Framework of conducting a reliability analysis of concrete beams using stochastic nonlinear FE models in LS-Dyna

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Research Overview

Objective:

Develop a reliability-based framework accounting for the spatial variation of concrete using stochastic FE to assess the safety of in-service concrete beams.

Methodology:

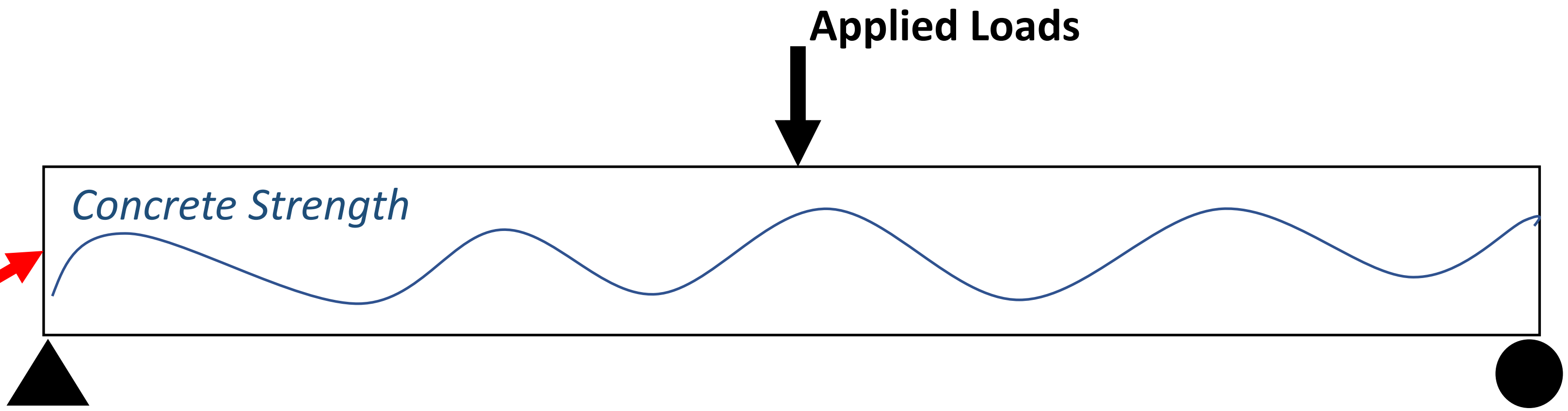
1. Create and validate a nonlinear FE model of the concrete beam using LS-DYNA.
2. Develop a Python code to discretize the validated model to include the stochastic mesh of concrete strength.
3. Develop an automated computer code to generate many stochastic FE models of the validated beam.
4. Conduct a reliability analysis considering different levels of concrete spatial variability using the automated framework to assess the safety of concrete beams designed per the North American building codes.

Research Gaps

Assessing Existing Concrete Beams:

- North American design codes does not account for the **spatial variability** present in the concrete that makes up the beam when calibrating the design equations although they affect the safety of the member.

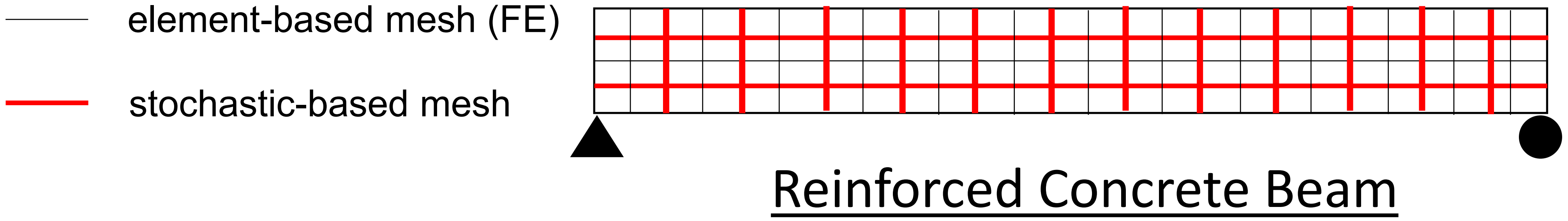
How does the spatial variation of the concrete impact the reliability of the in-service structural member?



