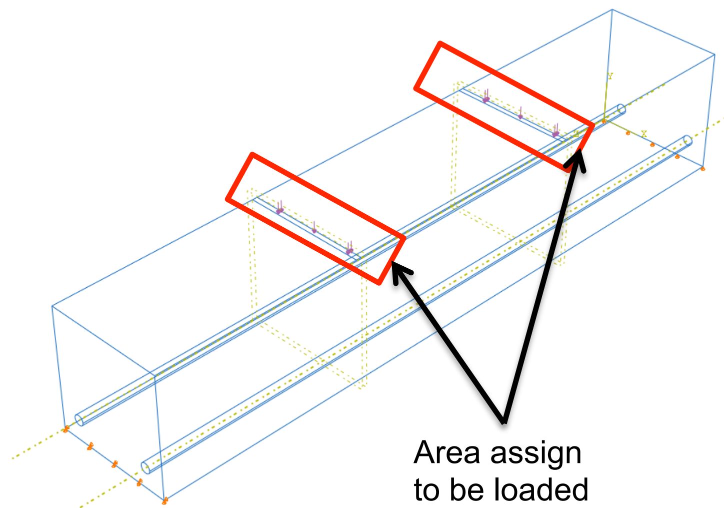


- <u>Meshing and interaction:</u>
  - Element to model concrete → C3D20
  - Element to model rebar → C3D8
  - Mesh edge size for concrete → 0.3”
  - Mesh edge size for rebar → 0.25”
  - Total elements in the model → 45,056
  - Total variables → 579,285
  - Interaction between concrete and rebar → embedded

- <u>Loading and B.C.:</u>
  - Simply supported
  - Loaded area → 0.125” x 6”
  - Loading level → from 0 to 2.2 kips at four steps



FE Modeling

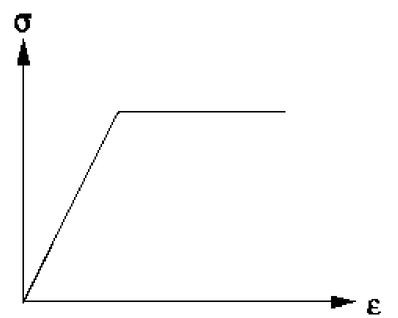
- Materials properties

➢ Elastic properties:

- $E_c = 57,000\sqrt{\sigma \downarrow cu}$ (ACI 318, units in psi)
- v_c = 0.16 (Ref. Bonfiglioli *et. al.* [2003])
- E_s → Experimentally obtained → 30×10^6 psi
- v_s = 0.3

➢ Plastic properties and interaction:

Model	Purpose
Hsu and Hsu [1994]	To obtain complete σ-ε
Perfect elastic-plastic material property	σ-ε behavior of steel
Nayal and Rasheed model [2006] (Modified by Walhalathantri et. al. [2011])	Simulate interaction between concrete and rebars



Perfect elastic-plastic model

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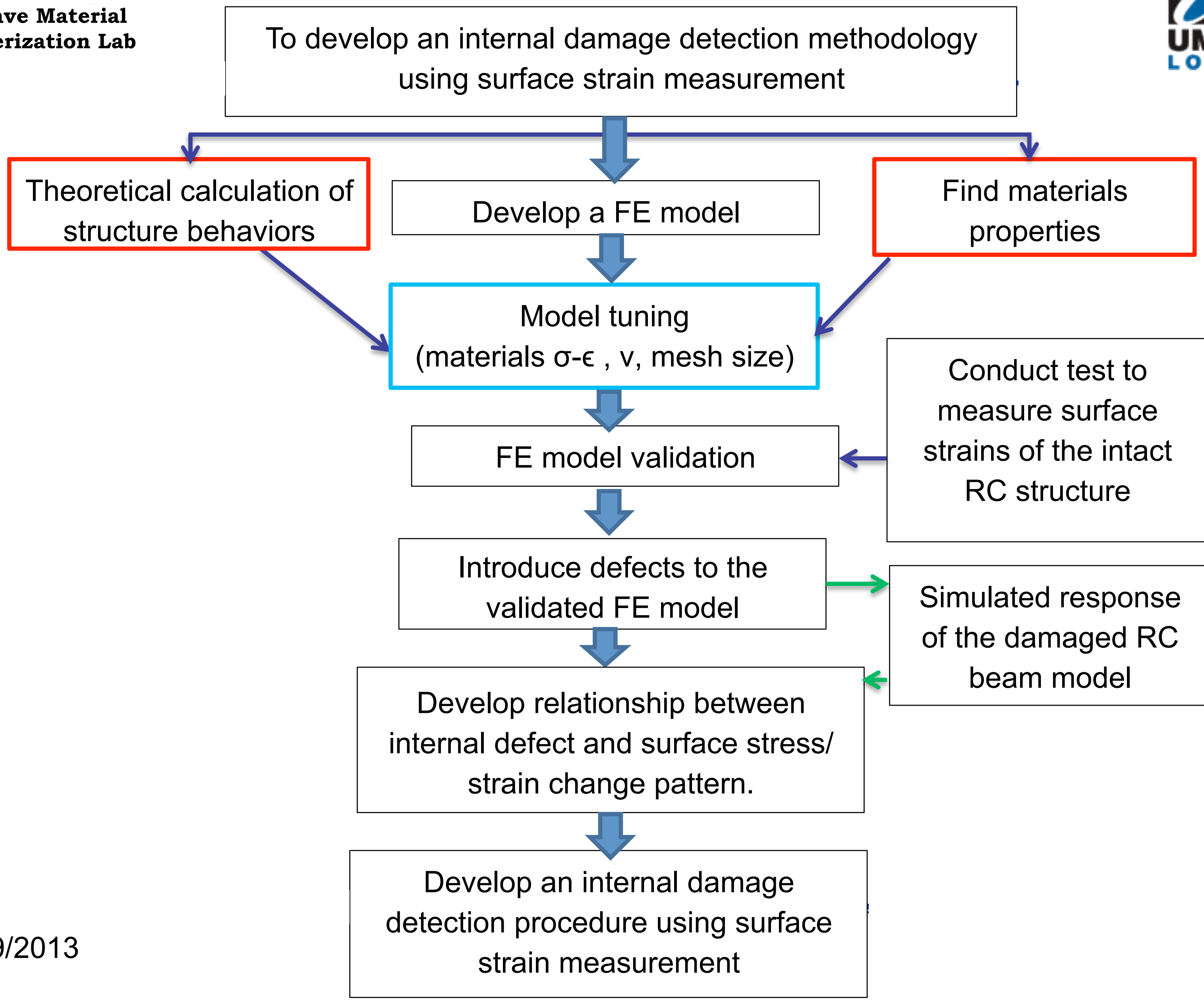

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Materials Properties

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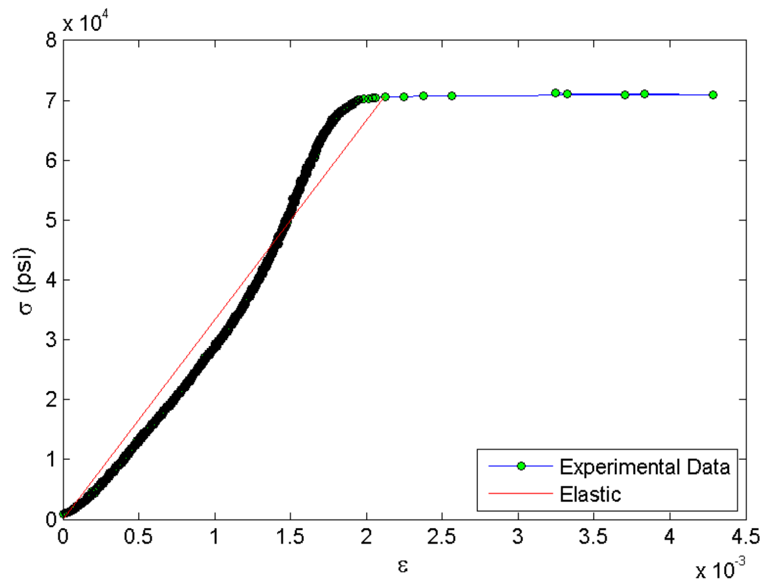
❑ Materials Testing

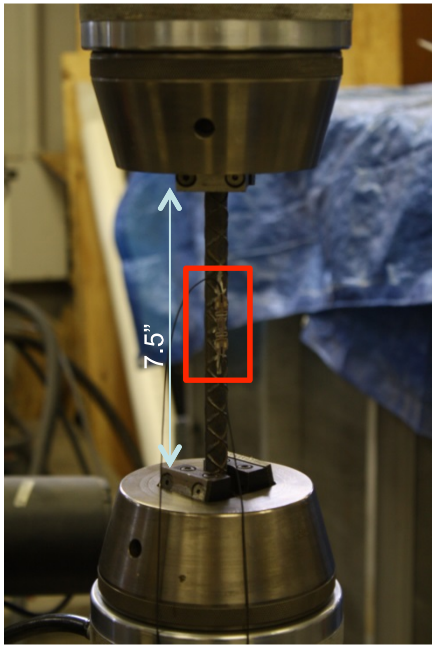
- Steel → tension test of rebar
- Concrete → ASTM standard compression test (C39/C39M)

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

- Compression test of concrete
  - ➢ ASTM C39/C39M
  - ➢ Specimen: Two 4” x 8” cylinders
  - ➢ Test result: σ_{cu} = 6,500 psi

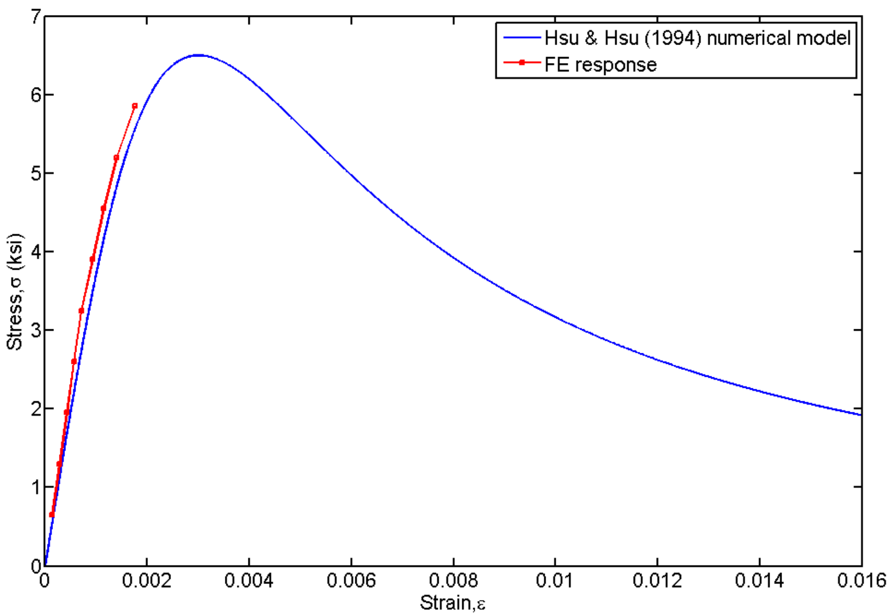


Experimental σ-ε of steel rebar



Materials Properties

- Hsu and Hsu model [1994]



Complete σ-ε curve of concrete obtained from Hsu & Hsu model

- $\sigma_c = \frac{\beta \left(\frac{\varepsilon_c}{\varepsilon_o}\right)}{\beta - 1 + \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^{\beta}} * \sigma_{cu}$

- A dependent parameter, $\beta = 1/1+(\sigma_{cu}/\varepsilon_o E_o)$
- Strain at peak stress, ϵ_o= 8.9 x 10^{-5} σ_{cu} + 3.28312 x 10^{-3}
- Peak tangential modulus, E_o= 1.2431 x 10^{2} σ_{cu} + 3.28312 x 10^{3}

Where,

- σ_c = compressive stress values
- σ_{cu} = Ultimate compression stress (obtained from standard compression test ASTM C39/C39M)
- ϵ_c = compressive strain (domain)

- Inelastic strain, $\varepsilon_c^{in} = \epsilon_c - \varepsilon_{oc}^{el}$

$\varepsilon_{oc}^{el} = \sigma_c / E_o$

- Damage parameter, $d_t = \varepsilon_c^{in} / \epsilon_c$
- Plastic strain, $\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_t \sigma_c}{(1-d_t) E_o}$

Stress, σ_c	Damage parameter, d_t	Inelastic strain, ε_c^{in}
3.25E+03	0.00E+00	0.00E+00
3.56E+03	8.69E-03	6.20E-05
3.72E+03	1.01E-02	7.24E-05
3.88E+03	1.17E-02	8.38E-05
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Materials Properties

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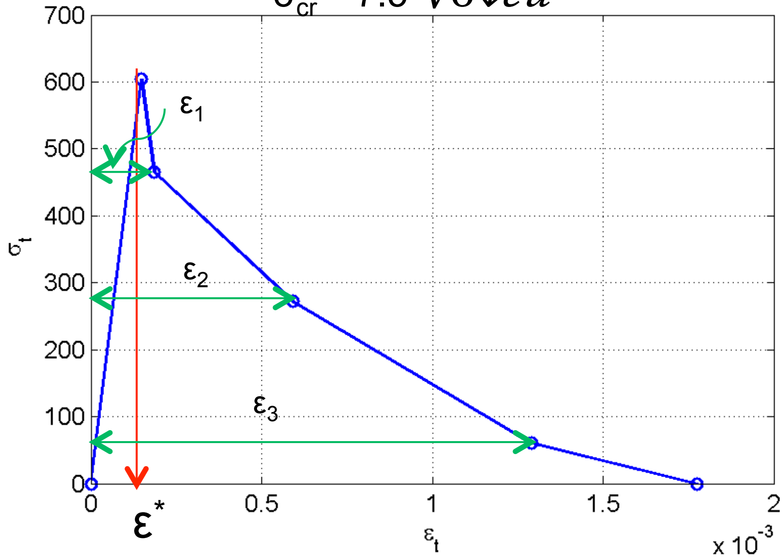
- Nayal and Rasheed tension stiffening model [2006] (Modified by Walhalathantri *et. al.* [2011])

- $\sigma_{cr} = 7.5 \sqrt{\sigma_{cu}}$

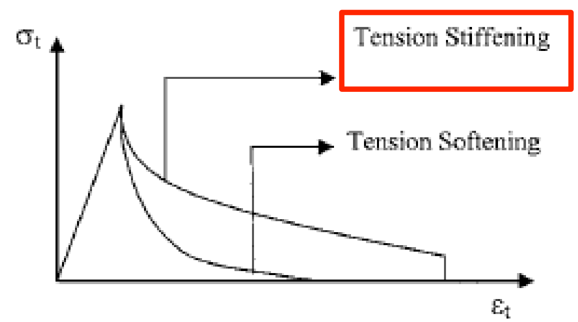


- Cracking strain, $\varepsilon_t^{ck} = \epsilon_c - \varepsilon_t^{el}$

$\varepsilon_t^{el} = \sigma_t / E_o$

- Plastic strain, $\varepsilon_t^{pl} = \varepsilon_c^{in} - \frac{d_t \sigma_c}{(1-d_t)E_o}$

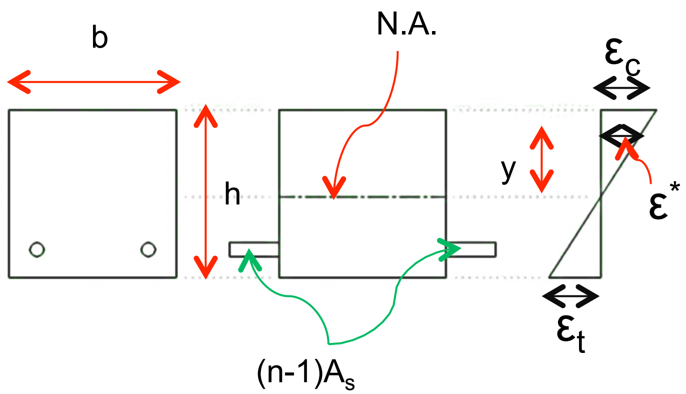
- Damage parameter, $d_t = \varepsilon_t^{in} / \epsilon_c$

