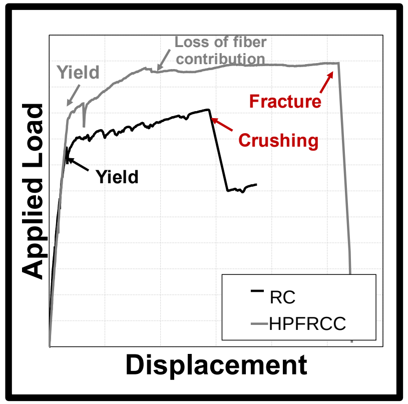
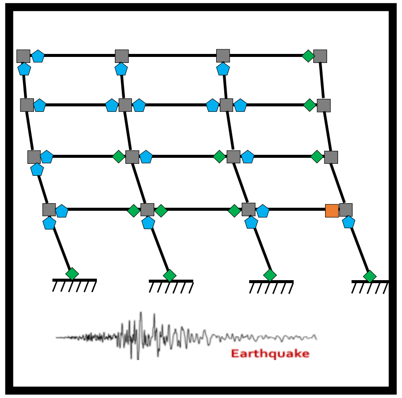
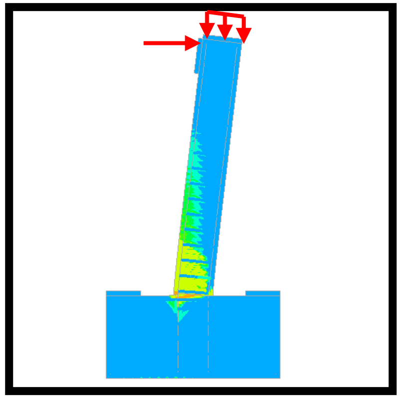
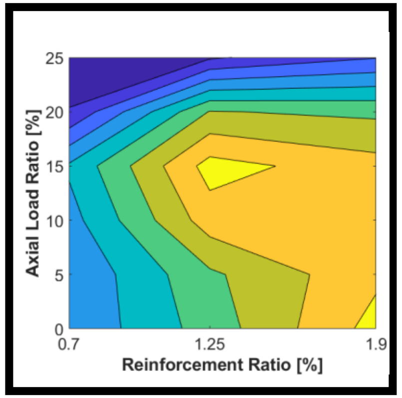
Seismic Response and Design Considerations of Structural Components and Systems using Highly Ductile Concrete Materials









H. Tariq, M. Pokhrel, R. Sthapit, J. Almeida, and M.J. Bandelt

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ACI Spring 2023 Convention

ACI/JCI – 6th Joint Seminar

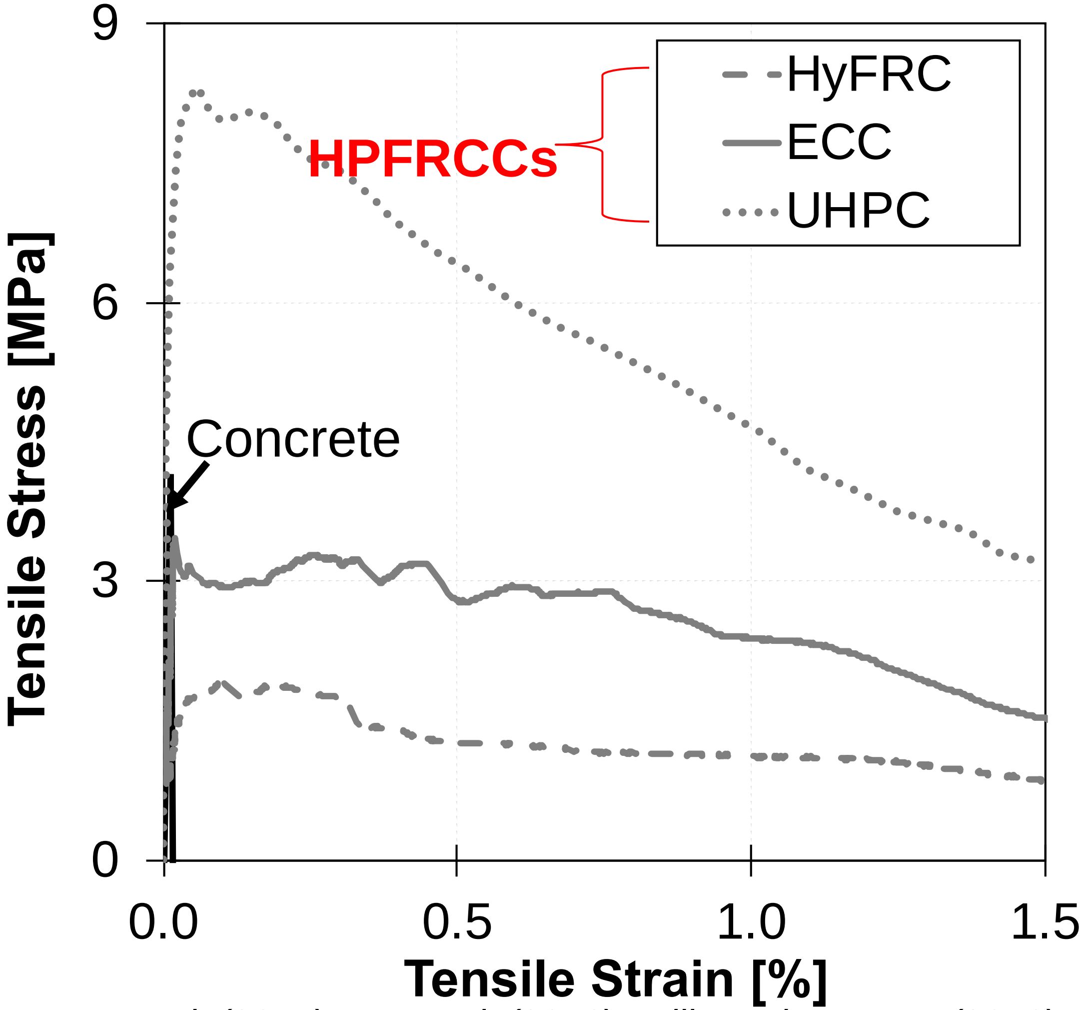
Advancing the Design of Concrete Structures