Reinforced Concrete Beam

Stochastic Finite Element (FE)

Stochastic FE requires discretizing the member into two meshes that act together:



- Stochastic FE refers to modeling certain parameters within the FE model to capture the spatial variability in 3-dimensions.
- This allows the user to capture the spatial variability in the structural response using random fields.
- In the case of a reinforced concrete beam, the stochastic mesh can be generated to capture the spatial variability of the concrete strength.

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Stochastic FE: Random Field Generation

EOLE Method for generating lognormal 3D Random Fields Li and Der-Kiureghian 1993):

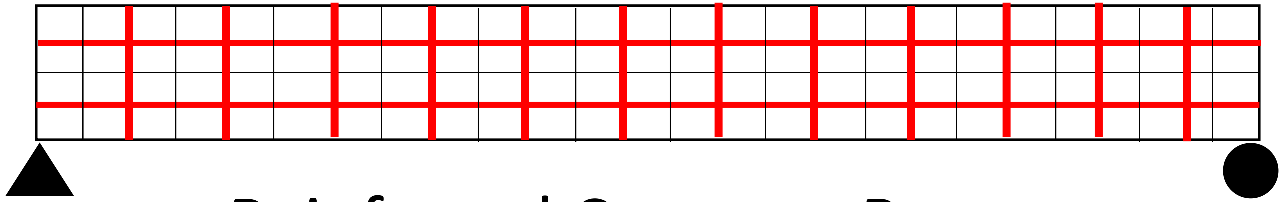
$$\hat{H}(\boldsymbol{Y}, \theta) = \mu_{lny} + \sigma_{lny} \sum_{i=1}^{M} \frac{\xi_i(\theta)}{\sqrt{\lambda_i}} \boldsymbol{\psi}_i^T \boldsymbol{C}_{\boldsymbol{Y},\boldsymbol{Y}_i}$$

- $\hat{H}(\boldsymbol{Y}, \theta)$ → Gaussian Field Realizations
- μ_{lny} → Mean
- σ_{lny} → Std. Deviation
- $\xi_i(\theta)$ → Random Std. Normal Variable
- $\boldsymbol{C}_{\boldsymbol{Y},\boldsymbol{Y}_i}$ → Covariance Matrix
- $\boldsymbol{\psi}_i^T$ → Eigen Vector of the Std. Normal Field
- λ_i → Eigen Value of the Std. Normal Field

- Stochastic FE (SFE) requires discretizing the member into two meshes that act together:

element-based mesh (FE)

stochastic-based mesh



Reinforced Concrete Beam

Stochastic FE: FE Model Validation

Task 1. Develop and validate nonlinear SFE model of EB FRP strengthened concrete beam using LS-DYNA.

Table 1. Validation of FE model against experimental results.

	(kN) P_y	(mm) δ_y	(kN) P_u	(mm) δ_u	(με) f_{frpt}
EXP	--	--	75.8	27.0	11,000
FE	66.8	6.0	84.6	27.1	10,800
EXP/FE	--	--	0.90	1.00	1.02

(Zhang et al. 2006)