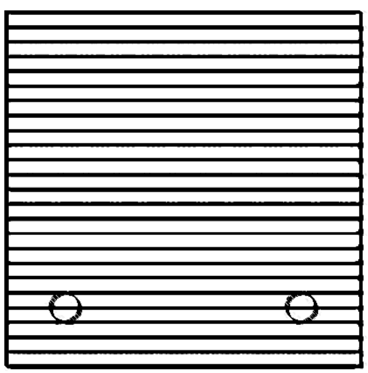


Tension stiffening (Ref. Nayal *et. al.* [2006])

Stress, σ_c	Strain, ϵ_t	Elastic strain, ε_t^{el}	Cracking strain, ε_t^{ck}	Damage parameter, d_t	Plastic strain, ε_t^{pl}
604.66	1.48E-04	1.48E-04	0.00E+00	0.00E+00	0.00E+00
465.59	1.85E-04	1.14E-04	7.10E-05	3.84E-01	7.09E-05
272.10	5.91E-04	6.65E-05	5.25E-04	8.88E-01	5.17E-04
60.46	1.29E-03	1.48E-05	1.27E-03	9.89E-01	-7.48E+02

Theoretical Calculations





- Effective flexural rigidity,

  $EI = \sum_{i=1}^{NL} E_i I_i$

- In un-cracked section,

  $EI = E_c\,(bh^3/12 + bh.\,e_1^3 + (n-1)A_s.\,e_2^3)$

  where,
  - e_1 = distance from concrete section c.g. to section c.g.
  - e_2 = distrance from equivalent concrete section c.g. to section c.g.
  - n = E / E

❑ From Euler–Bernoulli beam theory,

➢ $M_{int} = EI\varphi$

Where,

$\varphi = (\varepsilon_t + \varepsilon_c)/h$

E = Elastic modulus

I = Moment of inertia

$\varphi = (\varepsilon_t + \varepsilon_c)/h = \varepsilon^* / y$

$\therefore M_{int} = EI\, \varepsilon^* / y$

$\varepsilon^* = M_{int} * y/EI$

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FE Model Response

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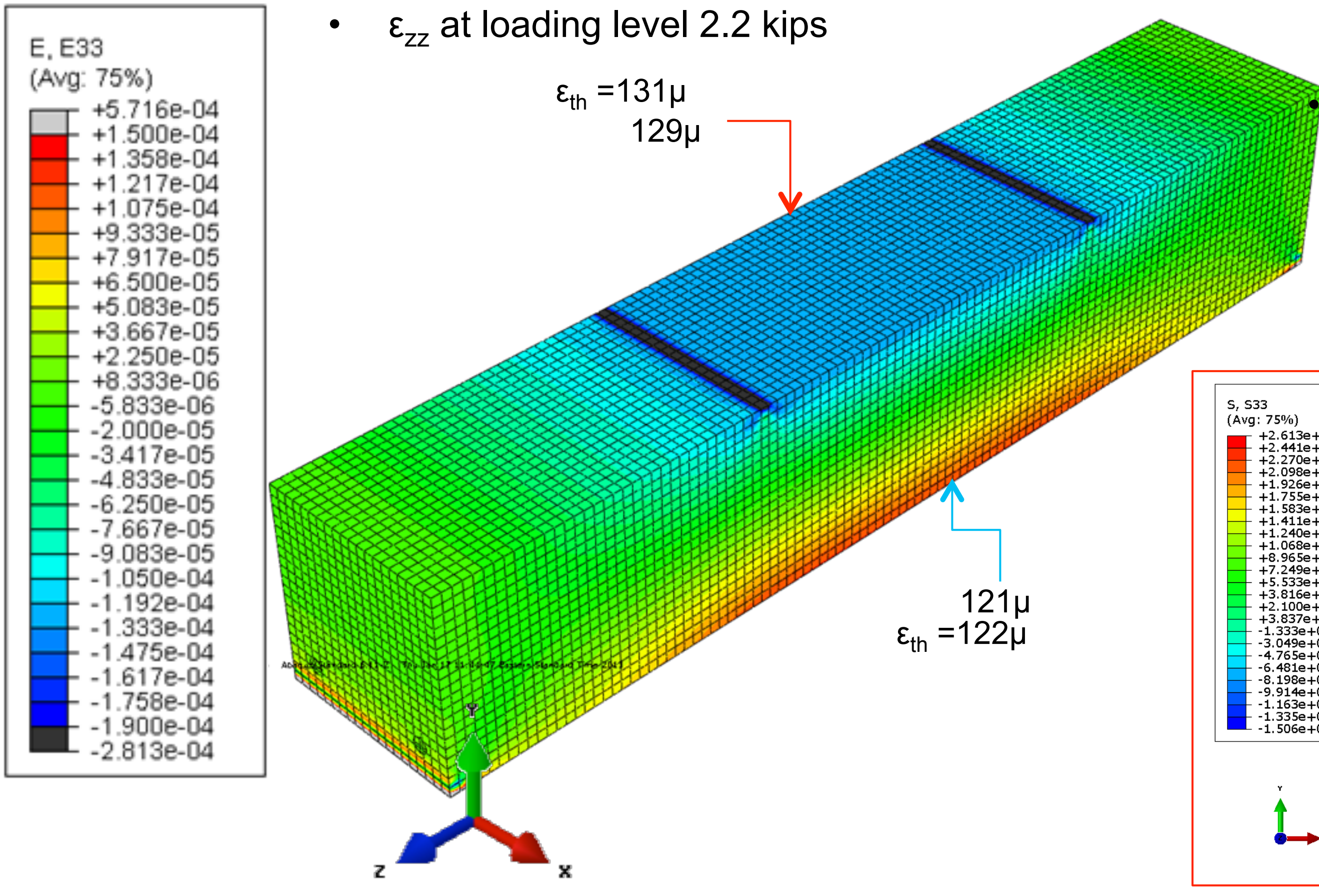
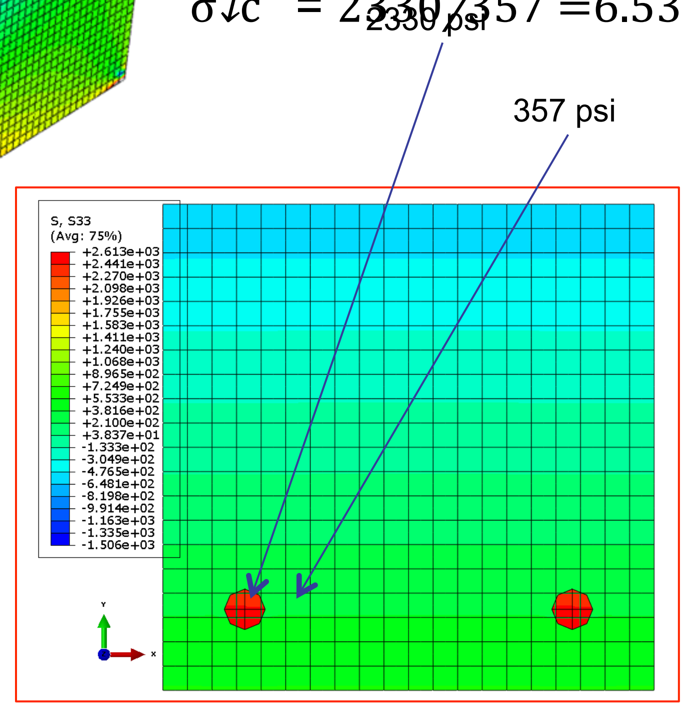
- FEA results
    - ε_{zz} at loading level 2.2 kips



- $n = E_s / E_c = 30/4.59 = 6.53$
- $n = E_s \varepsilon / E_c \varepsilon = \sigma_s / \sigma_c = 2330/357 = 6.53$



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FE Model Response

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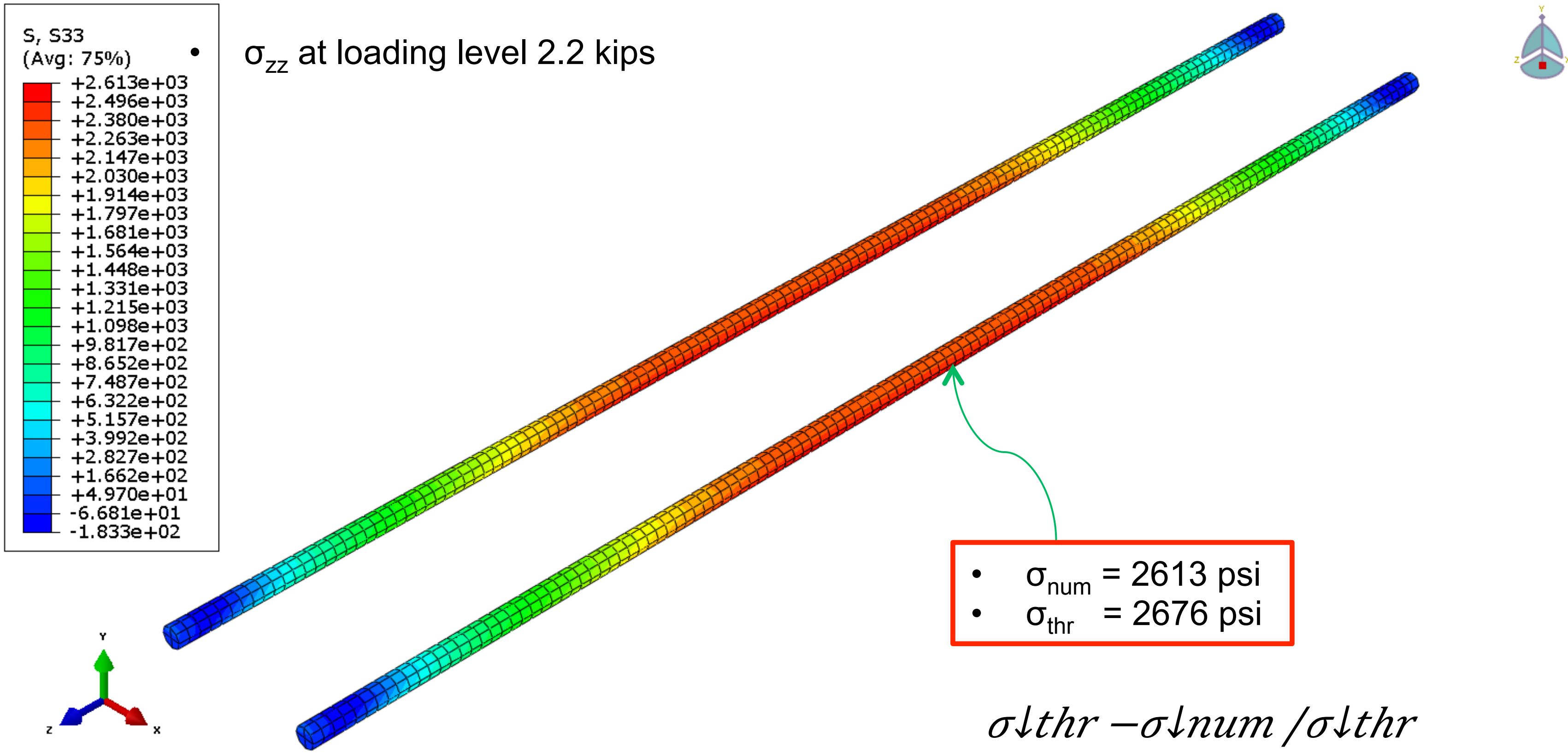
- Rebar stress from FEA results:



- σ_{zz} at loading level 2.2 kips

- σ_{num} = 2613 psi
- σ_{thr} = 2676 psi

$$\frac{\sigma_{thr} - \sigma_{num}}{\sigma_{thr}} * 100 = 2.35\ \%$$

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Research Roadmap

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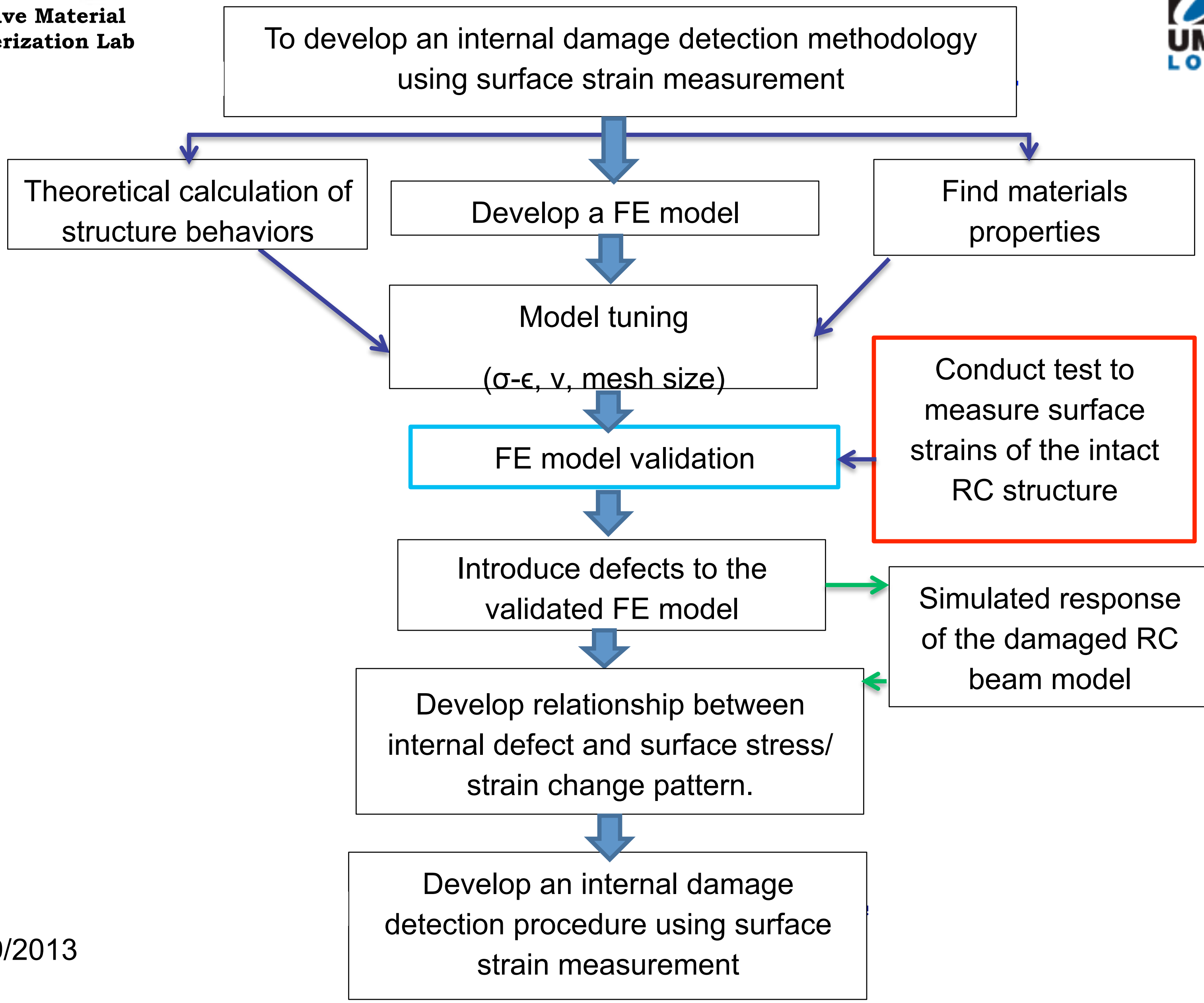
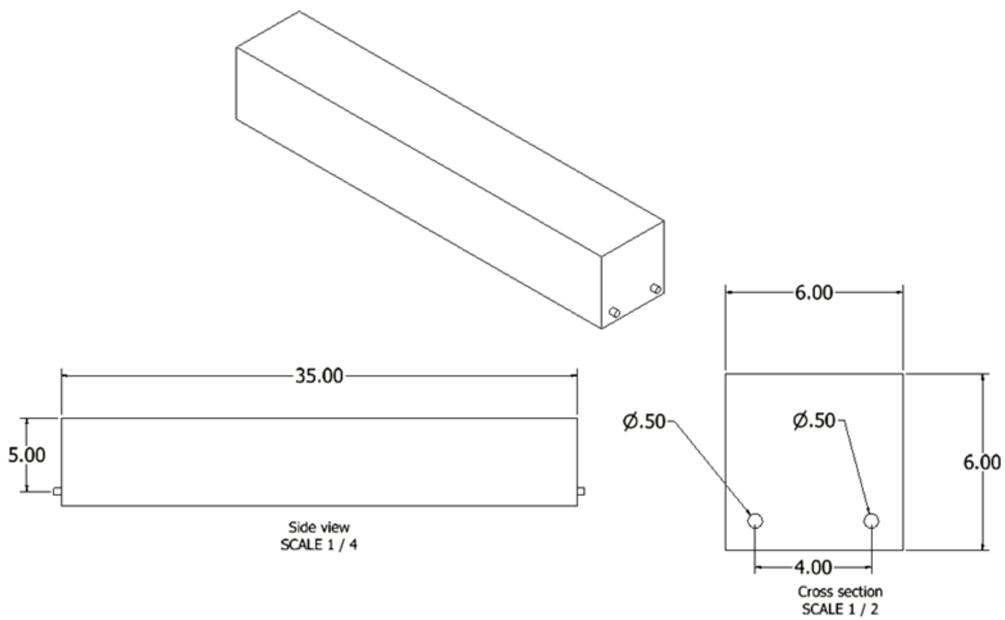


