From Localized Damage Modeling to Regional Collapse Risk:

# Advances in Performance Assessment of Reinforced Concrete Structures Under Extreme Events

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# Challenges facing simulation-based seismic performance assessment of structures

## *Motivation*

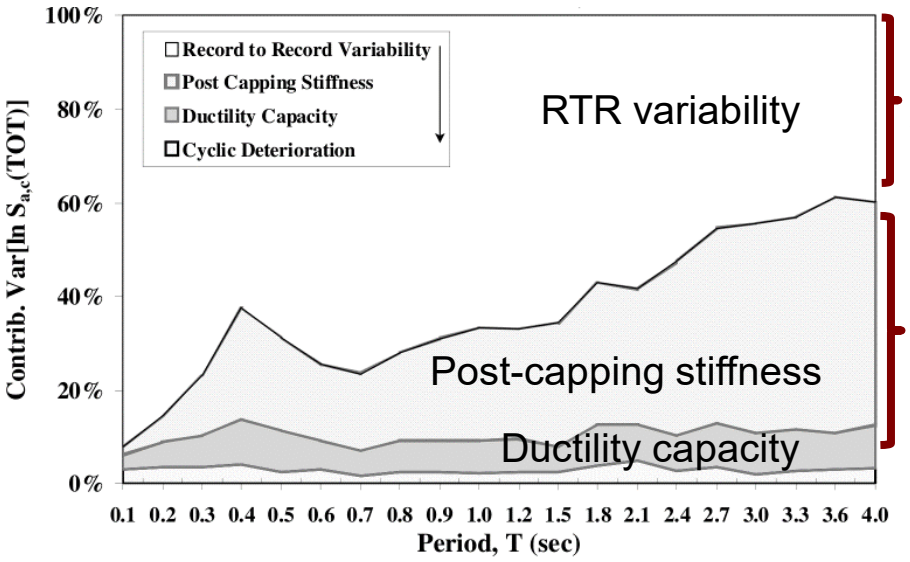
- Assessing the seismic safety of structures
- Improving building code provisions

Taiwan 2018 earthquake (Skynews)

## *Key Issues*

- Limitations of nonlinear structural analysis models
- **Sparsity of observations** on variability of earthquake ground motions across a region

# Challenges facing simulation-based seismic performance assessment of structures



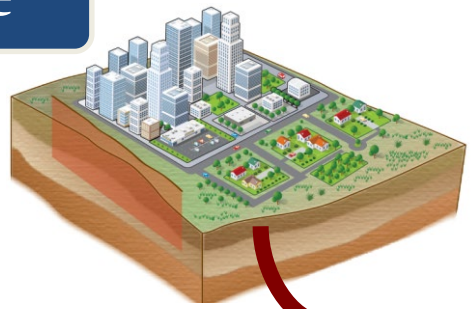

Ground motion attribute

Structural component model attributes

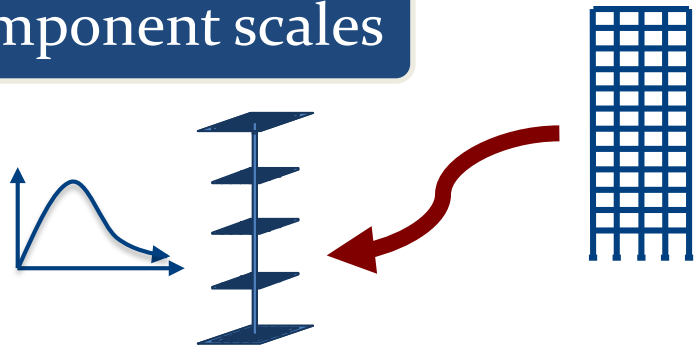
Contribution of uncertainty in system parameters to variance of collapse capacity

(Ibarra and Krawinkler 2005)

Regional scale



Material and component scales



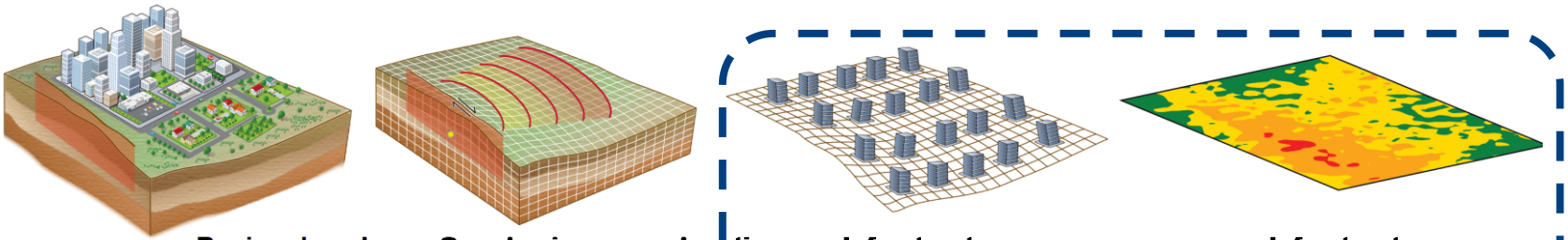
# Quantifying variability is the main objective at the regional scale

## *Tool*

Using high resolution physics-based ground motions generated by the DOE project: **High Performance, Multidisciplinary Simulations for Regional Scale Earthquake Hazard and Risk (EQSIM)**

## *Objective*

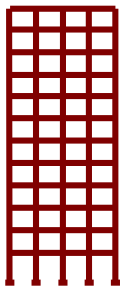
Developing a detailed understanding of the regional scale, site-specific variation of earthquake risk to RC buildings




(Rodgers et al., 2019; Rodgers, Pitarka and McCallen, 2019)