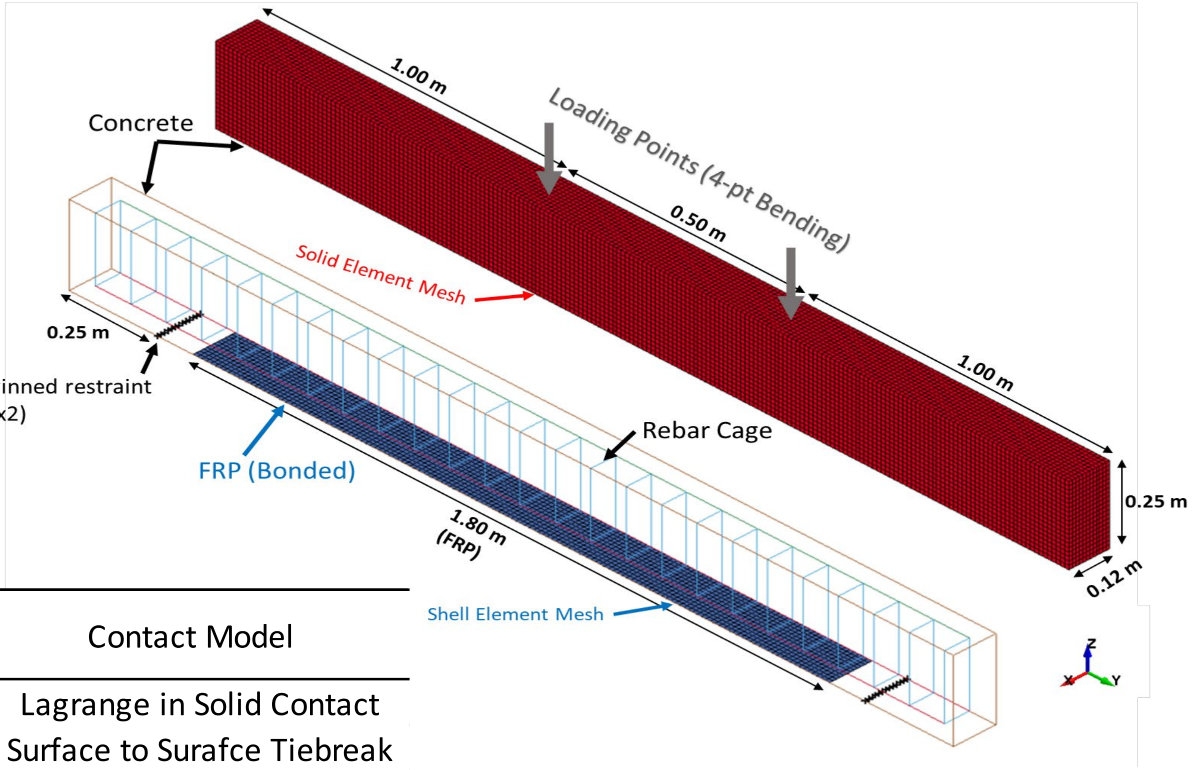


Table 2. Material Models (LS DYNA)

Material Name	Element Type	Material Model	Contact Model
Steel	Beam	003 - Plastic Kinematic	Lagrange in Solid Contact
FRP	4-Node Shell	054 - Enhanced Composite w/ Damage	Surface to Surafce Tiebreak
Concrete	8-Node Solid	072R3 - Concrete Damage Rel3	Both

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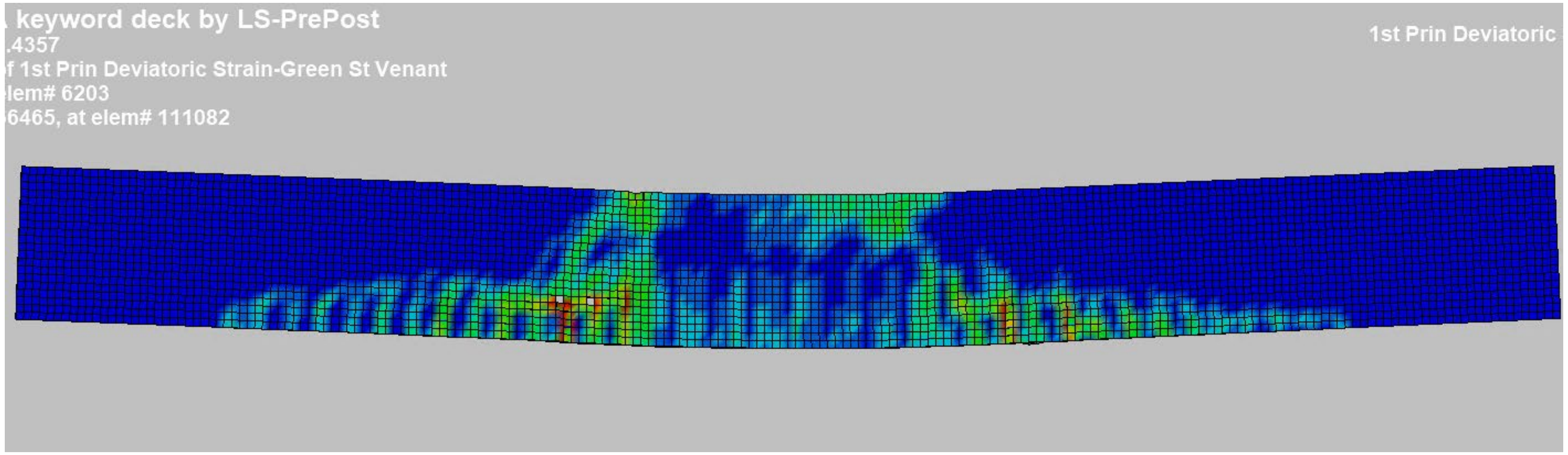
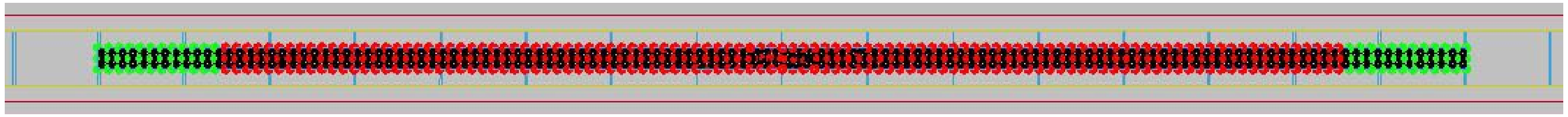
Stochastic FE: Strengthened Beam Failure