Experimental Work

- 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)



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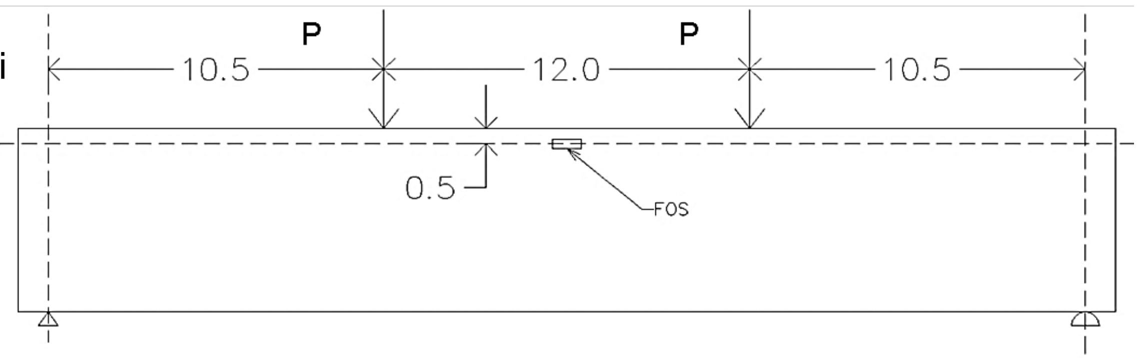
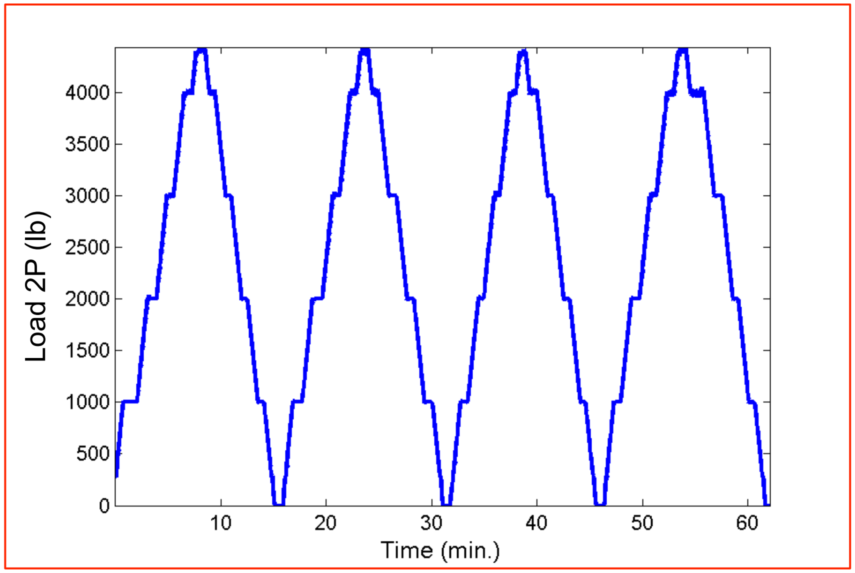
Experimental Work

- 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
  - $P_{max} = M_{cr} / l$ = 2.29 kips



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

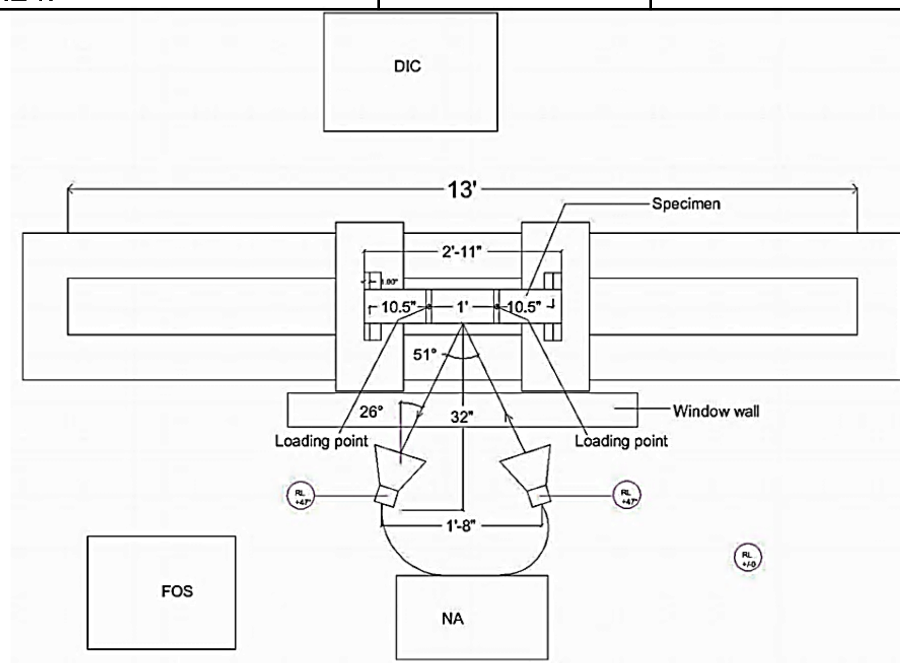


Experimental Work

- Test schedule

Experiment no.	Loading levels and cycles	Date	Sensors
Experiment 1	4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k	Aug. 1, 2012	DIC, FOS, and radar
Experiment 2	4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k	Sep. 27, 2012	FOS and radar
Experiment 3	4 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k	Oct. 05, 2012	FOS and radar
Experiment 4	3 cycles, Loading levels → 0.5 k, 1.0 k, 1.5 k, 2.0 k, and 2.2 k	Jan. 25, 2013	FOS and radar

- 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



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Experimental Work

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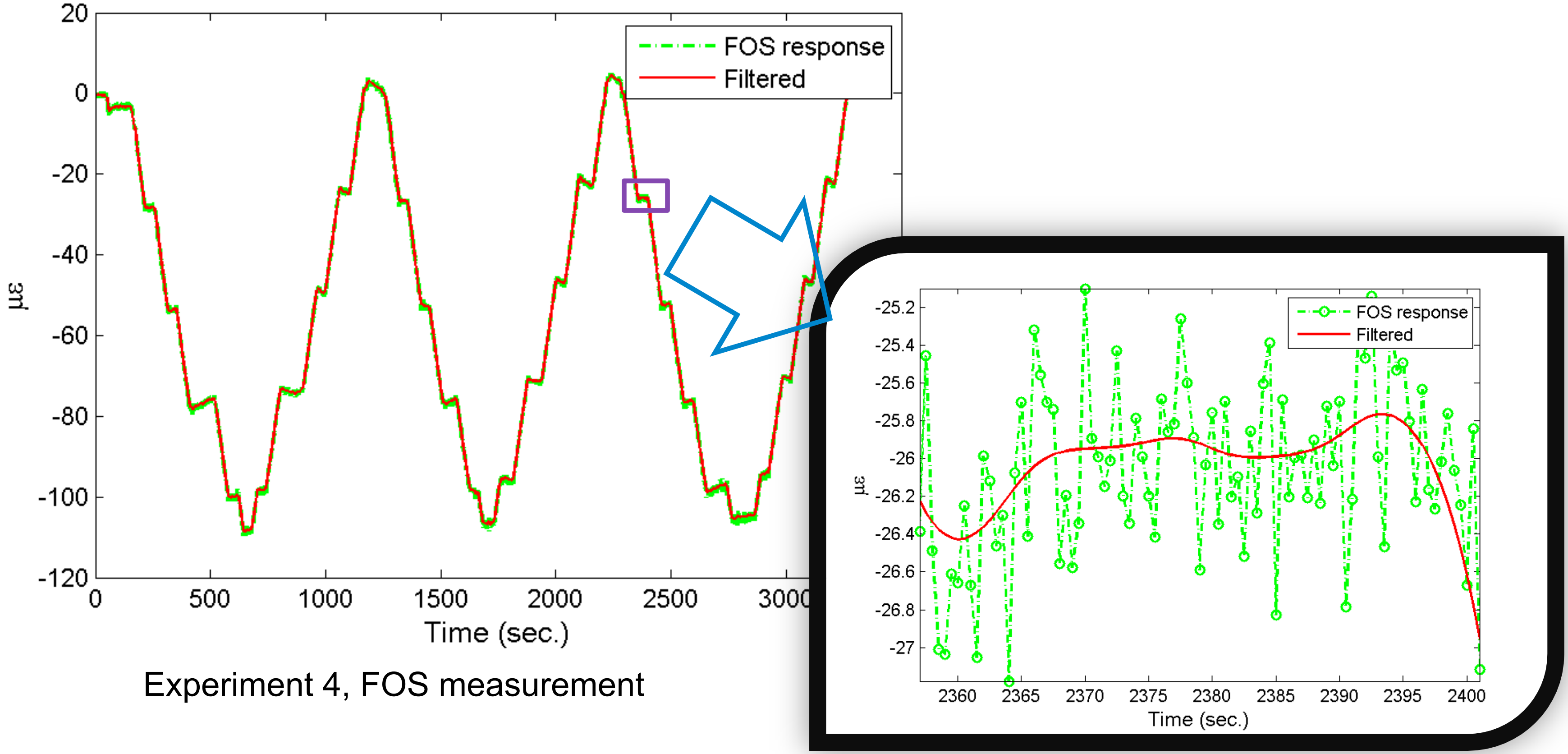
- FOS measurement:



Experiment 4, FOS measurement

FE Model Validation

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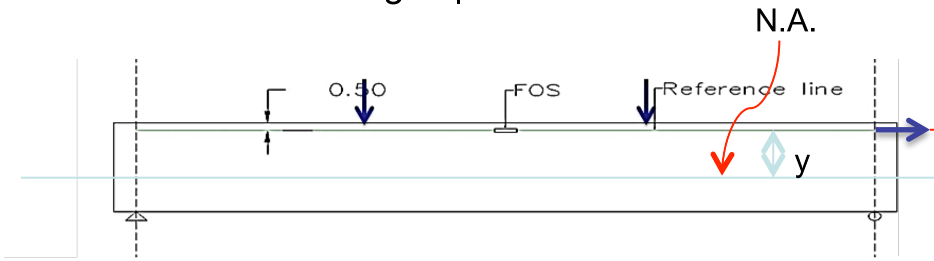
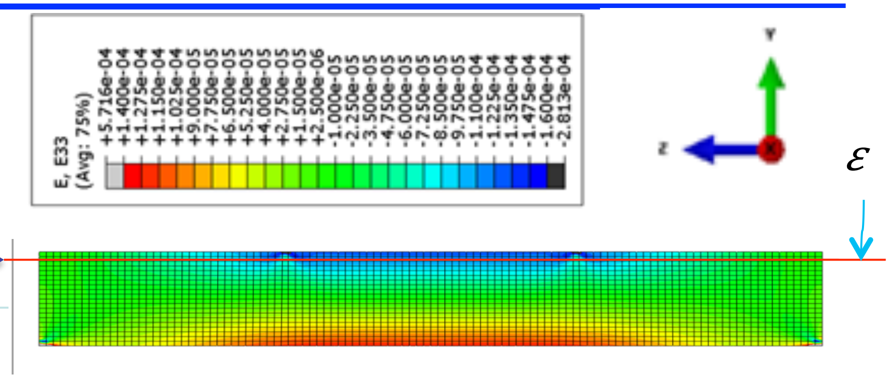
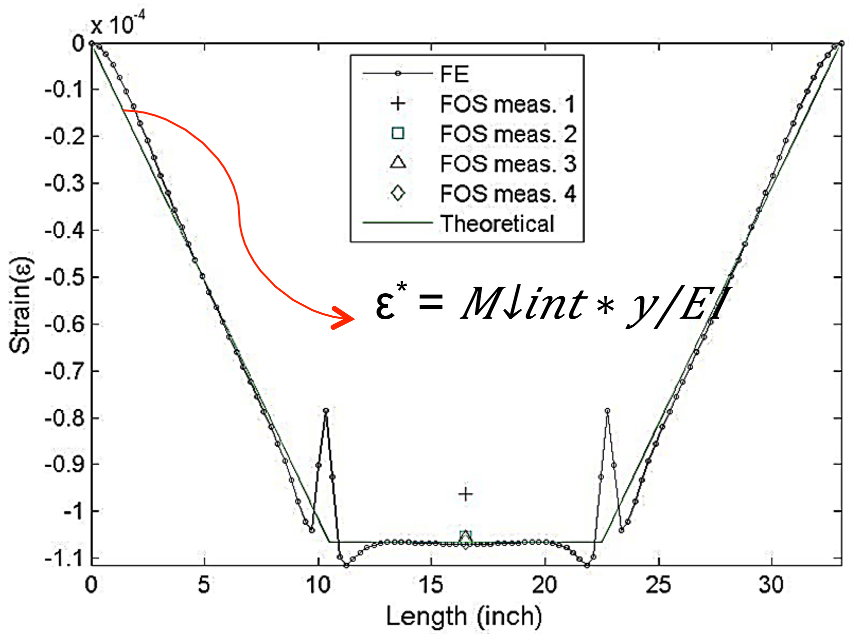
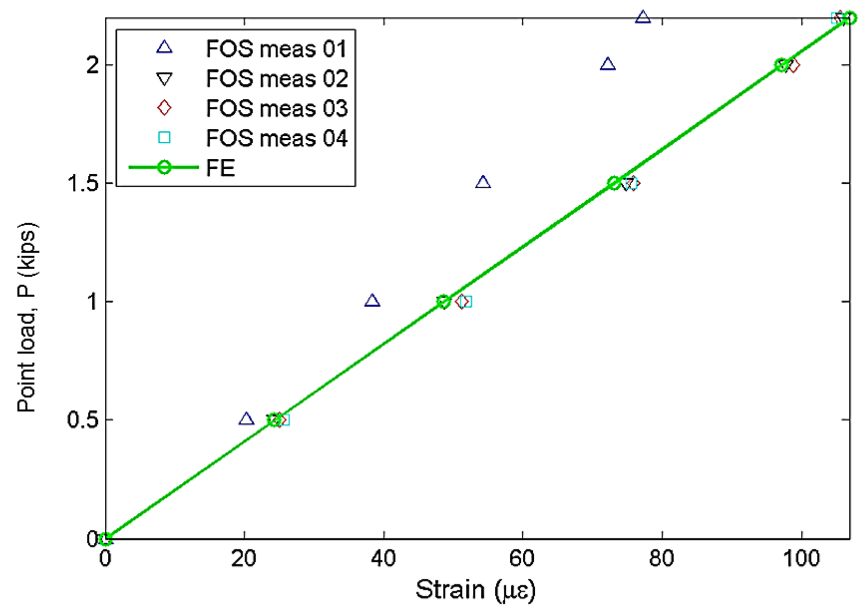
- Theoretical and FEA comparison
- Validation using experimental measurements