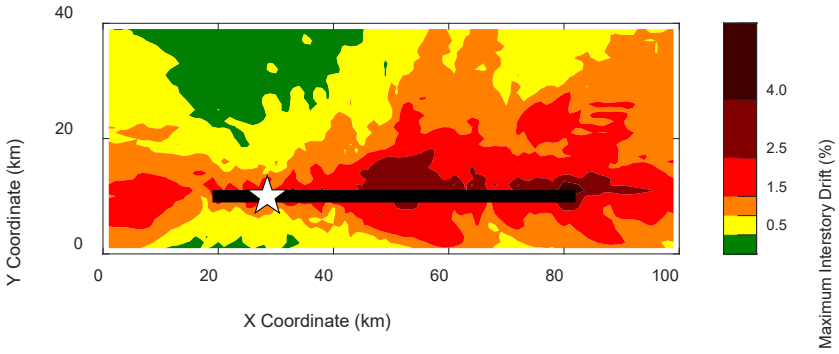
# Complex spatial distribution of structural risk over the near-fault region

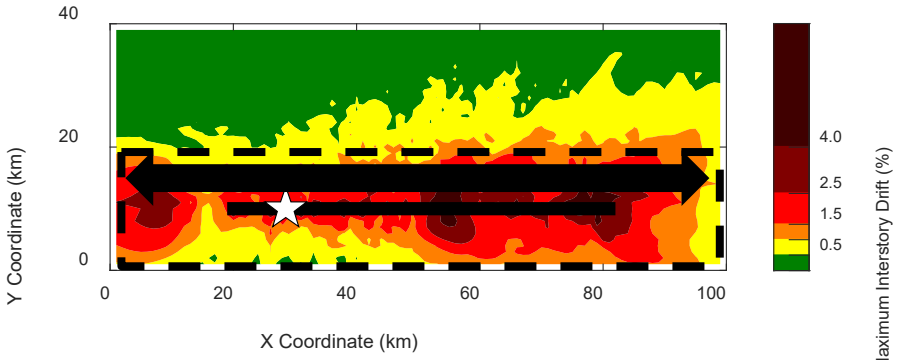
Structural risk due to a M7 fault rupture



12 story moment frame

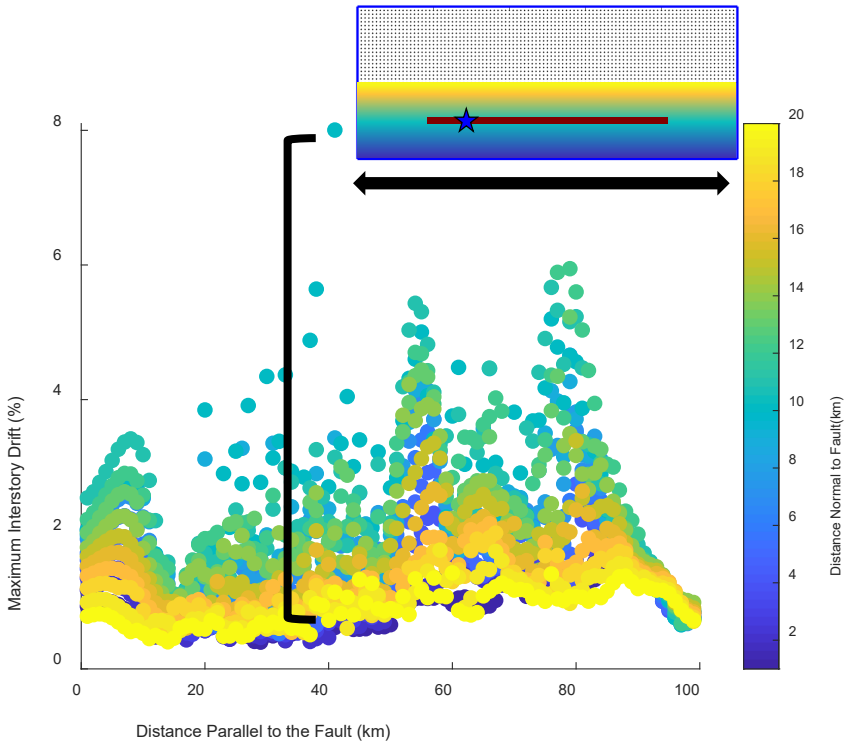
*Maximum interstory drift varies by a factor of 8 along the fault*