Task 1. Develop and validate nonlinear SFE model of EB FRP strengthened concrete beam using LS-DYNA.

Cracking at Failure (t > 1.75s):



Bond at Failure (t > 1.75s):

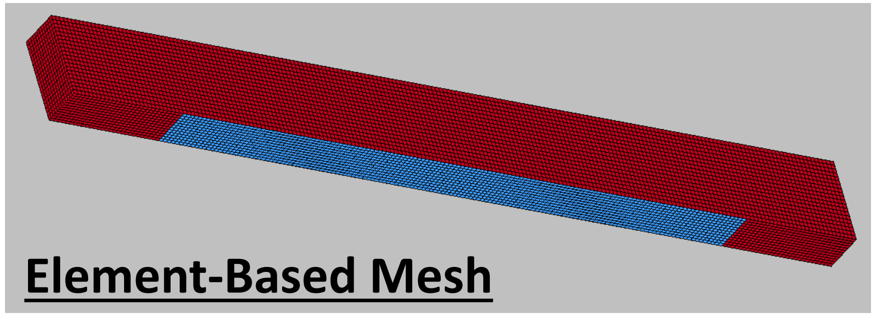


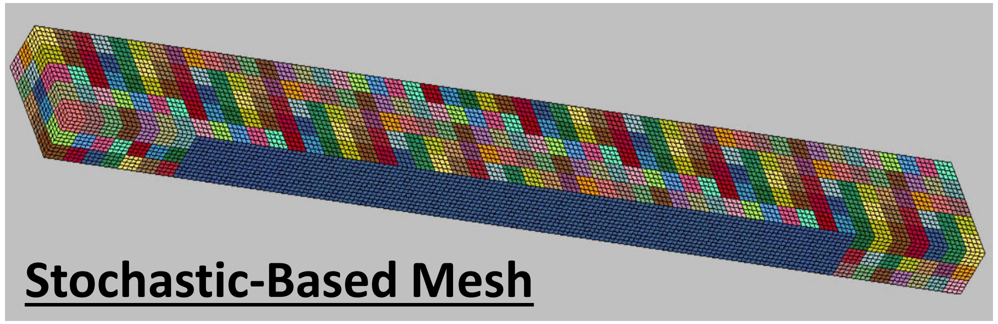
Stochastic FE: Strengthened Beam Failure

Task 2. Discretize the LS DYNA model to include a secondary stochastic mesh.

A command file (.Cfile) is generated to discretize the element-based FE mesh to have many *PARTs in LS DYNA so that the stochastic-based mech can be overlaid.