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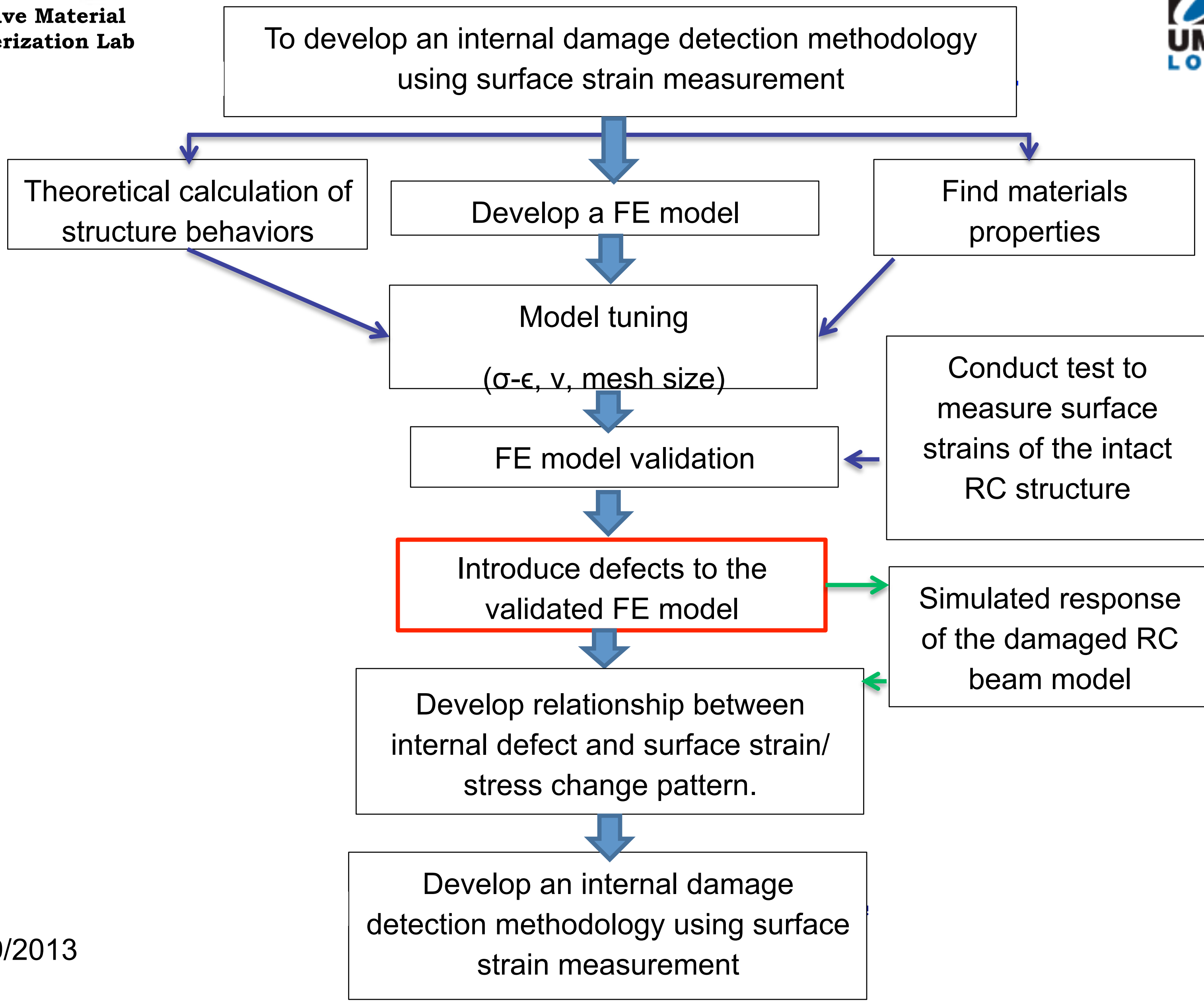

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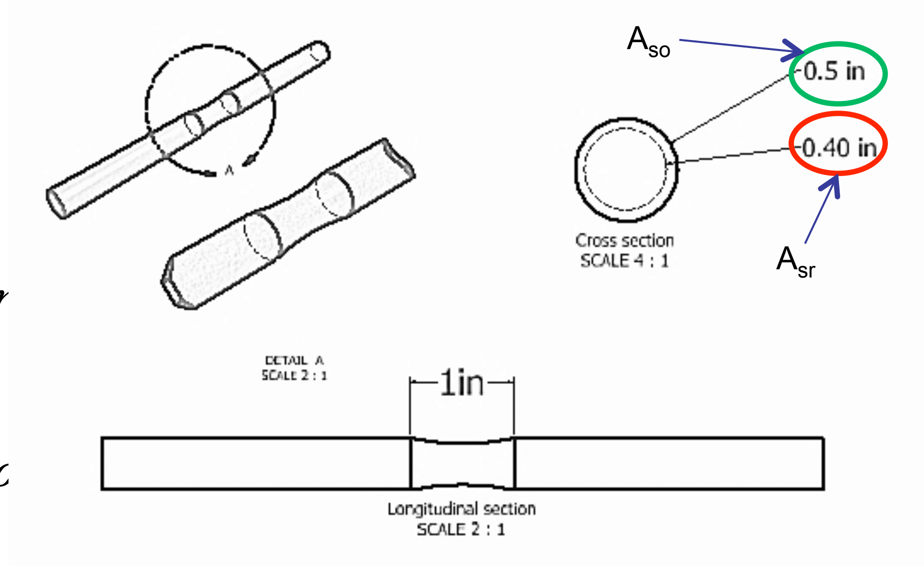
Damage Modeling

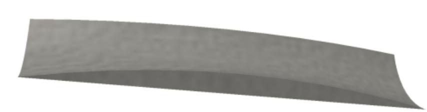
- Definition of damage:
  - Reduction of steel rebar cross section/volume
  - To simulate rebar corrosion
- Cross sectional reduction, ΔA_s = $A_{so} - A_{sr}$

  A_{so} *100
- Volume reduction, ΔV_s = $V_{so} - V_{sr} / V_{so}$

  *100

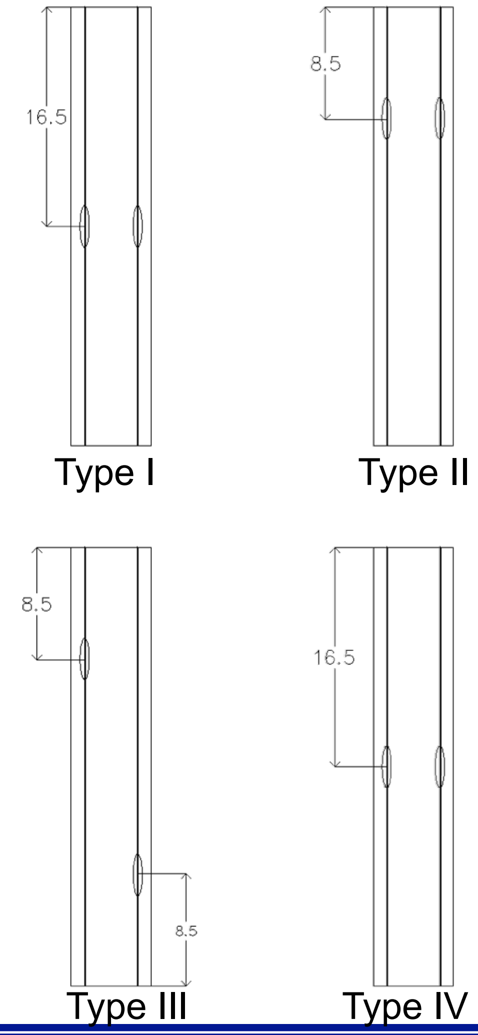


$\Delta A_s(\%)$	$V_{so} - V_{sr}(in^3)$	ΔV_s (1-in defect)	ΔV_s (5-in defect)
10	0.013	6.633	5.736
15	0.020	10.204	8.768
20	0.026	13.265	11.402
25	0.033	16.837	14.419
30	0.040	20.408	17.836
36	0.048	24.48	21.635



Damage Modeling

- <u>Artificial damage scenarios:</u>
  - (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%

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Damage Modeling

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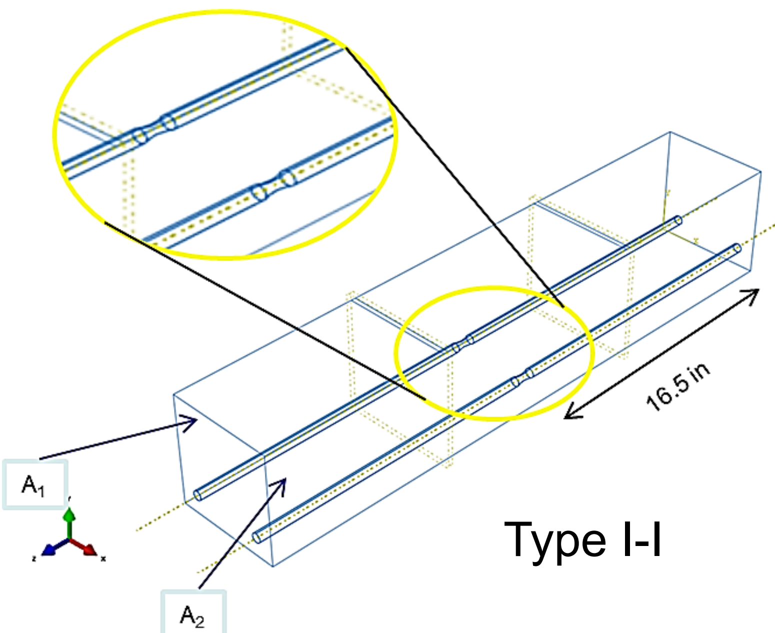
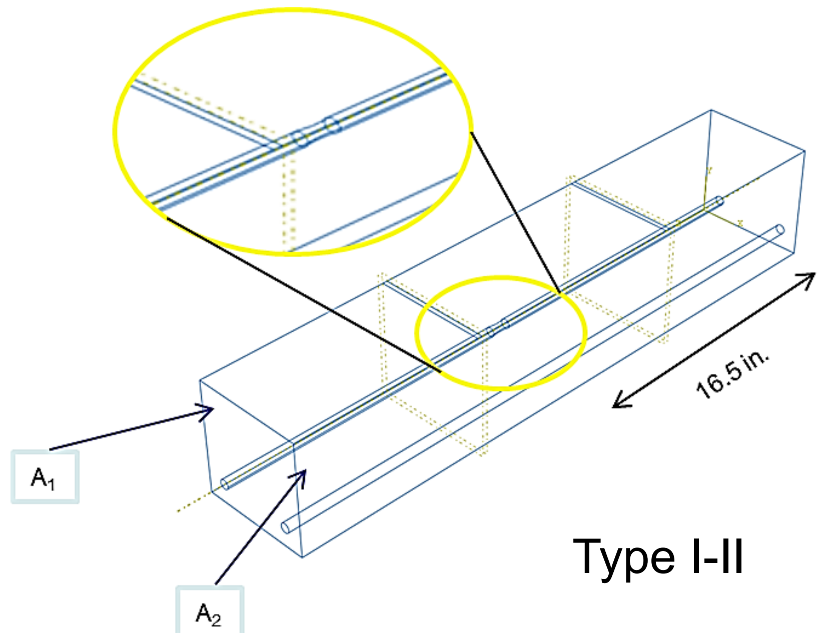
- Subcategories of Type I are
  - (a) Type I-I (Symmetric) and
  - (b) Type I-II (Nonsymmetrical)
- Damage intensity, $\Delta A_s \rightarrow$ 36%, 30%, 25%, 20%, 15%, and 10%



Type I-I



Type I-II

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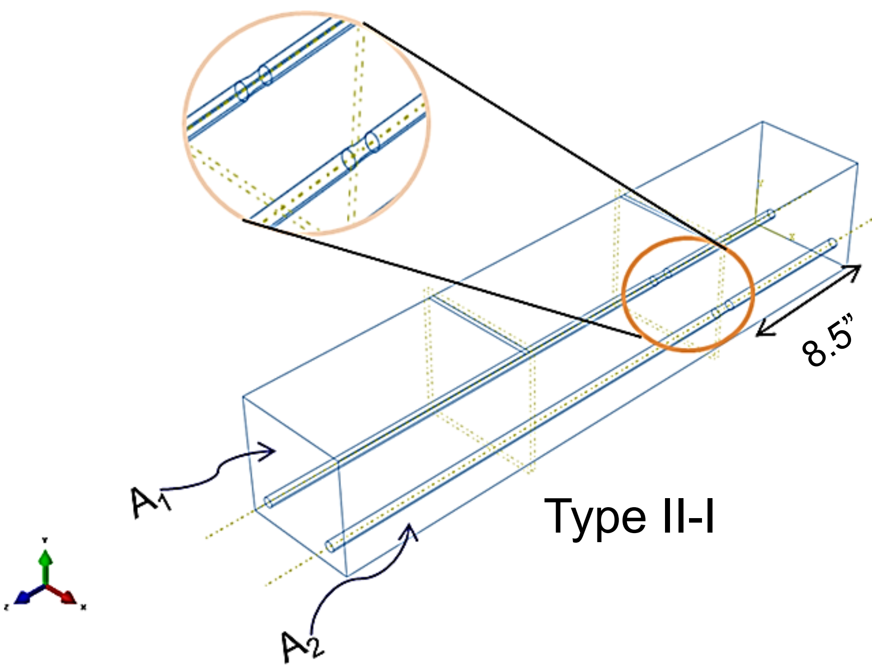
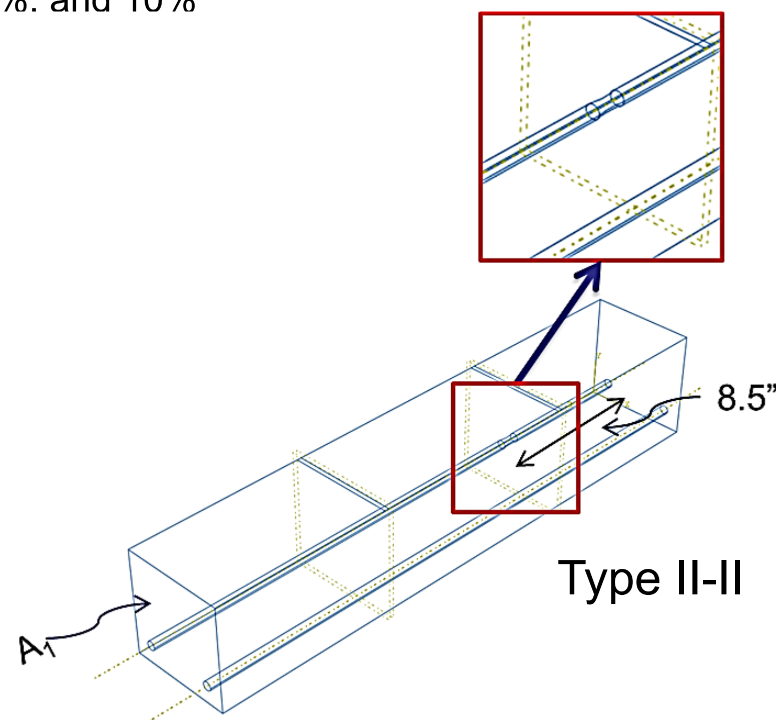
Damage Modeling

- Subcategories of Type II are
  (a) Type II-I (Symmetric) and
  (b) Type II-II (Nonsymmetrical)
- Damage intensity, ΔA_s→ 36%, 30%, 25%, 20%. 15%. and 10%