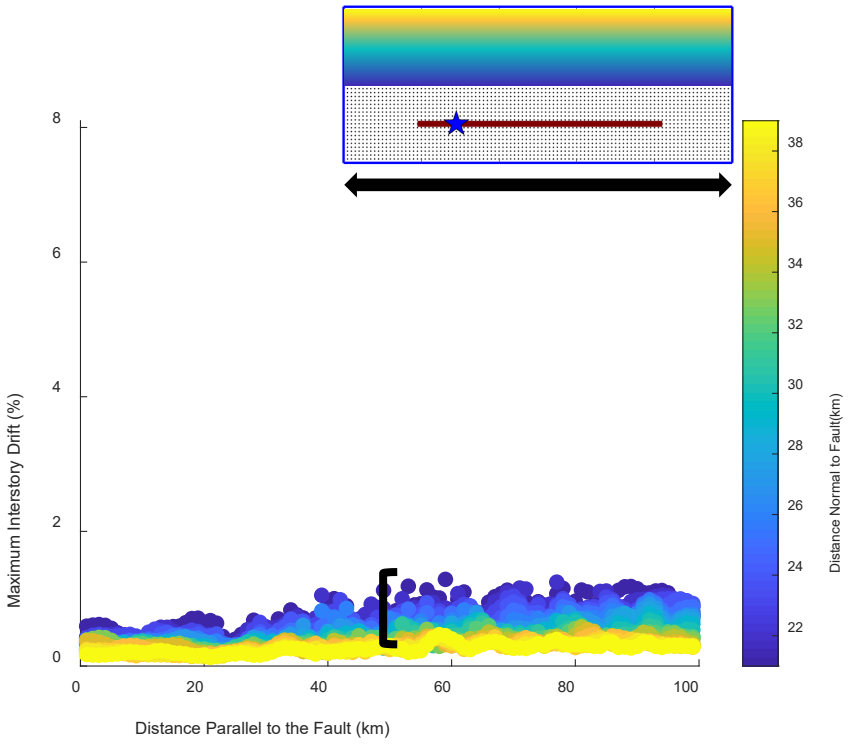



# Higher structural demands and variability in the near-fault region

< 10 km normal to fault

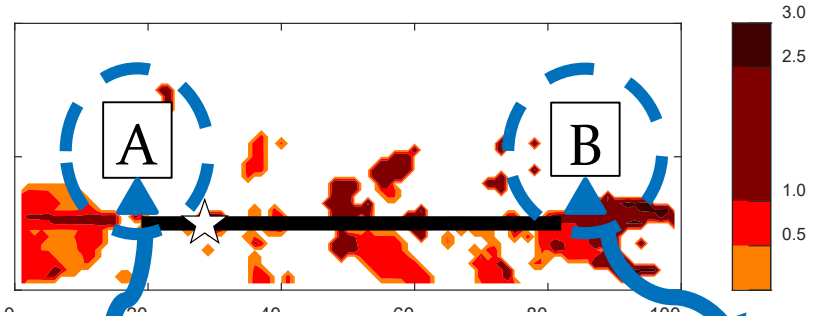



> 10 km normal to fault

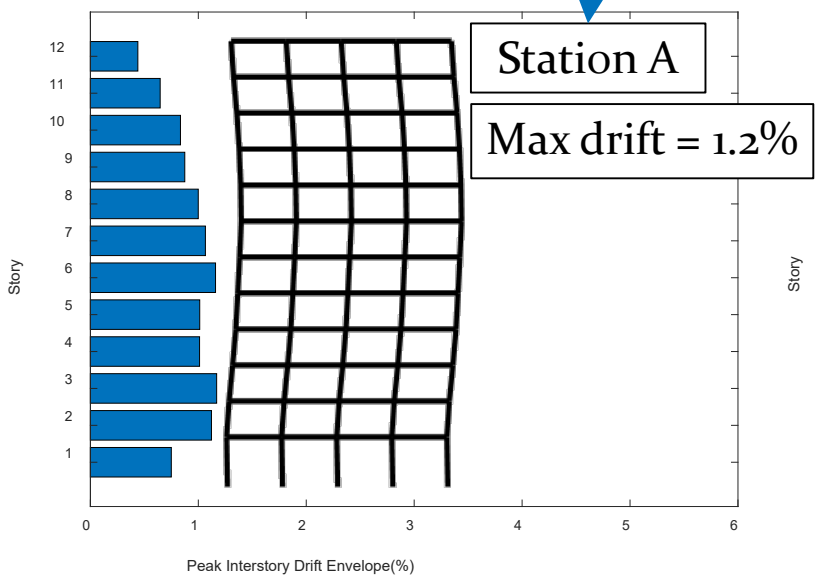


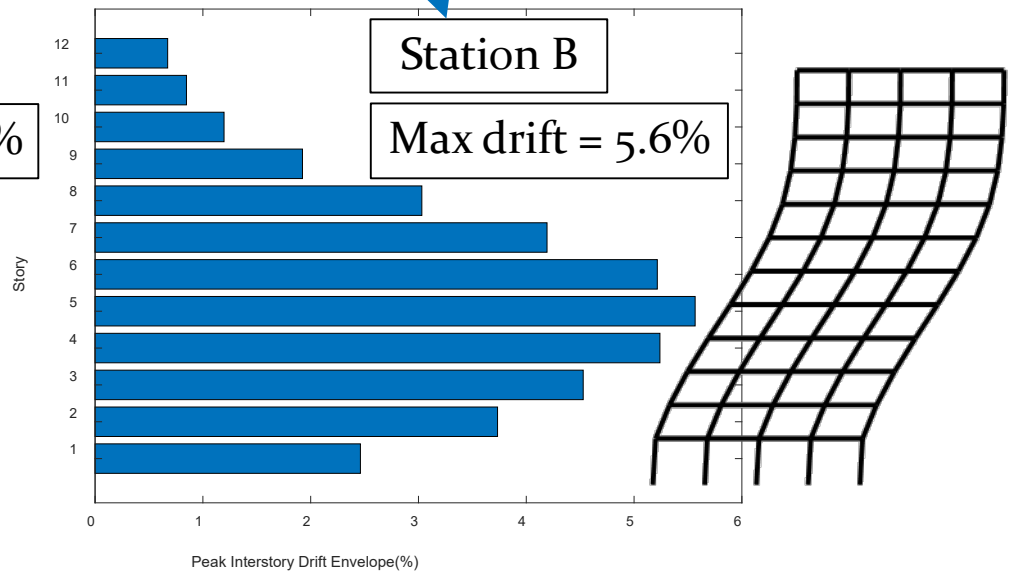
# Higher structural demands due to forward directivity effects