To represent the concrete as a 3D random field, unique ***PART, *MAT, *CONTACT, *SET_SEGMENT**, and ***ERODE, *ELEMENT** are assigned to each stochastic element in the stochastic-based mesh



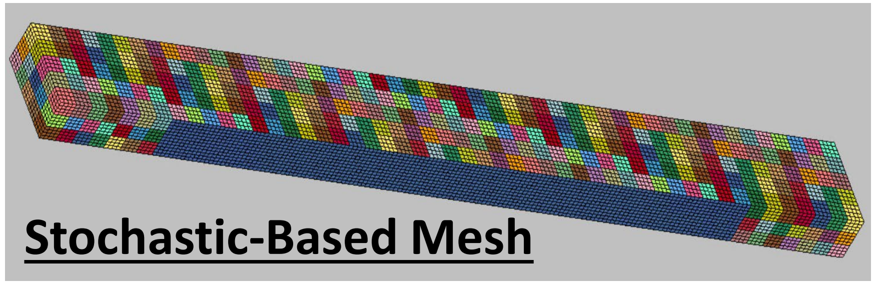


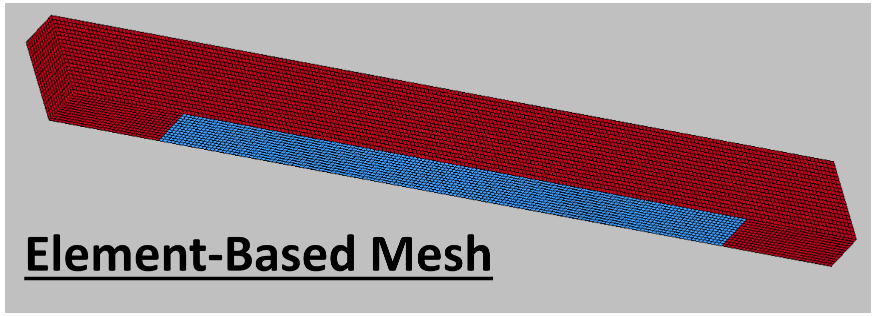
Discretization of Concrete Beam

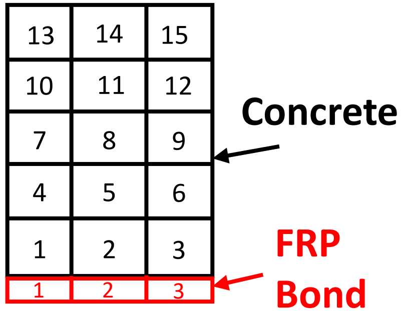
Stochastic FE: Automated Computer Code

Task 3. Develop a computer code to conduct reliability assessment using SFE models of the validated beam.