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Damage Modeling

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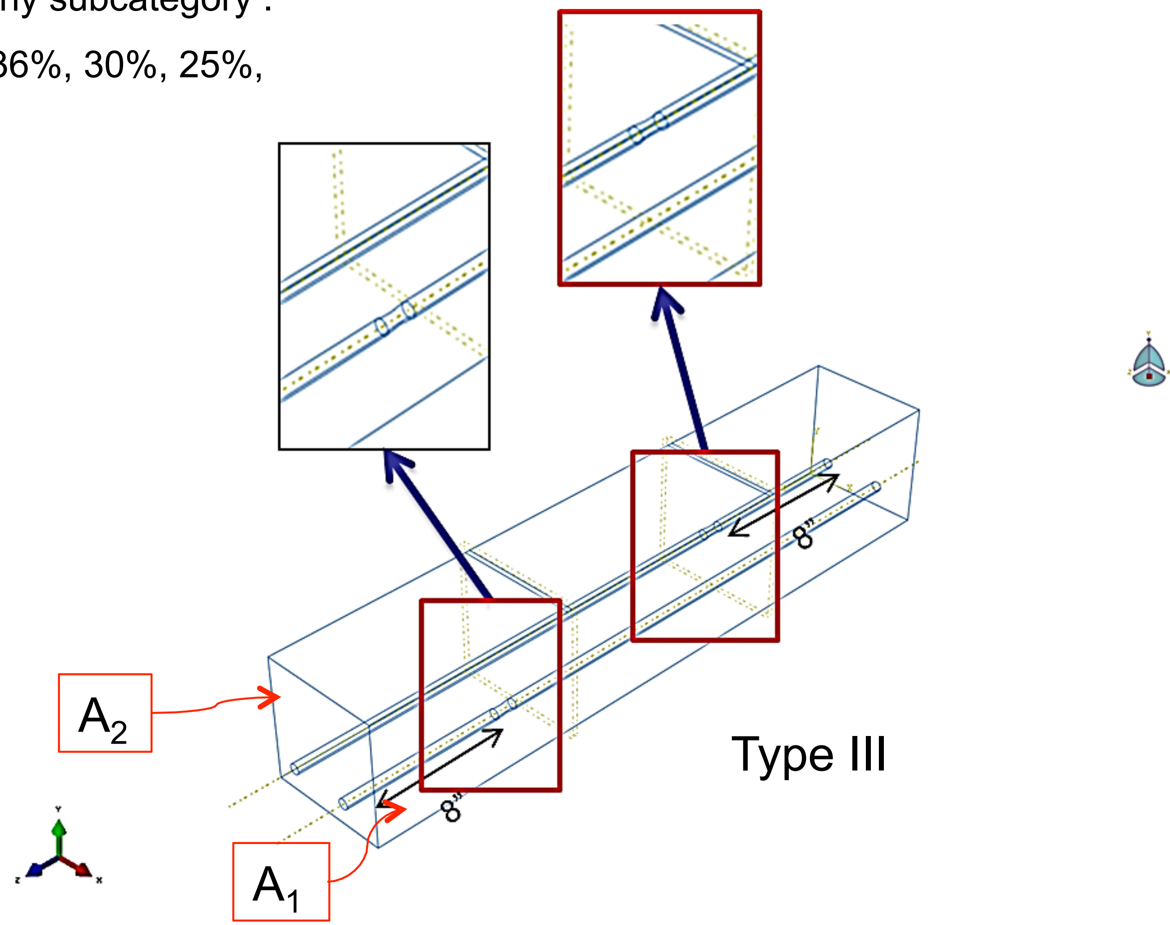
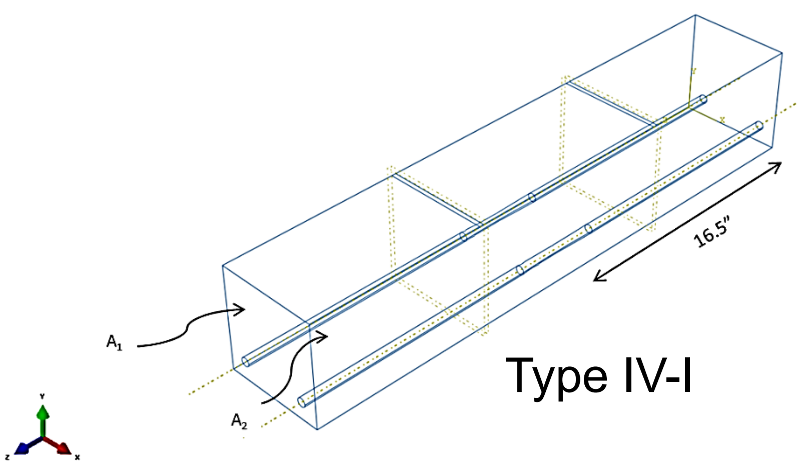
- Type III does NOT have any subcategory .
- Damage intensity, $\Delta A_s \rightarrow$ 36%, 30%, 25%, 20%, 15%, and 10%

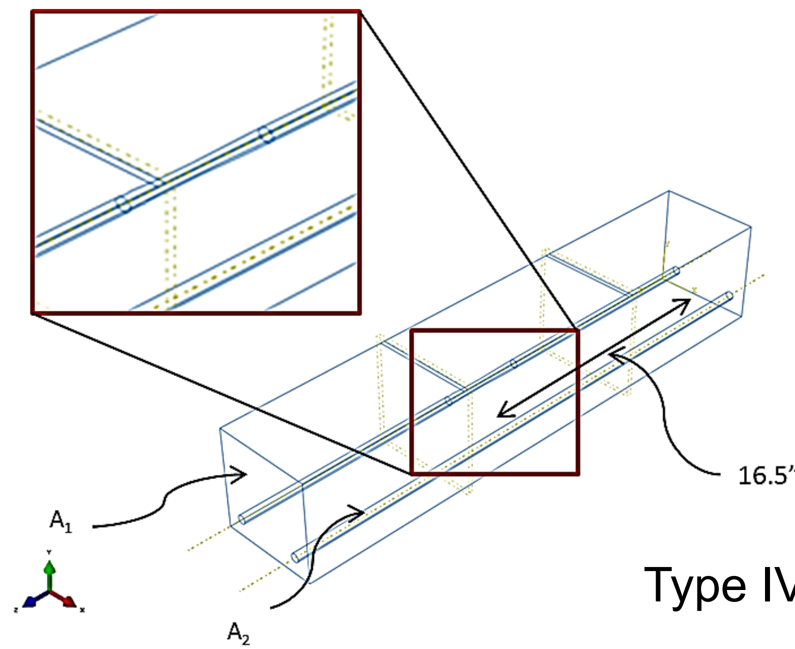


Damage Modeling

- 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%, and 10%



Type IV-I



Type IV-II

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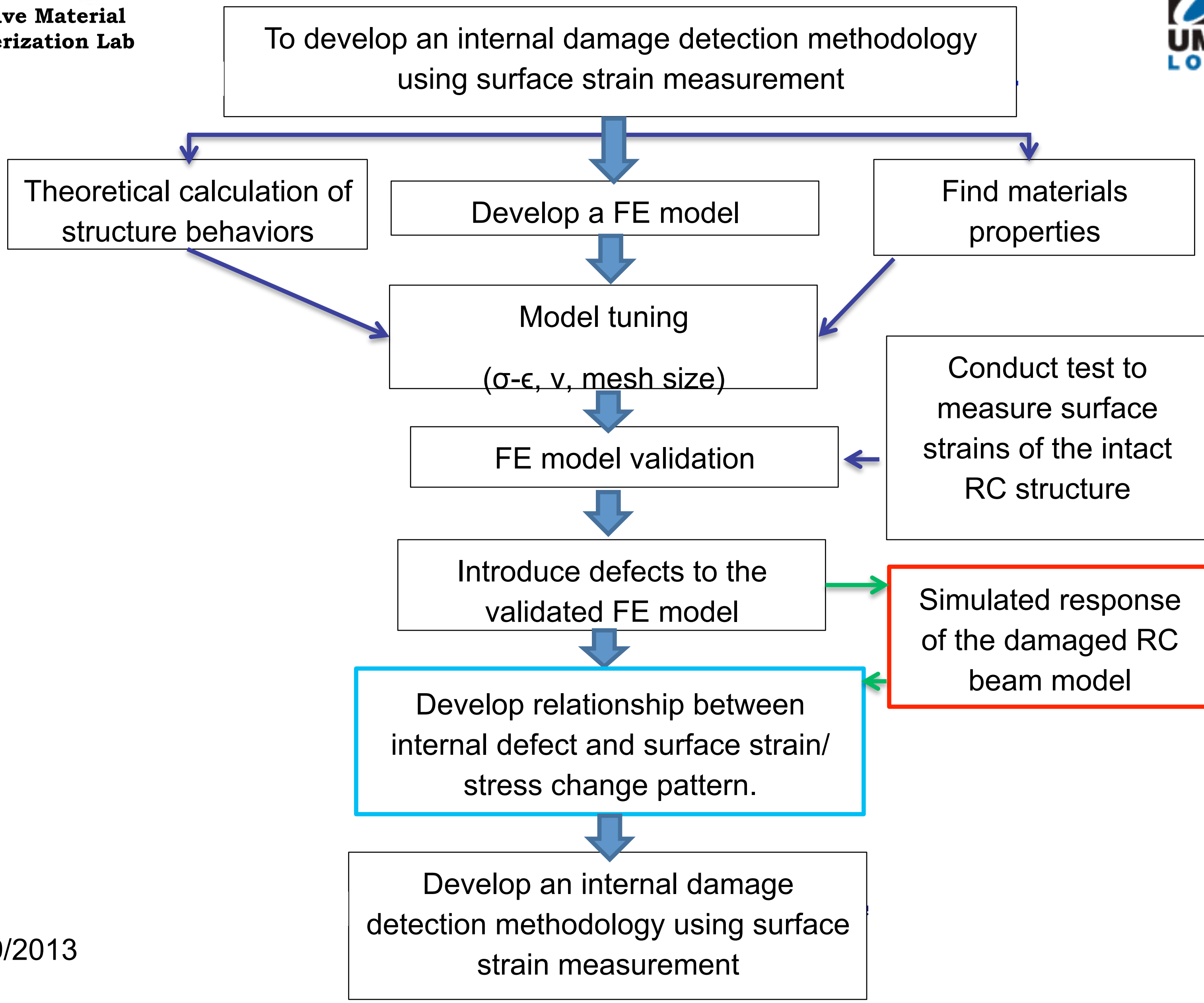

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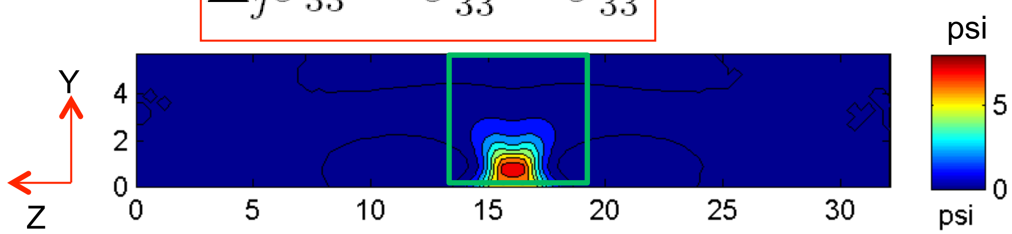
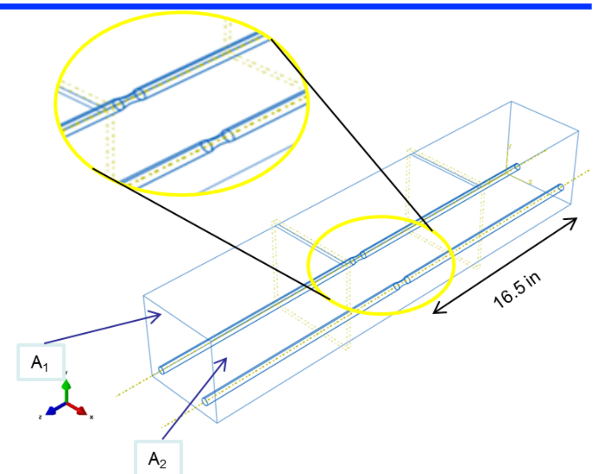
Surface Strain Change and Damage

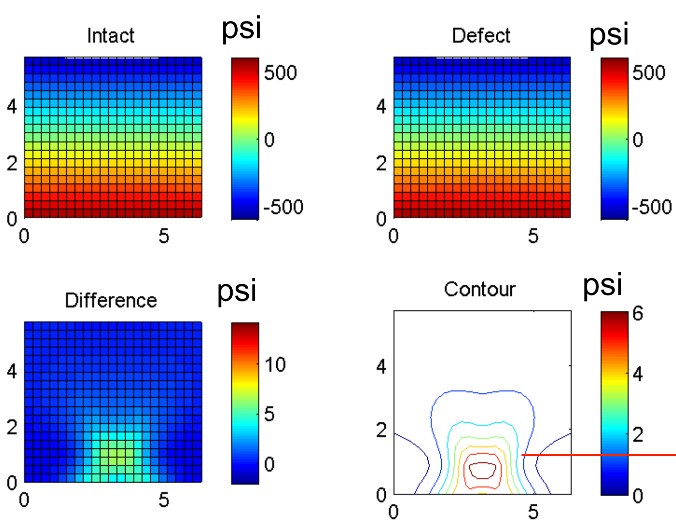
UMASS LOWELL

- Surface stress change of Type I damage:

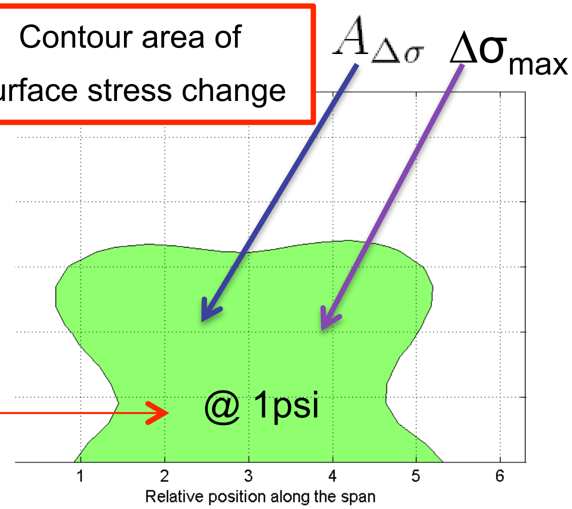
$$\Delta_j \tilde{\sigma}_{33} = \tilde{\sigma}^j_{33} - \tilde{\sigma}^o_{33}$$







Contour area of surface stress change

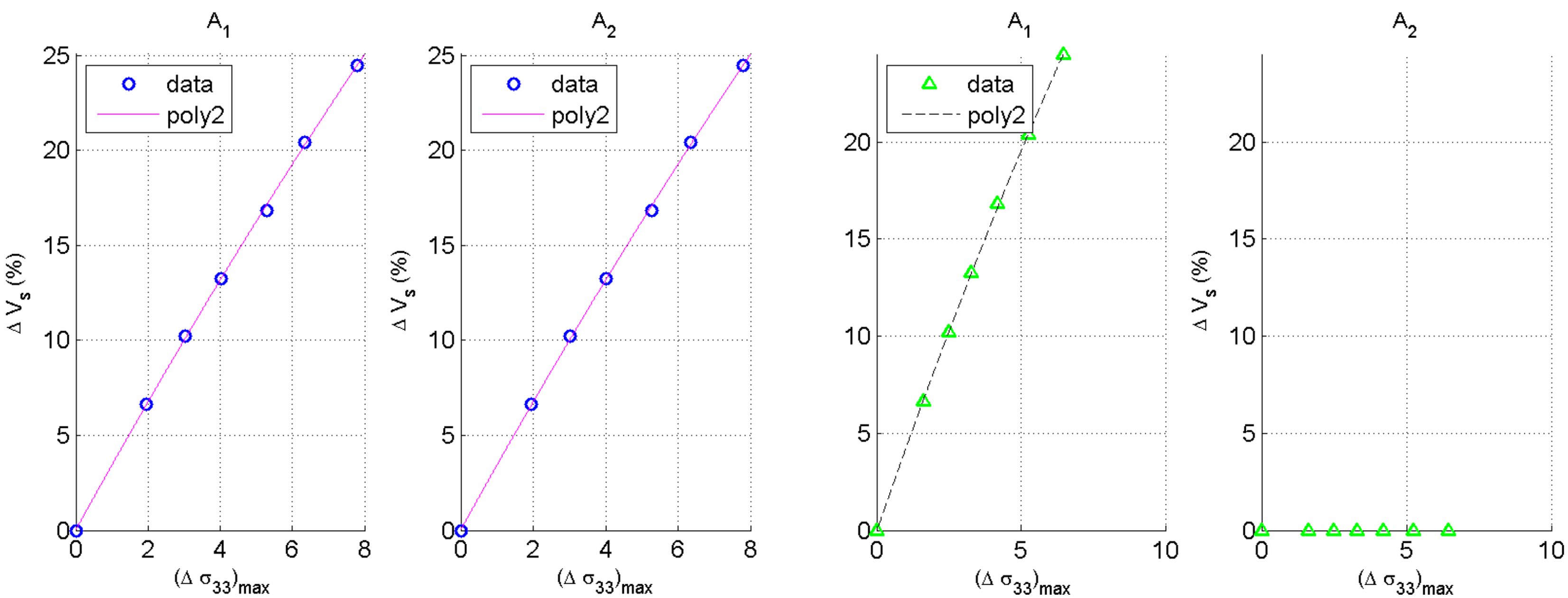


ΔA_s (%)	ΔV_s (%)	$A_{\Delta\sigma}$
10	6.632653	3.139
15	10.20408	4.834
20	13.26531	6.085
25	16.83673	7.451
30	20.40816	8.461
36	24.4898	9.72

Surface Strain Change and Damage

- Relationships between $\Delta\sigma_{max}$ and ΔV_s of Type I damage:

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



Type I-I $\Delta\sigma_{max}^{1} \approx \Delta\sigma_{max}^{2}$

Type I-II $\Delta\sigma_{max}^{1} \gg \Delta\sigma$

$\Delta\sigma_{max}^{2} \rightarrow 0$

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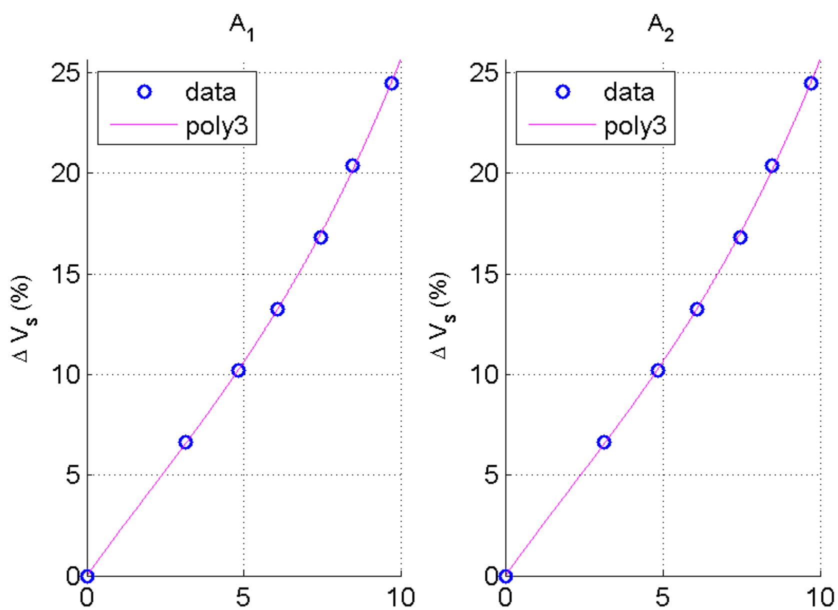
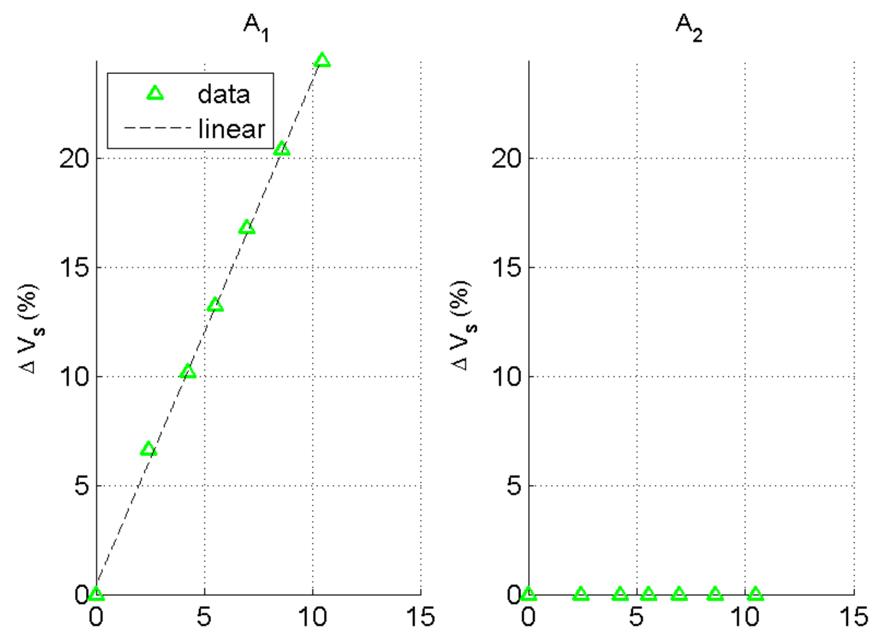
Surface Strain Change and Damage

UMASS LOWELL

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





$A_{\Delta\sigma}$ Type I-I $A^1_{\Delta\sigma} \approx A^2_{\Delta\sigma}$

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

$A^2_{\Delta\sigma} \to 0$

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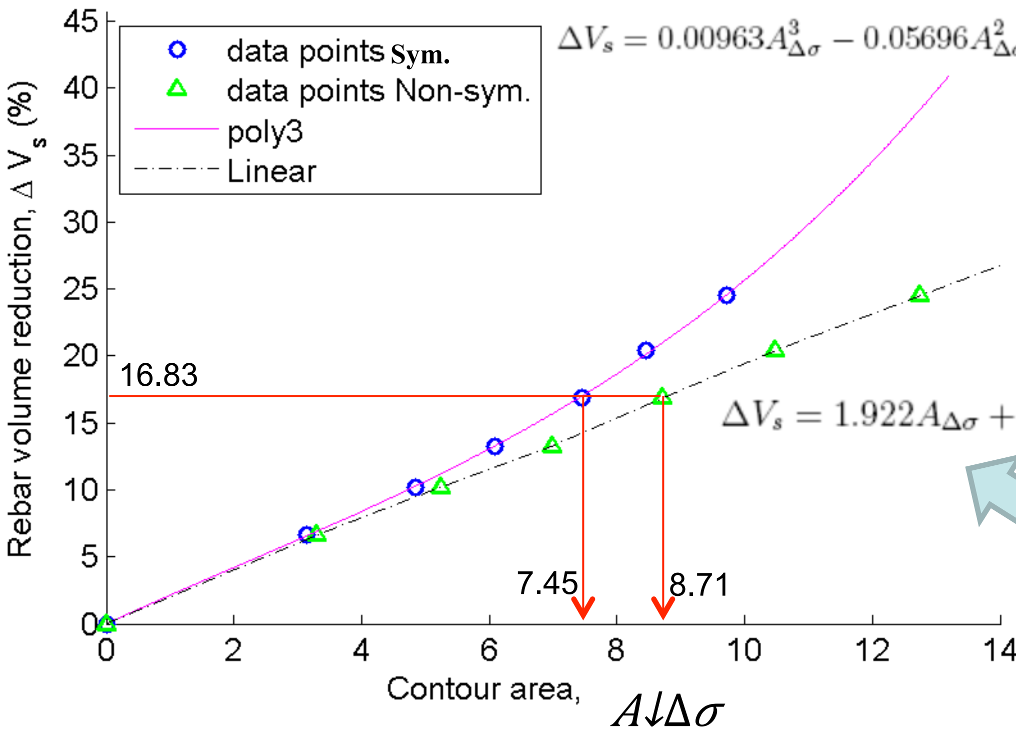
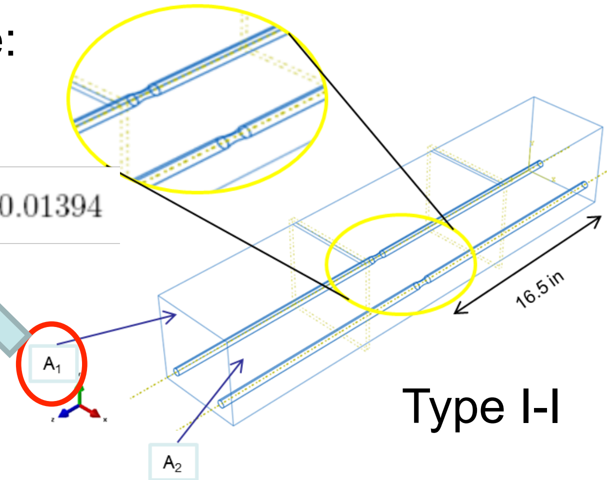
Surface Strain Change and Damage

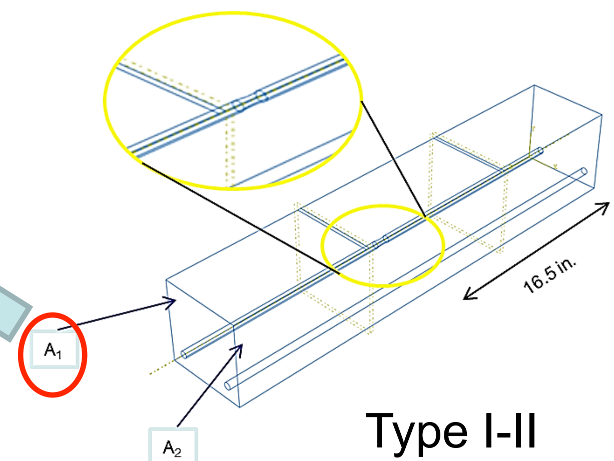
- Relationship between $A_{\Delta\sigma}$ and ΔV_s of Type I damage:
  → Relationships for A_1 side



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

$$\Delta V_s = 1.922A_{\Delta\sigma} + 0.094$$





Surface Strain Change and Damage

- Relationships between $\Delta\sigma_{max}$ and ΔV_s of Type I damage:

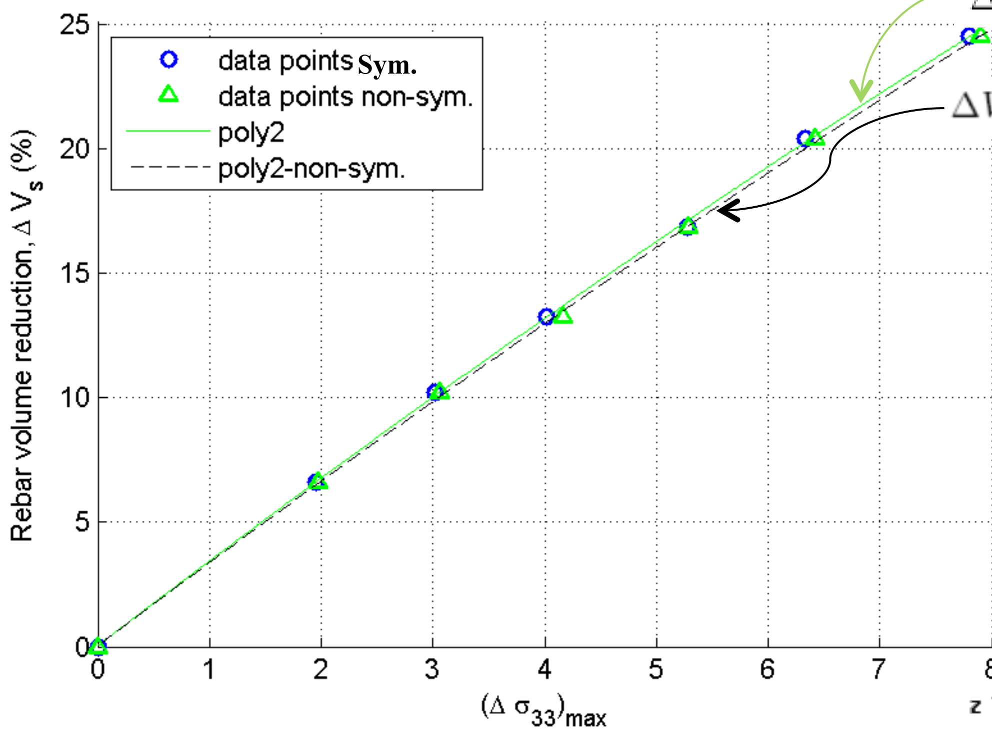
→ Relationships for A_1 side

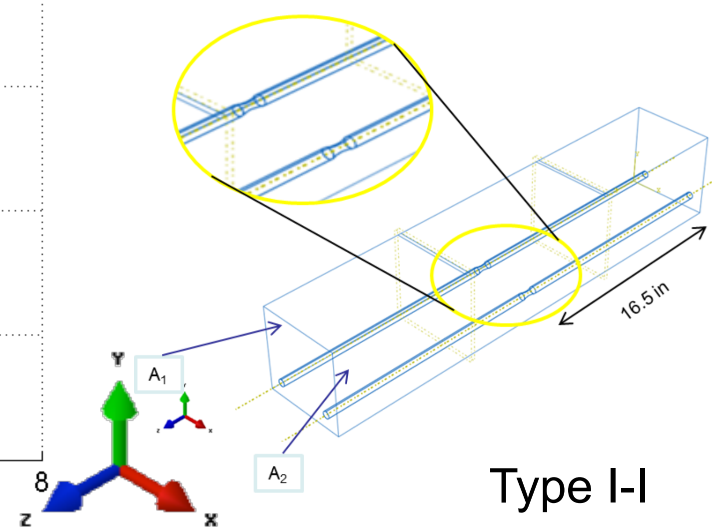
Type I-I

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

Type I-II

$$\Delta V_s = -0.03449\Delta\sigma_{max}^2 + 3.37\Delta\sigma_{max} + 0.04028$$





Type I-I

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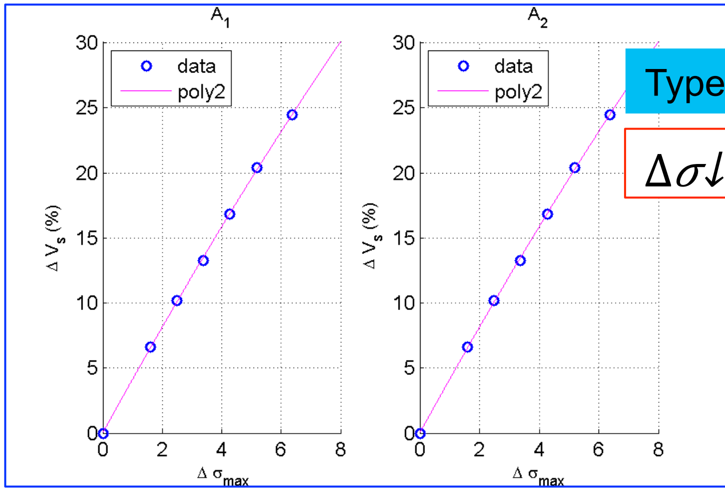
Surface Strain Change and Damage