Classification of pulse-like ground motions by Shahi and Baker, 2014



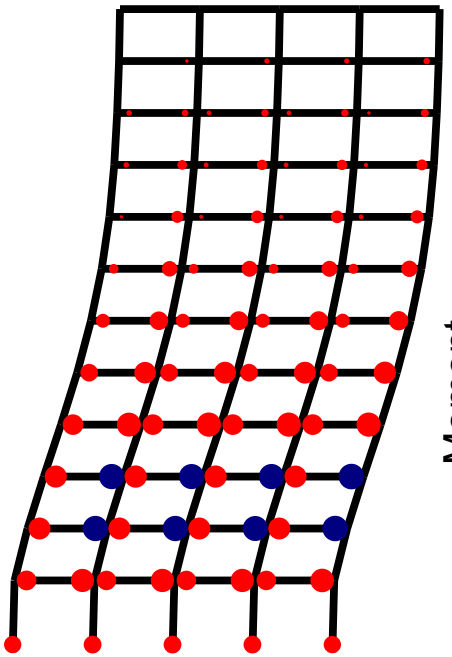

Pulse period normalized by the building fundamental period

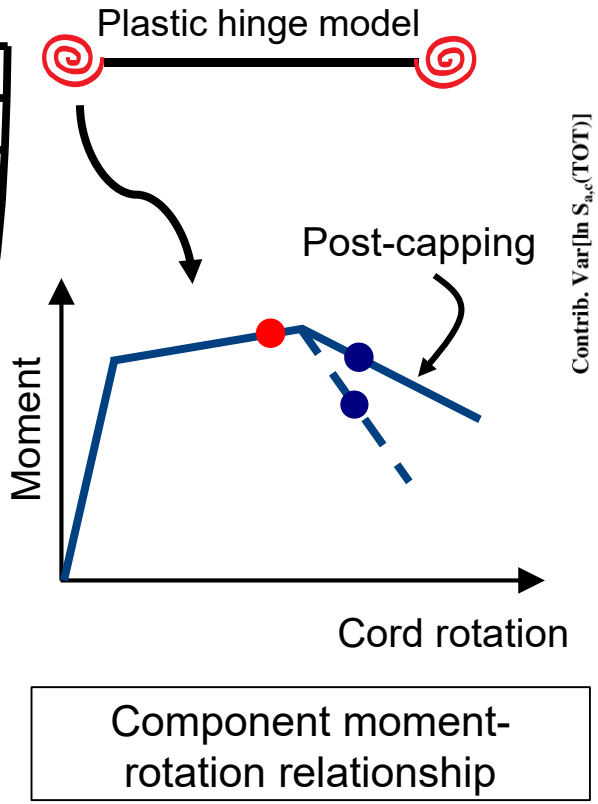


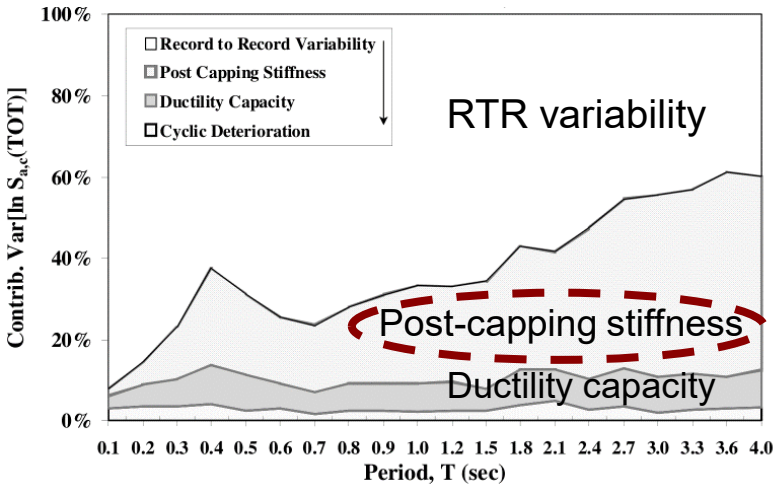
# Predicting component deterioration is crucial for assessing collapse

plastic hinges






Component moment-rotation relationship

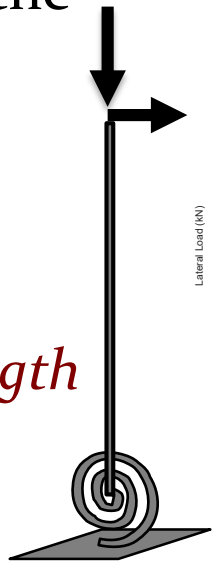



Contribution of uncertainty in system parameters to variance of collapse capacity

(Ibarra and Krawinkler 2005)

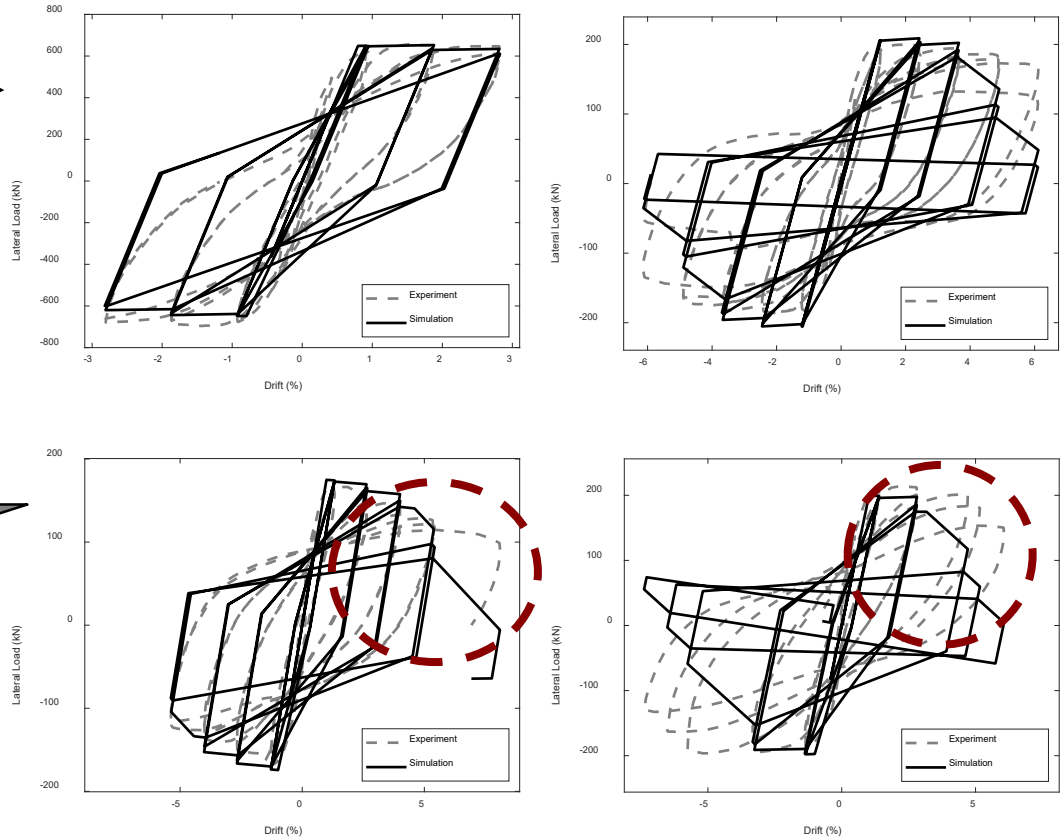
# How accurate are the underlying component models?