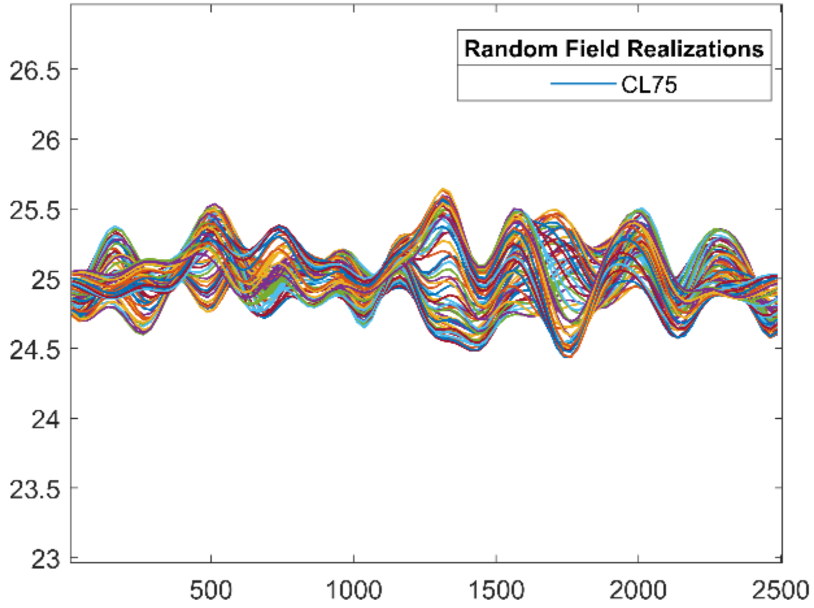
LS DYNA ⟷ **Python** ⟵ **MATLAB**







Cross-section



Random Field of Concrete Strength

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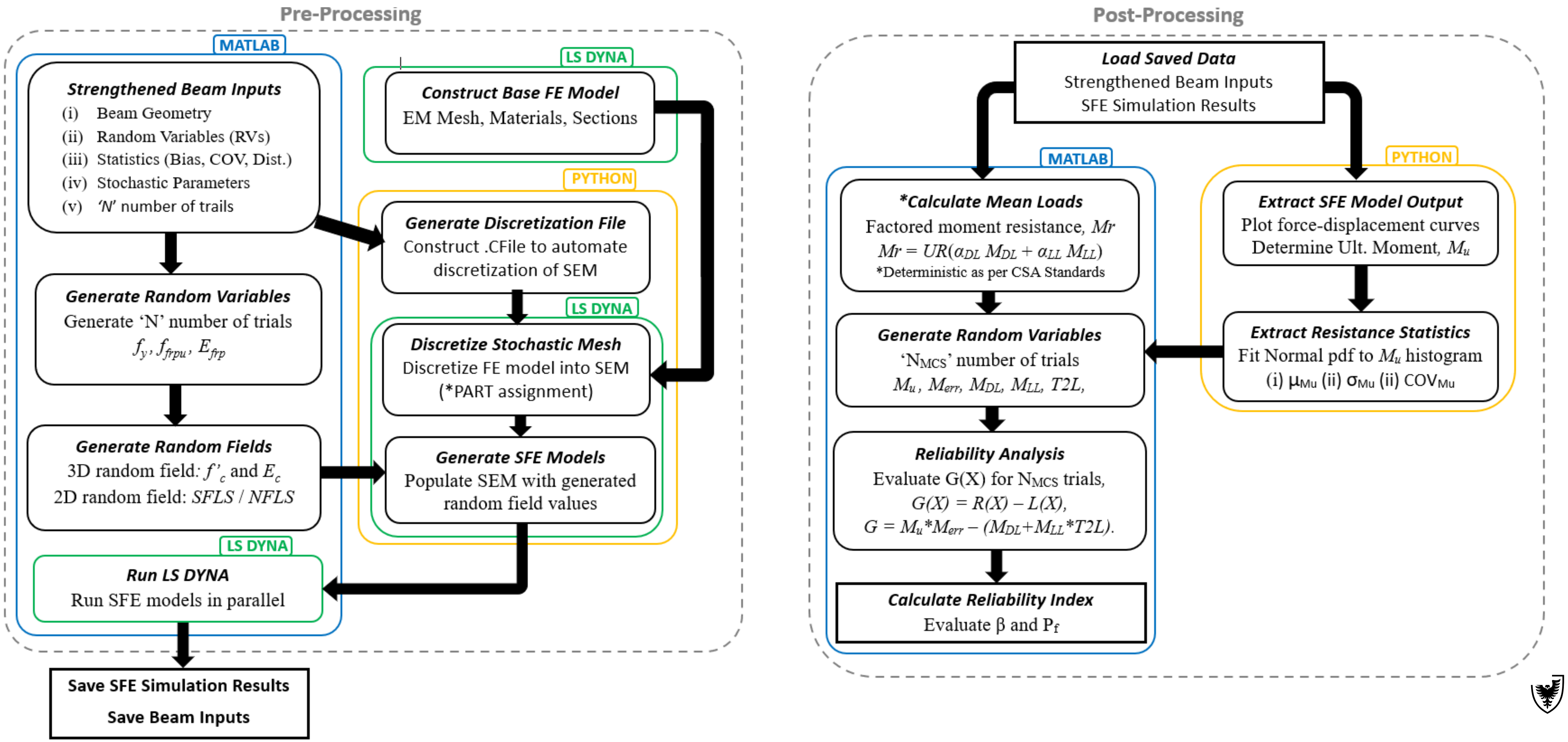
Stochastic FE: Reliability Analysis Framework

Task 3. Develop a computer code to conduct reliability assessment using SFE models of the validated beam.