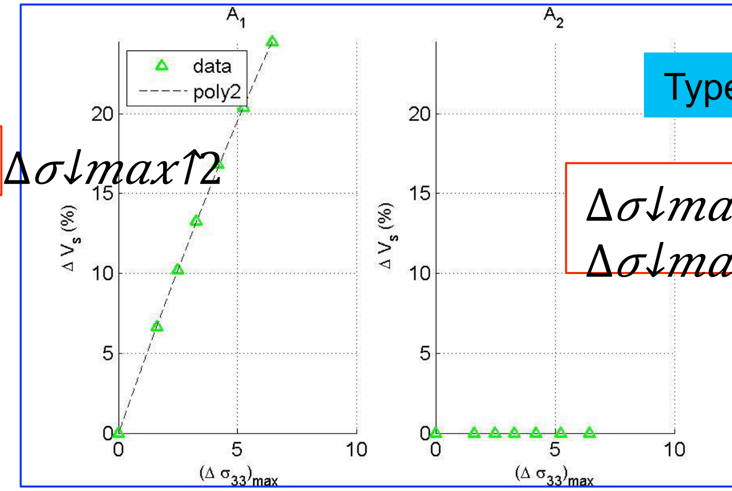
UMASS LOWELL

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



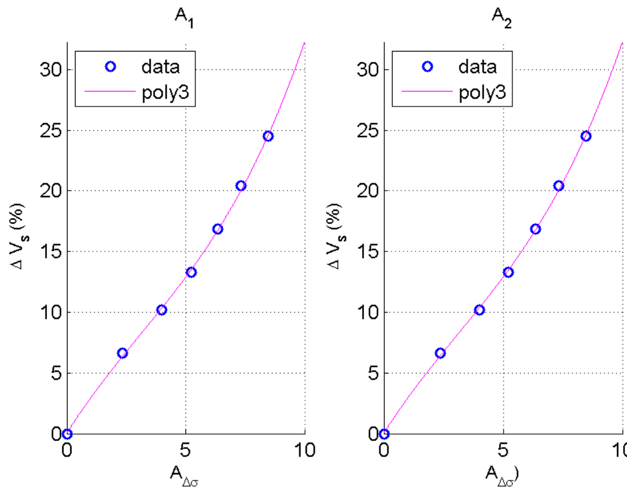
Type II-I

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



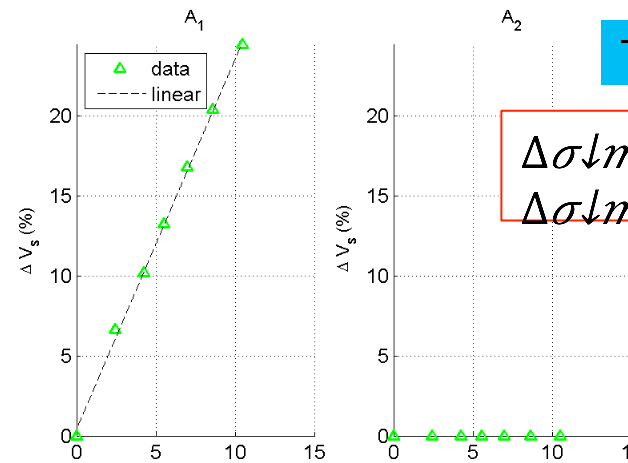
Type II-II

$\Delta\sigma_{max}^{1} \gg > \Delta\sigma_{max}^{2} \rightarrow 0$



Type II-I

$A^{1}_{\Delta\sigma} \approx A^{2}_{\Delta\sigma}$



Type II-II

$\Delta\sigma_{max}^{1} \gg > \Delta\sigma_{max}^{2} \rightarrow 0$

A_{Δ} A_{Δ}

Surface Strain Change and Damage

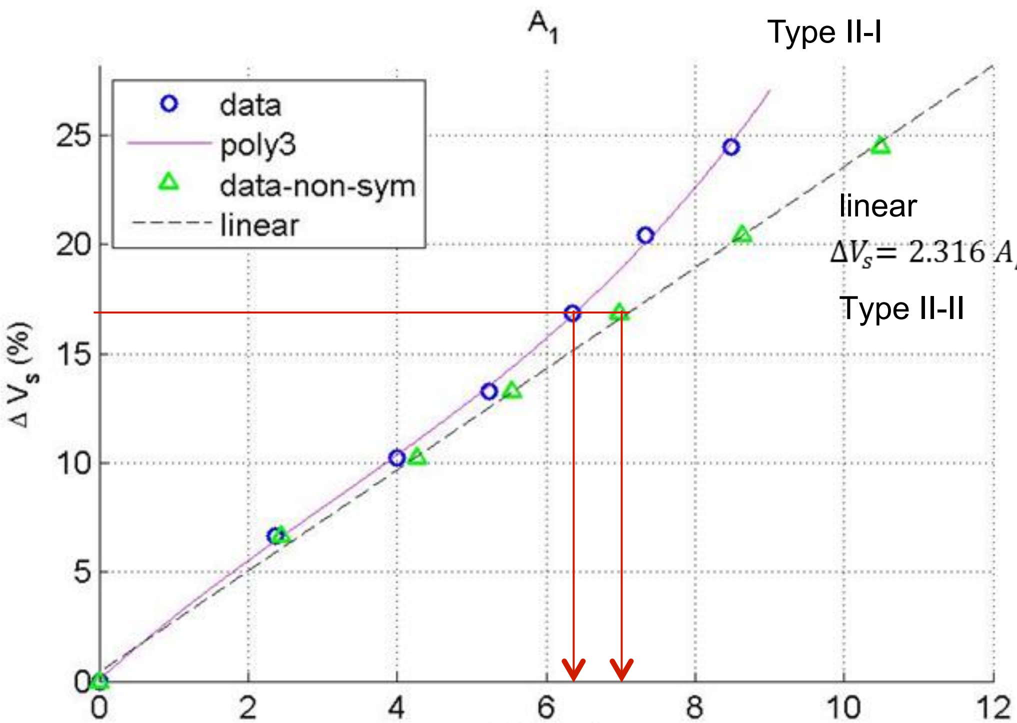
- Relationships between $A_{\Delta\sigma}$ and ΔV_s of Type II defect:

  → Relationships for A_1 side

ploy3

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

Type II-I



linear

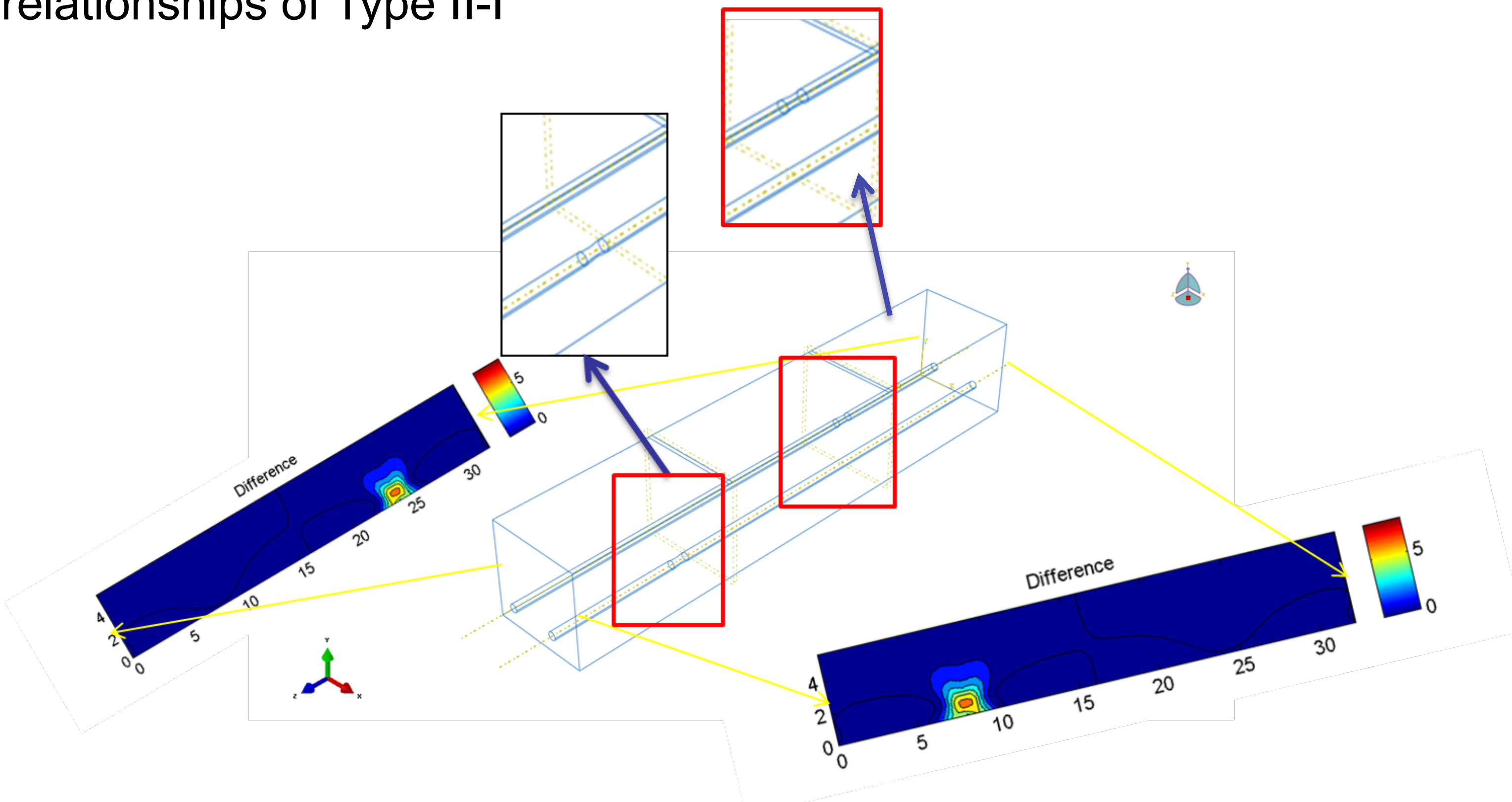
$$\Delta V_s = 2.316\, A_{\Delta\sigma} + 0.4188$$

Type II-II

$A\downarrow\Delta\sigma$

Surface Strain Change and Damage

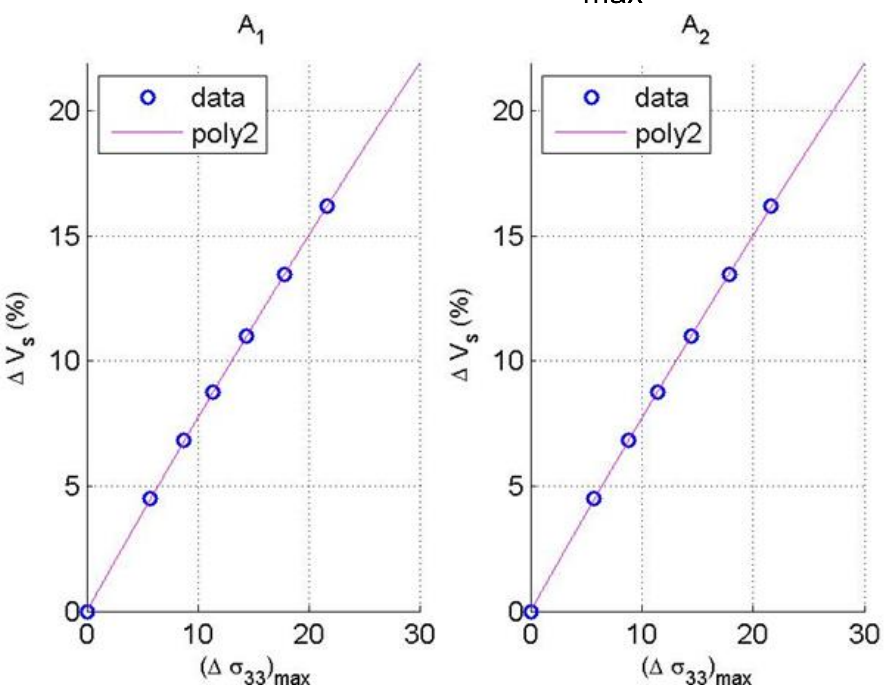
- Surface stress change of defect Type III:
  - Relationships among $A_{\Delta\sigma}$, $\Delta\sigma_{max}$, and ΔV_s in Type III follow relationships of Type II-I

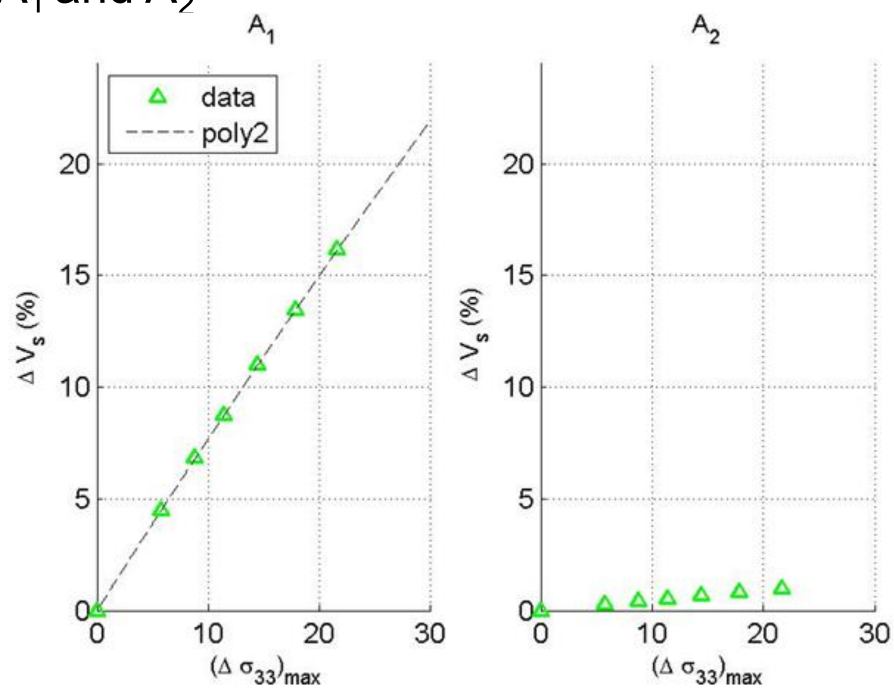


Surface Strain Change and Damage

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

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





Type IV-I

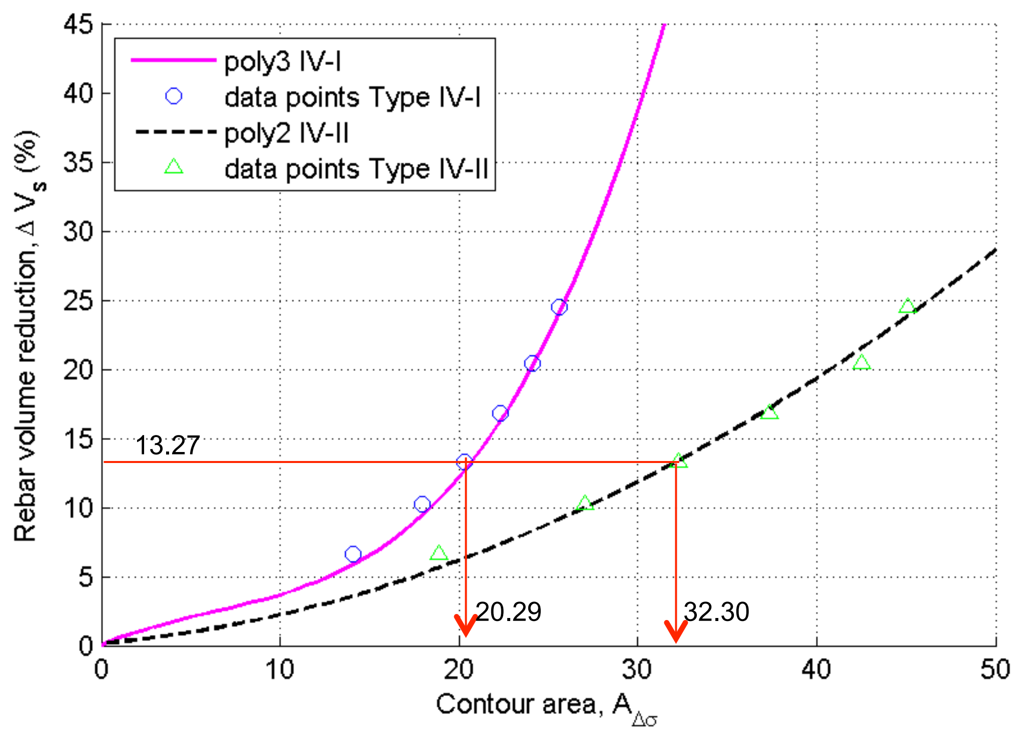
$\Delta\sigma_{max}^{1} \approx \Delta\sigma_{max}^{2}$

Type IV-II

$\Delta\sigma_{max}^{1} \gg \Delta\sigma_{m}$

Surface Strain Change and Damage

- Relationship between $A_{\Delta\sigma}$ and ΔV_s of Type IV defect:
  - Type IV−I , $\Delta V_s = 0.002\, A_{\Delta\sigma}^3 - 0.0416\, A_{\Delta\sigma}^2 + 0.5687\, A_{\Delta\sigma} - 0.002163$
  - T … 44



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Surface Strain Change and Damage

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

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

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Co-efficient / Defect types	p	q	r	C1
Type I-I	0.00963	-0.0569	2.1690	0.0139
Type I-II	0.00000	0.0000	1.9220	0.0940
Type II-I	0.02307	0.2155	3.0690	0.0564
Type II-II	0.00000	0.0000	2.3160	0.4188
Type III	0.02307	0.2155	3.0690	0.0564
Type IV-I	0.00200	-0.0416	0.5687	-0.00216
Type IV-II	0.00000	0.0080	0.1800	0.1344

Co-efficient / Defect types	A	B	C2
Type I-I	-0.0394	3.4420	0.04076
Type I-II	-0.03449	3.3700	0.04028
Type II-I	-0.05026	4.1590	0.03931
Type II-II	-0.07840	4.3070	0.06134
Type III	-0.07840	4.3070	0.06134
Type IV-I	-0.00208	0.7823	0.00674
Type IV-II	-0.00183	0.7849	0.00622