- Plastic hinge models are conservative in the post-peak range
- There is large uncertainty in predicting *strength degradation*



Plastic hinge model

Experiment




Modified Ibarra-Medina-Krawinkler model

Prediction equations:
Haselton et al. 2015

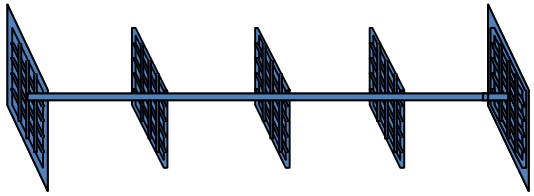
# Key question: how to model localized component damage?

## Common modeling approaches

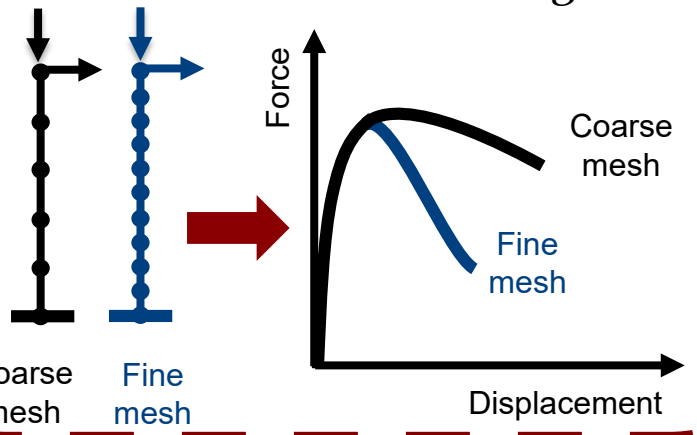
### Plastic hinge model

- Require component-based calibration
- Model parameters difficult to estimate
- Associated numerical difficulties
- Cannot capture P-M interaction

### Fiber-section model



Mesh-sensitive response in the presence of constitutive softening

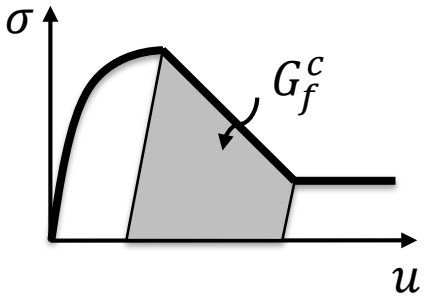


# Remedy to mesh-sensitivity: adding a *length scale* to the softening problem

## Energy-based methods

*Adjust input to match the mesh size length scale*

(Coleman and Spacone 2001)

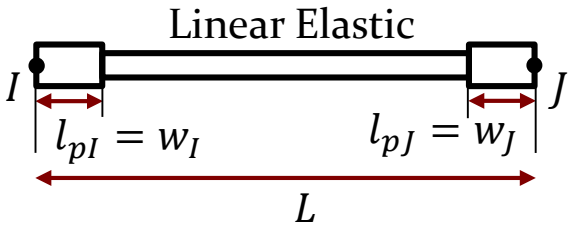



**Concrete compressive fracture energy**

## Plastic-hinge integration

*Impose a fixed length scale*

(Scott and Fenves 2006)




## *Nonlocal models*

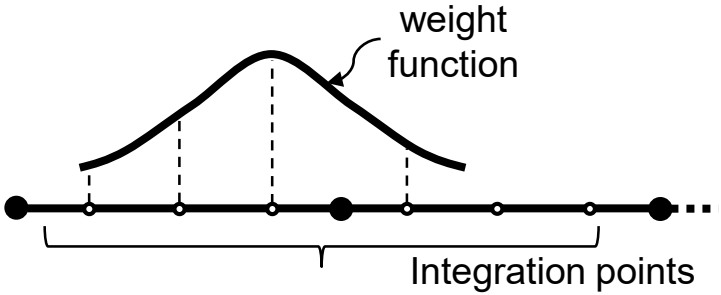
*Not so common (yet)…*

- Valipour and Foster (2009)
- Feng et al. (2015)
- Zhang and Khandelwal (2016)
- Sideris and Salehi (2016, 2017)
- **Kenawy et al. (2018, 2020)**

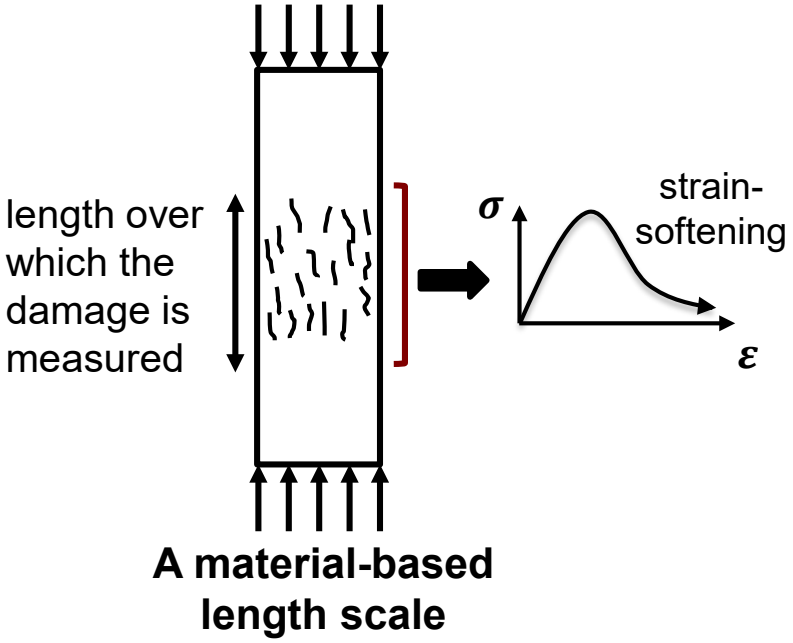
# Nonlocal model: spatial averaging of deformation overcomes mesh-sensitivity