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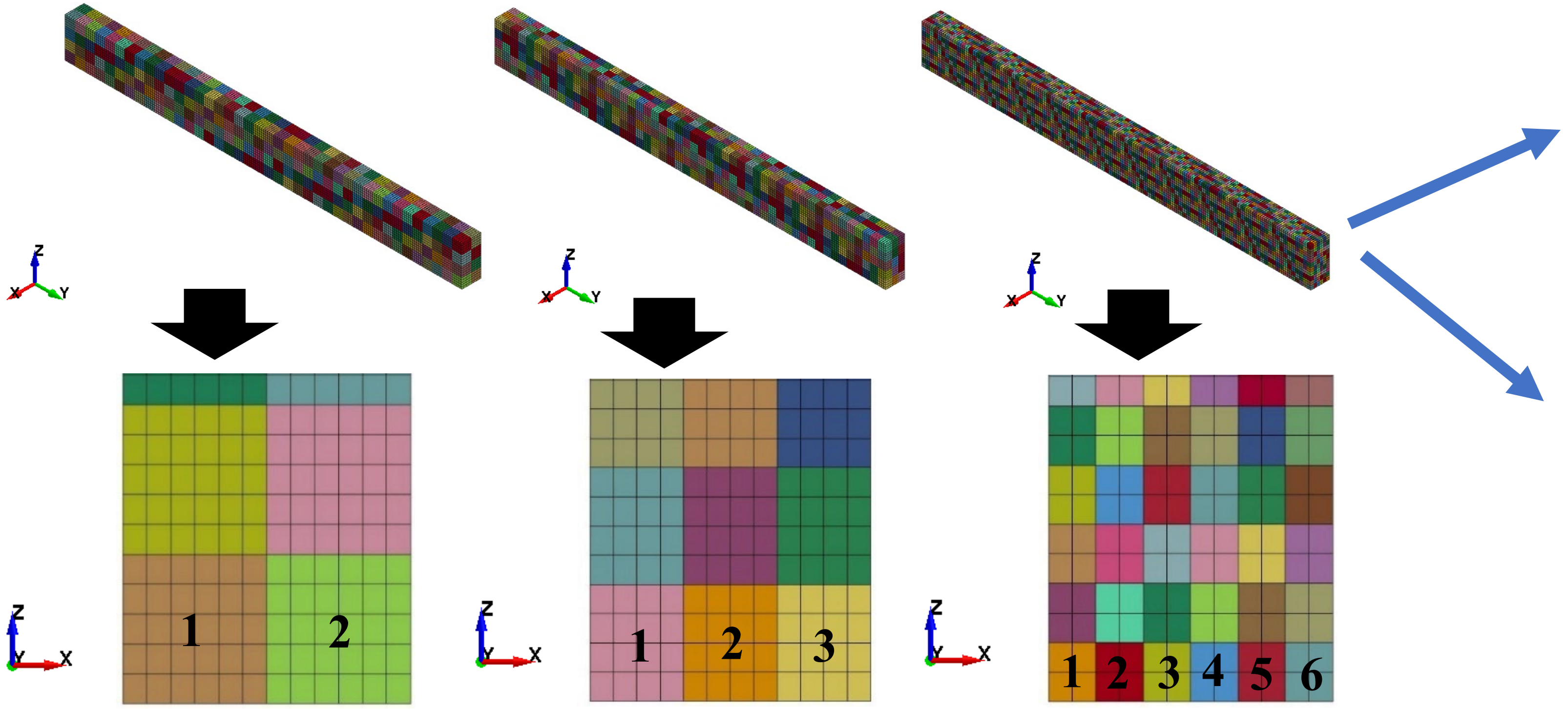
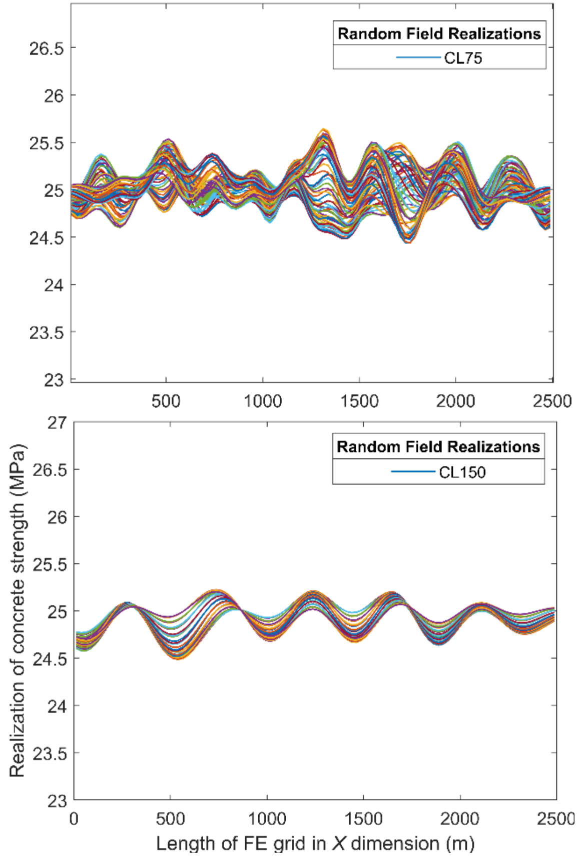
Stochastic FE: Stochastic Input

Task 3. Develop a computer code to conduct reliability assessment using SFE models of the validated beam.