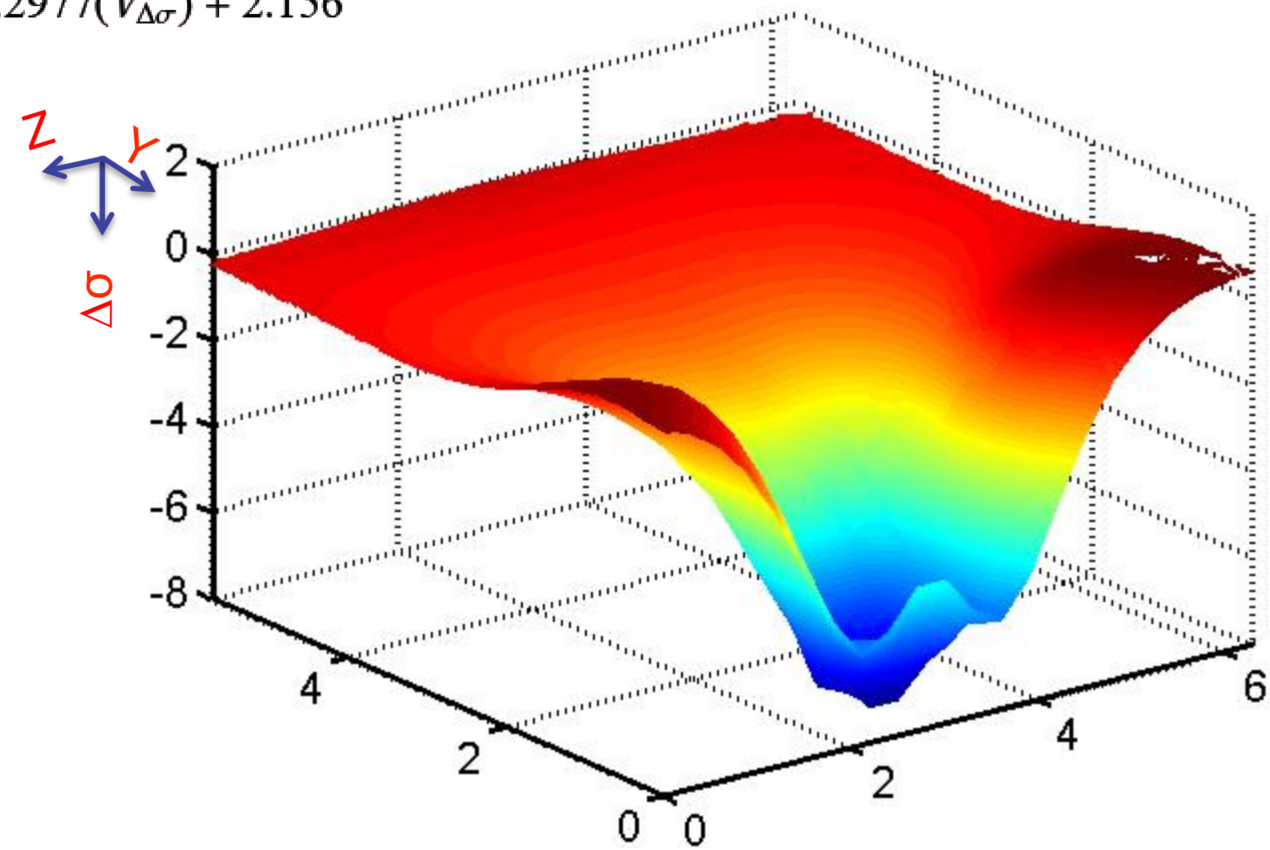
- Relationships can be used to determine the internal defect intensity.

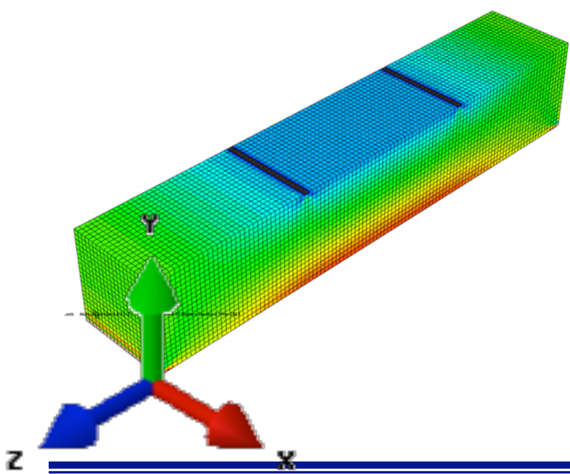
Surface Strain Change and Damage

- 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.





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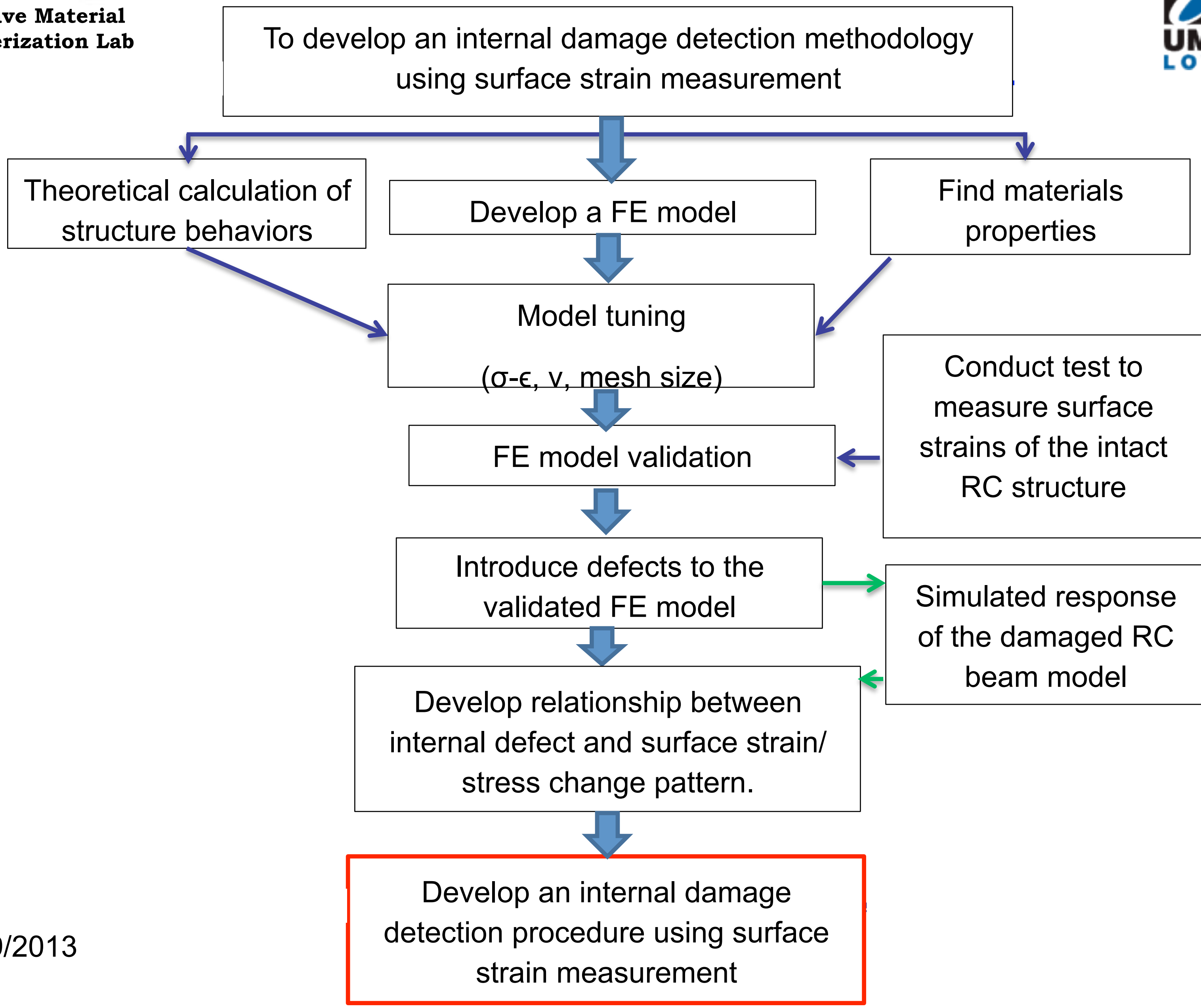
Research Roadmap

UMASS LOWELL



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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.

Measure the surface strain field (ϵ_{33}) on the both sides of the intact RC beam

$$\tilde{\epsilon}_k^{ro} \xrightarrow{\text{Filter to reduce noise}} \tilde{\epsilon}_k^{o} \xrightarrow{\text{Material properties}} \tilde{\sigma}_k^{o}$$

↓

Measure the surface strain field (ϵ_{33}) on the both sides of the RC beam after a defect is occurred

$$\tilde{\epsilon}_k^{rj} \xrightarrow{\text{Filter to reduce noise}} \tilde{\epsilon}_k^{j} \xrightarrow{\text{Material properties}} \tilde{\sigma}_k^{j}$$

↓

Find the stress difference ($\Delta\sigma_{33}$)

$$\Delta_j \tilde{\sigma}_k = \tilde{\sigma}_k^j - \tilde{\sigma}_k^o$$

↓

Find $\Delta\sigma_{max}$ and $A_{\Delta\sigma}$

$$\Delta_j \tilde{\sigma}_k^j \xrightarrow[\text{Contour area of certain } \Delta\sigma_k^j]{\text{Contour mapping}} A_{\Delta\sigma}^k$$

↓

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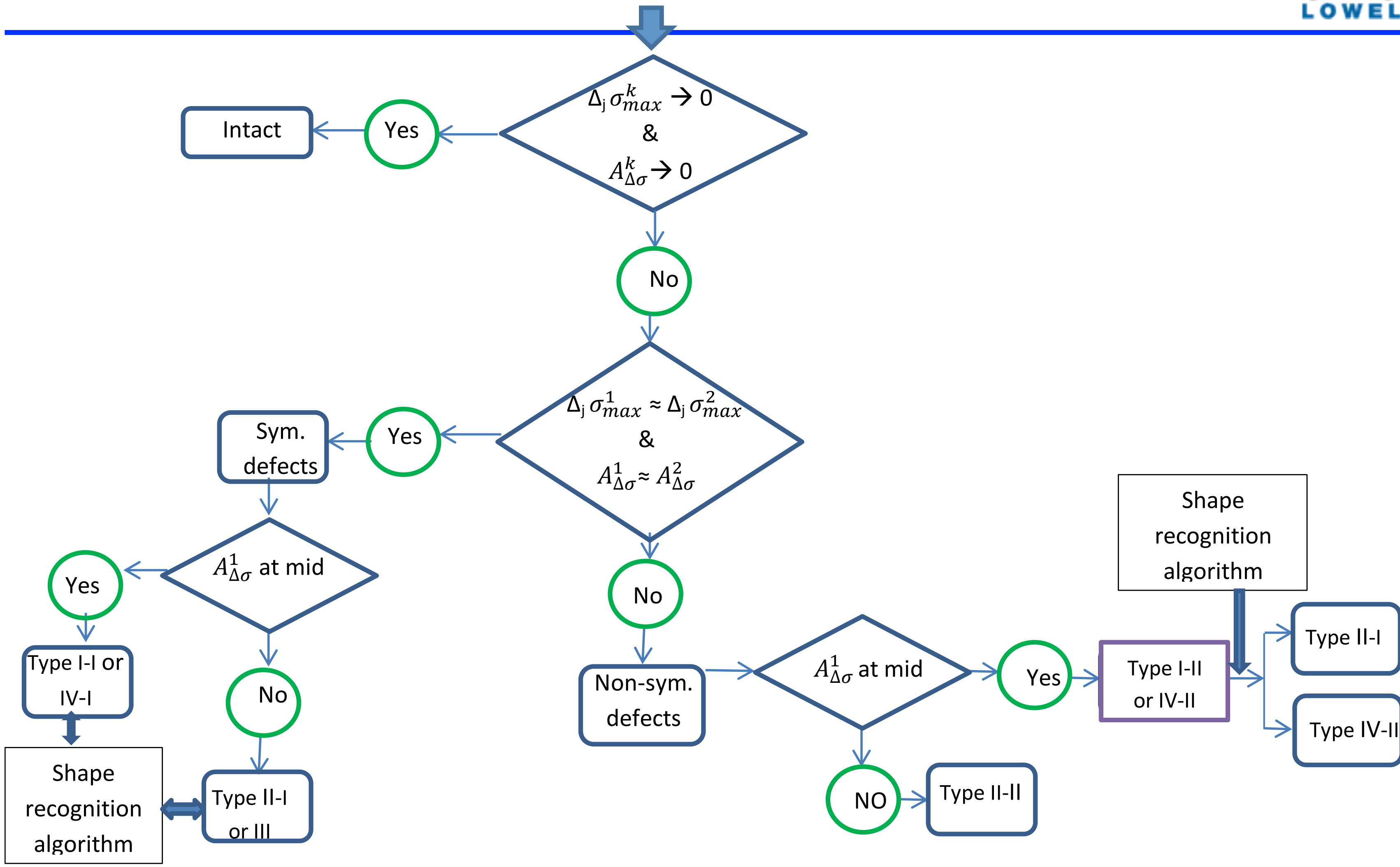
Proposed Damage Detection Procedure

UMASS LOWELL



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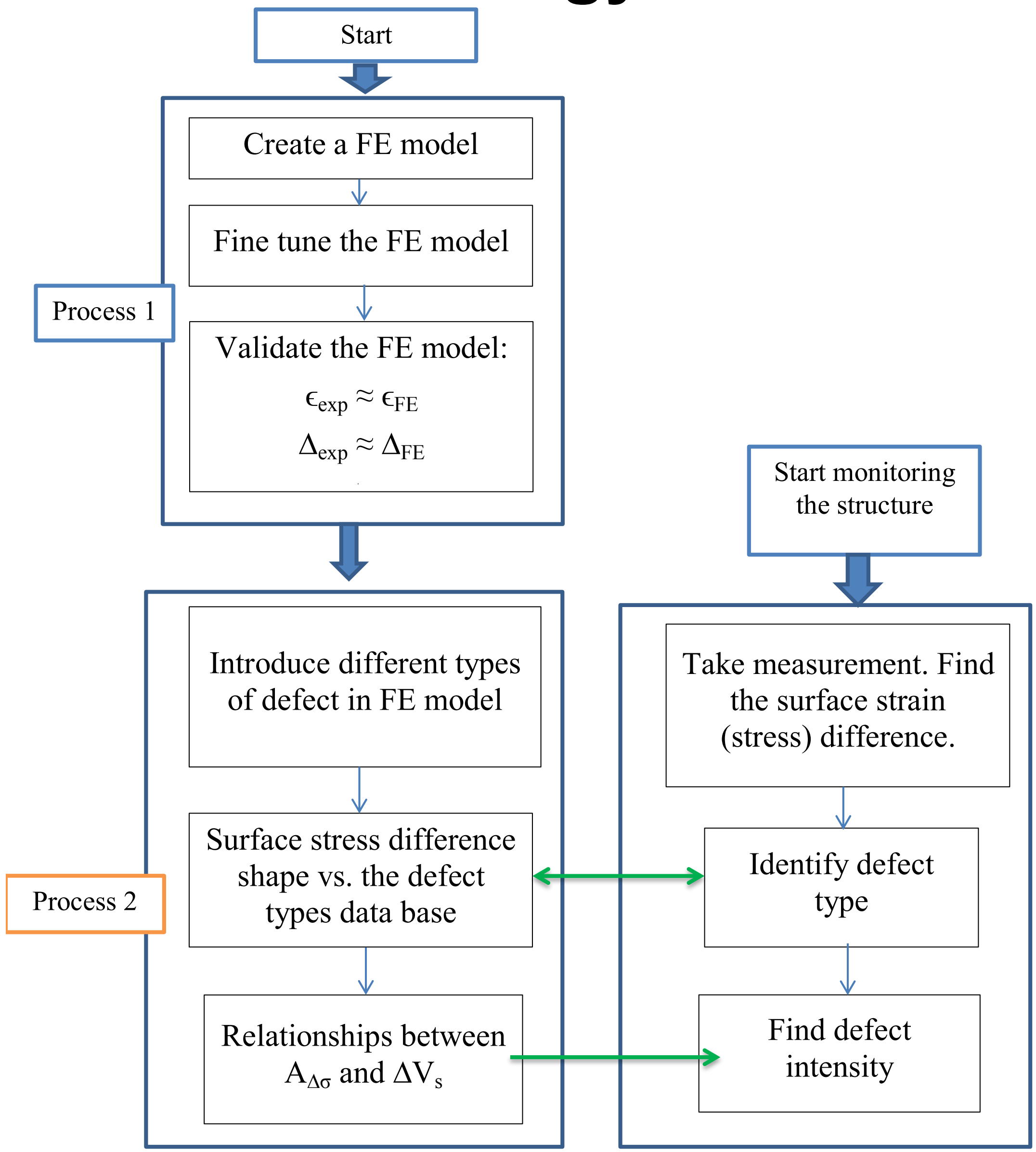
Structural Health Monitoring Strategy



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 $\Delta\sigma_{max}$) 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 to Professor Tzu-Yang Yu for being my advisor
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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 → elastic
5. No cracking in the section of the beam