*Spatial averaging of deformation*

$$\widetilde{\varepsilon(x)} = \int_L \bar{w}(x,r)\varepsilon(r)\,dr$$



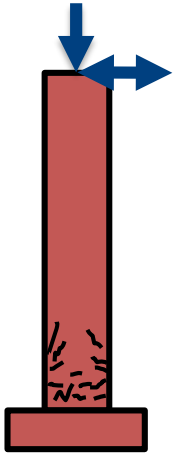

Averaging domain



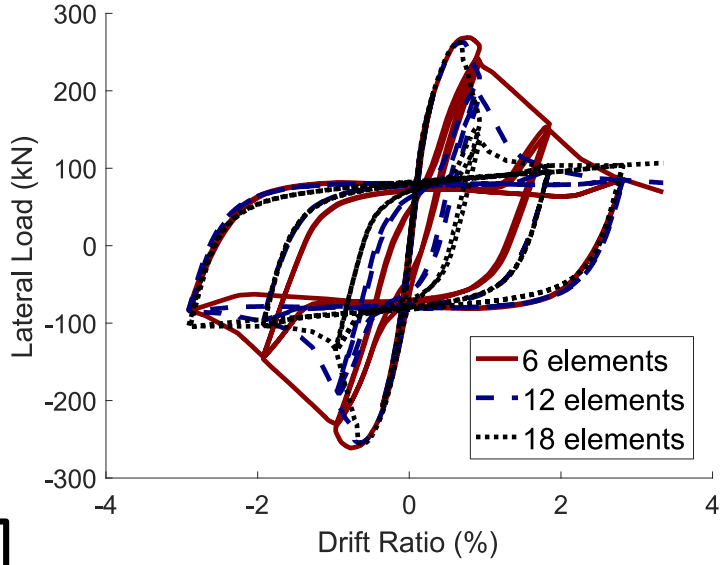

- ***Represent localized damage in an 'averaged' sense***
- ***Easy to generalize***

# The predictions of the nonlocal approach are mesh-independent

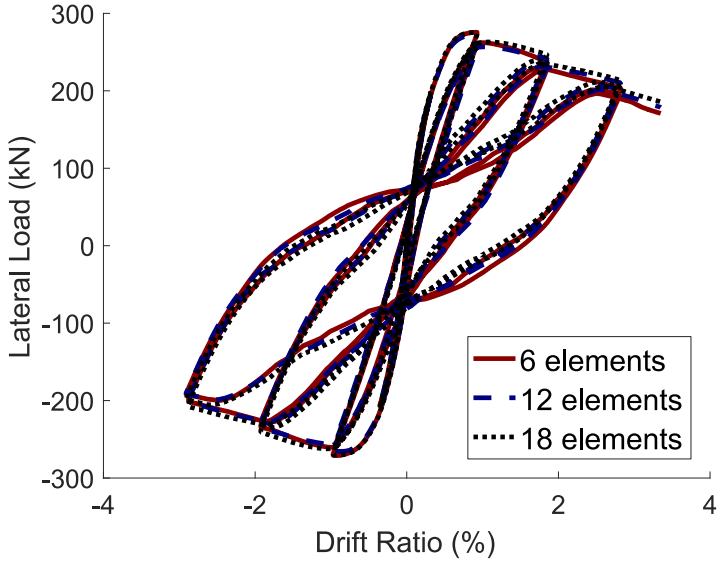
- Sensitivity of the post-peak response to the member discretization



Quasi-static cyclic analysis



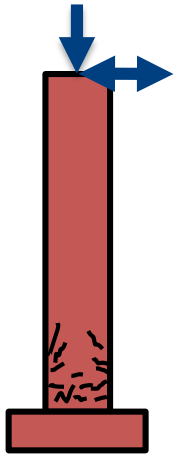

Conventional approach: *mesh-sensitive*

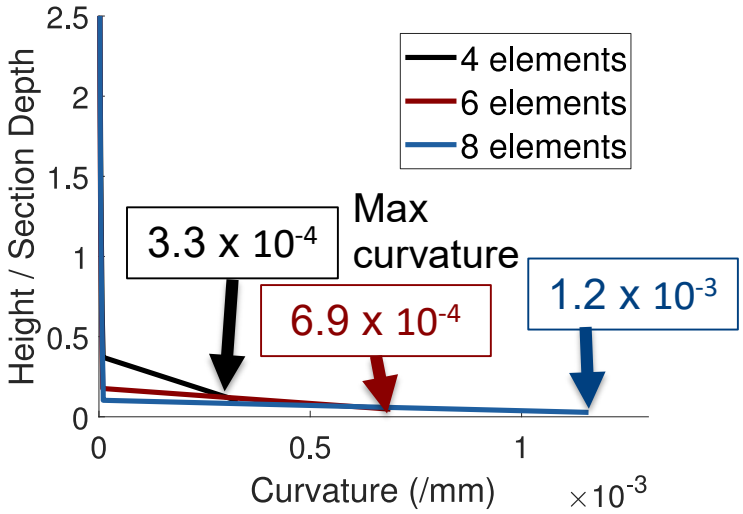



Nonlocal model: *mesh-independent*

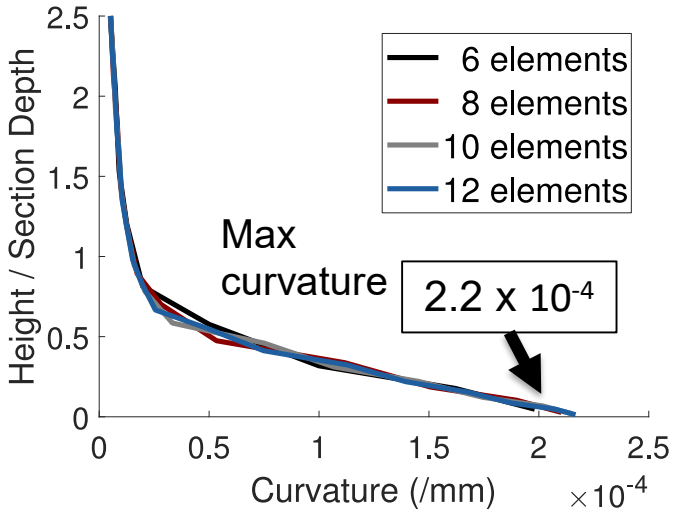
# The predictions of the nonlocal approach are mesh-independent