Section View of SFE Model with Various Mesh Density



Random Field of Concrete Strength

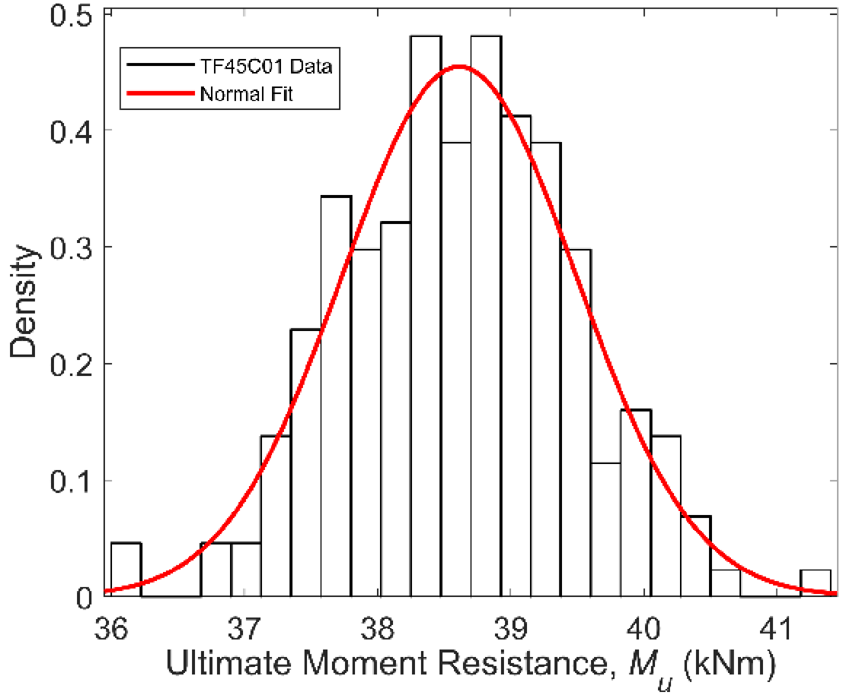
Stochastic FE: Resistance Model

Resistance model established using the ultimate response of 3,066 SFE models, fitted with gaussian distributions.

Table 5. Strengthened beam resistance statistics.

Strengthened Beam ID	Failure Mode	μ_{Mu}	σ_{Mu}	COV_{Mu}
TF25C01	Y-IFC	33.87	1.07	0.0316
TF25C03	Y-IFC	33.59	1.07	0.0319
TF45C01	Y-IFC	38.59	0.91	0.0236
TF45C03	Y-IFC	38.47	0.99	0.0257
CF25C01	Y-Crush	65.95	0.47	0.0072
CF25C03	Y-Crush	65.43	2.07	0.0316
CF45C01	Y-Crush	83.18	2.46	0.0296
CF45C03	Y-Crush	82.90	2.84	0.0343

μ_{Mu} = Mean of M_u; σ_{Mu} = Standard Deviation of M_u; COV_{Mu} = coefficient of variation of M_u



Histograms of M_u with fitted normal pdf (Tension-Controlled).

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Ch 3. SFE Reliability: Summary

- An automated framework is presented for conducting stochastic FE reliability analysis using an LSDYNA-Python-MATLAB interface.
- Numerical example using stochastic FE on the reliability of 8 FRP strengthened concrete beams in LS DYNA.
- Results showed that automation of the discretization of the stochastic mesh in LS DYNA allowed for better efficiency through batch creation of multiple stochastic FE models to be solved in parallel.
- The use of stochastic FE in establishing the resistance model in structural reliability analysis will aid in improving the evaluation of components with complex performance functions such as FRP strengthened concrete beams.

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Thank You

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