- Sensitivity of the inelastic curvature to the member discretization



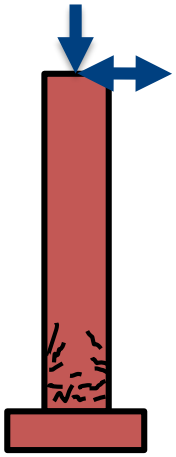


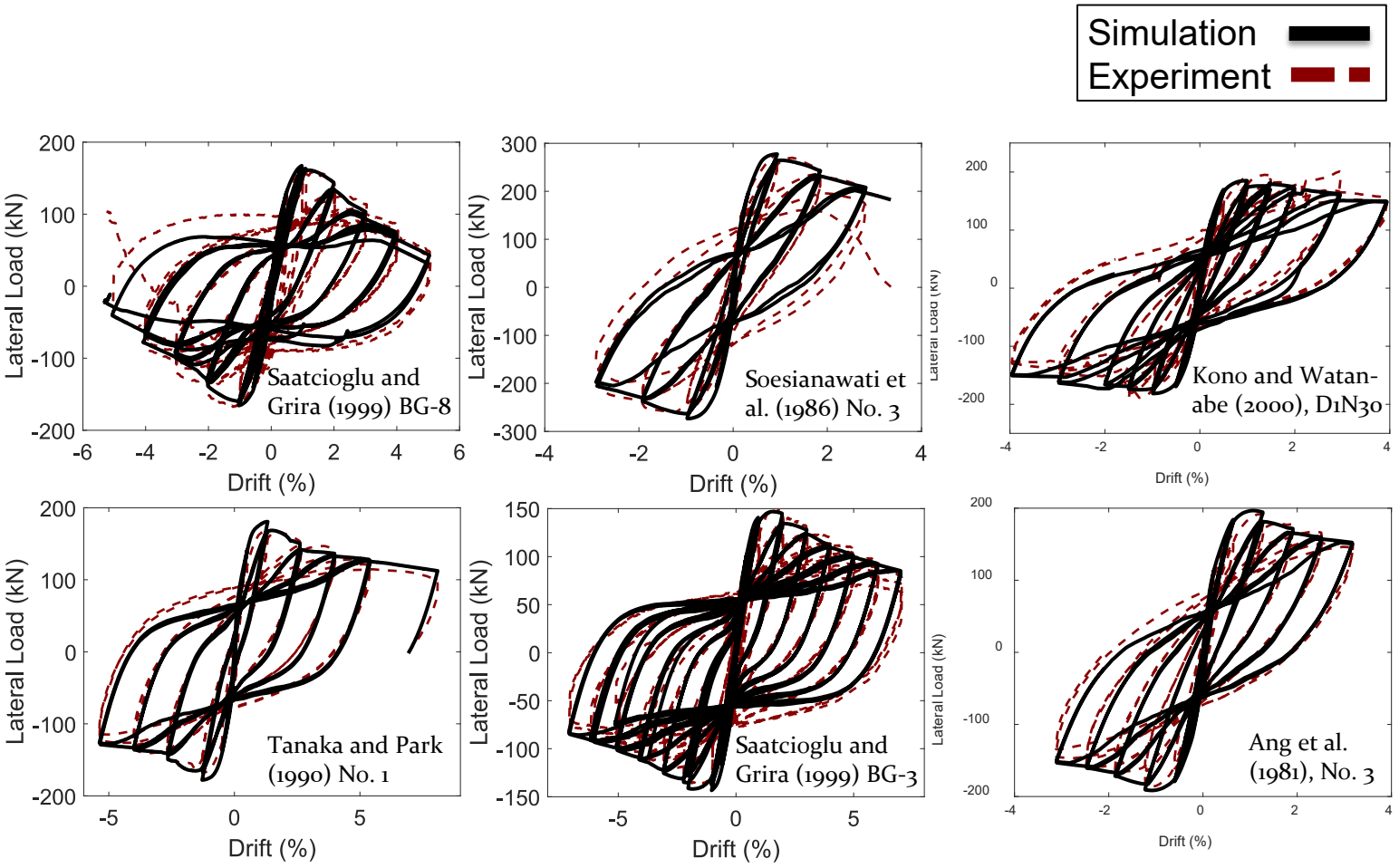

Conventional approach:
*mesh-sensitive*




Nonlocal model:
*mesh-independent*

# Mesh-independent blind agreement with experimental observations





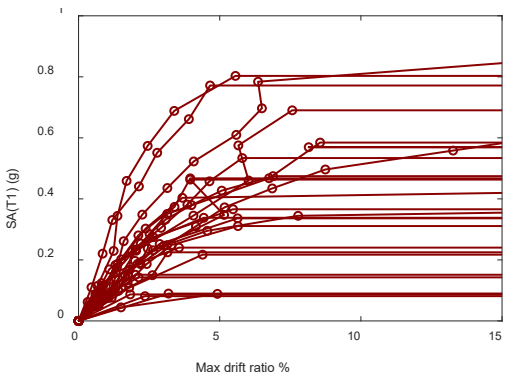
# How does using nonlocal modeling affect collapse assessment?

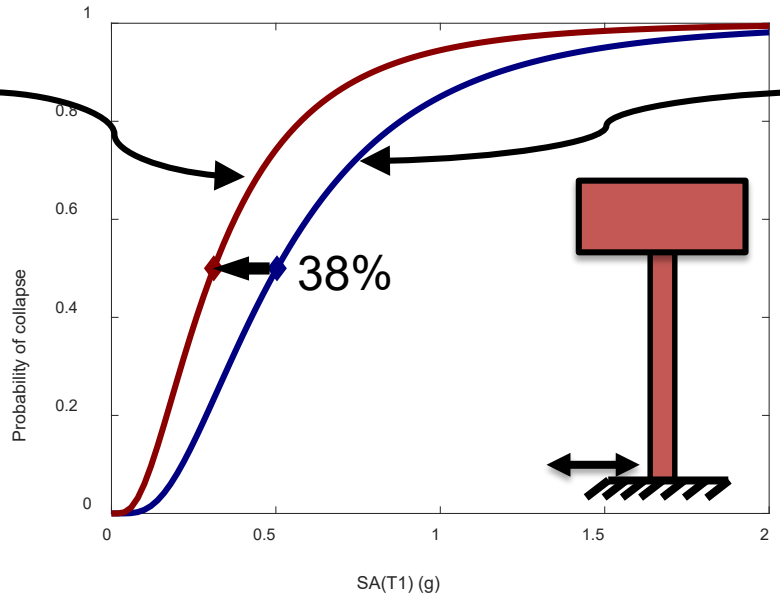
Seismic collapse fragility curve

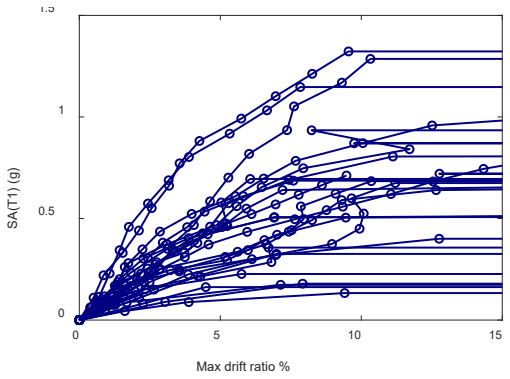
**Local model – *5 elements***
**Nonlocal model**

***Local model***
**Median collapse capacity**
$\overline{SA}\ (T_1) = 0.31\ g$

***Nonlocal model***
**Median collapse capacity**
$\overline{SA}\ (T_1) = 0.5\ g$



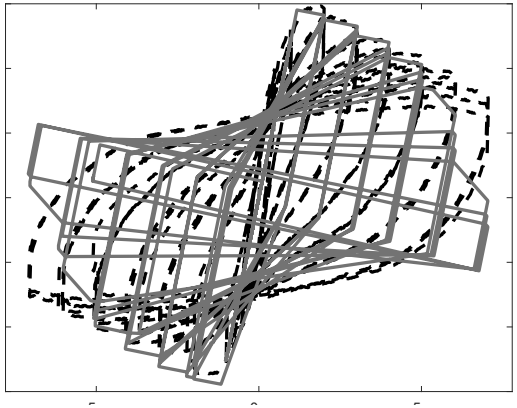

Probability of collapse

# Collapse assessment of RC column using plastic hinge and nonlocal models

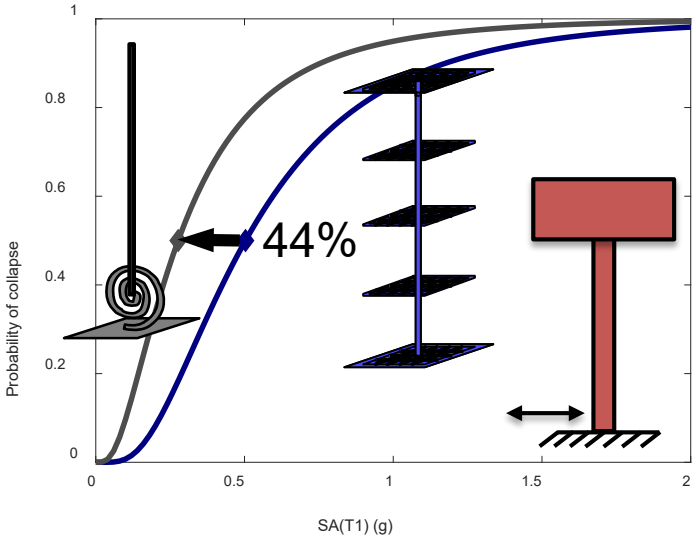
We do not usually have the answer.

Plastic hinge model
Nonlocal model

Load vs. displacement

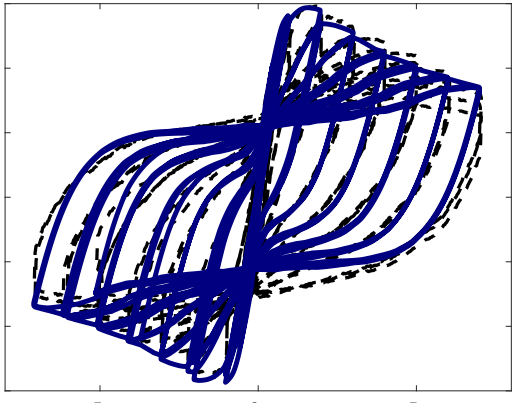


Plastic hinge model




Probability of collapse

Load vs. displacement



Nonlocal fiber-section model

# Summary

- There is large uncertainty in designing structures to resist earthquakes in both the knowledge of the earthquake loading and the resistance of structures

*Understanding earthquake loading*

- Physics-based ground motions offer opportunities to understand the variability in earthquake hazard and risk in the near-field.
- Quantifying the variability of risk will improve near-fault structural design guidelines.

*Simulating structural resistance*

- Quantification of collapse risk requires rigorous models to predict degradation.
- Nonlocal models predict strength degradation due to concrete softening.
- Extending nonlocal models to capturing other sources of deterioration is crucial for collapse assessment of RC structures.