San Francisco, California

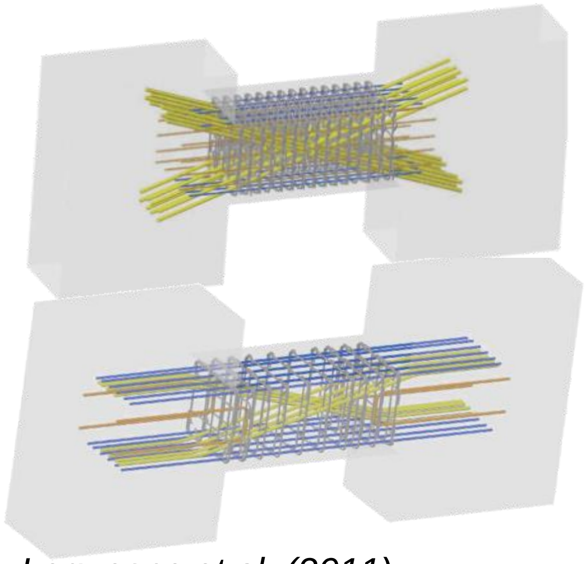
3 April 2023

HIGHLY DUCTILE CONCRETE MATERIALS

High Performance Fiber Reinforced Cementitious Composites



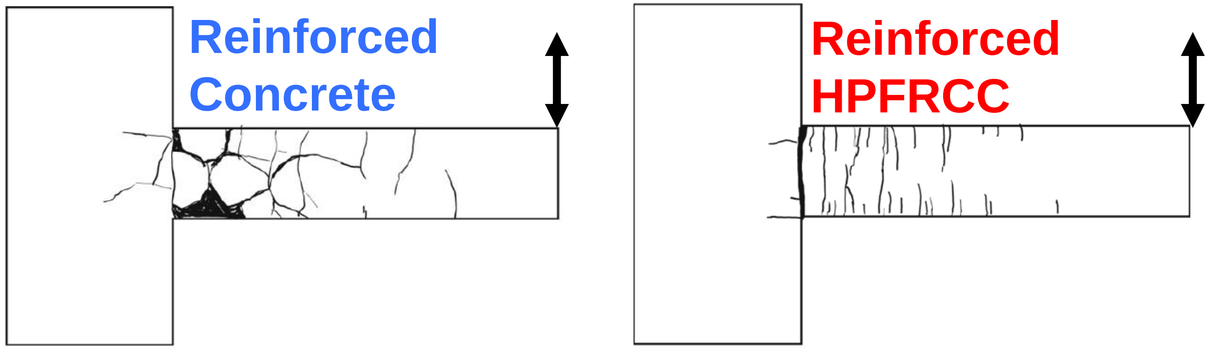
Moreno et al. (2014), Jen et al. (2016), Wille and Naaman (2010)



Lequesne et al. (2011)

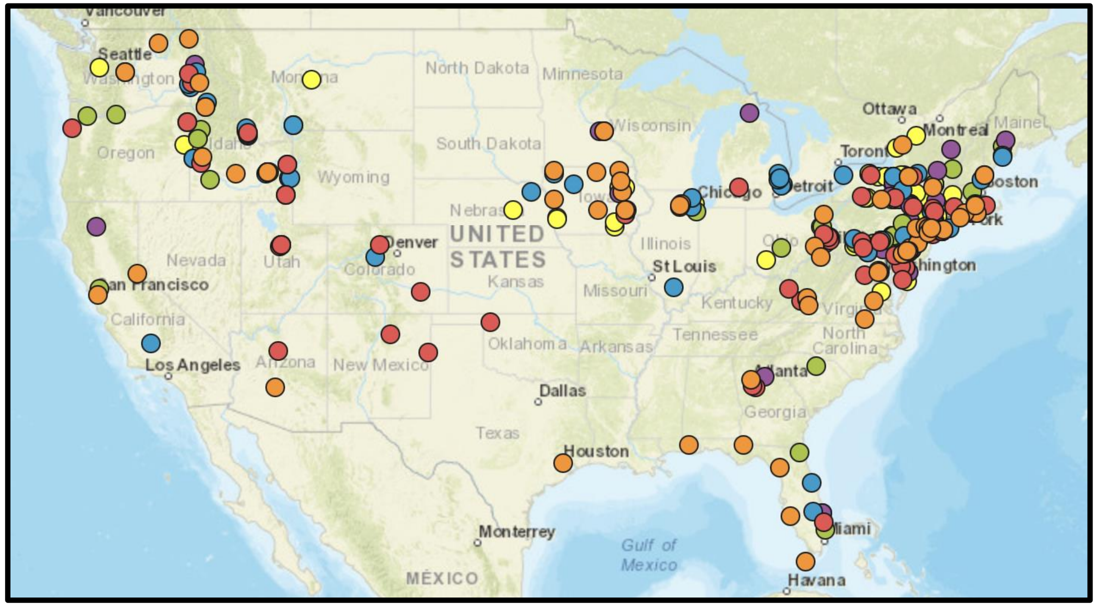
Reinforced Concrete
Rebar: 1,012 kg
Cost: $2,231

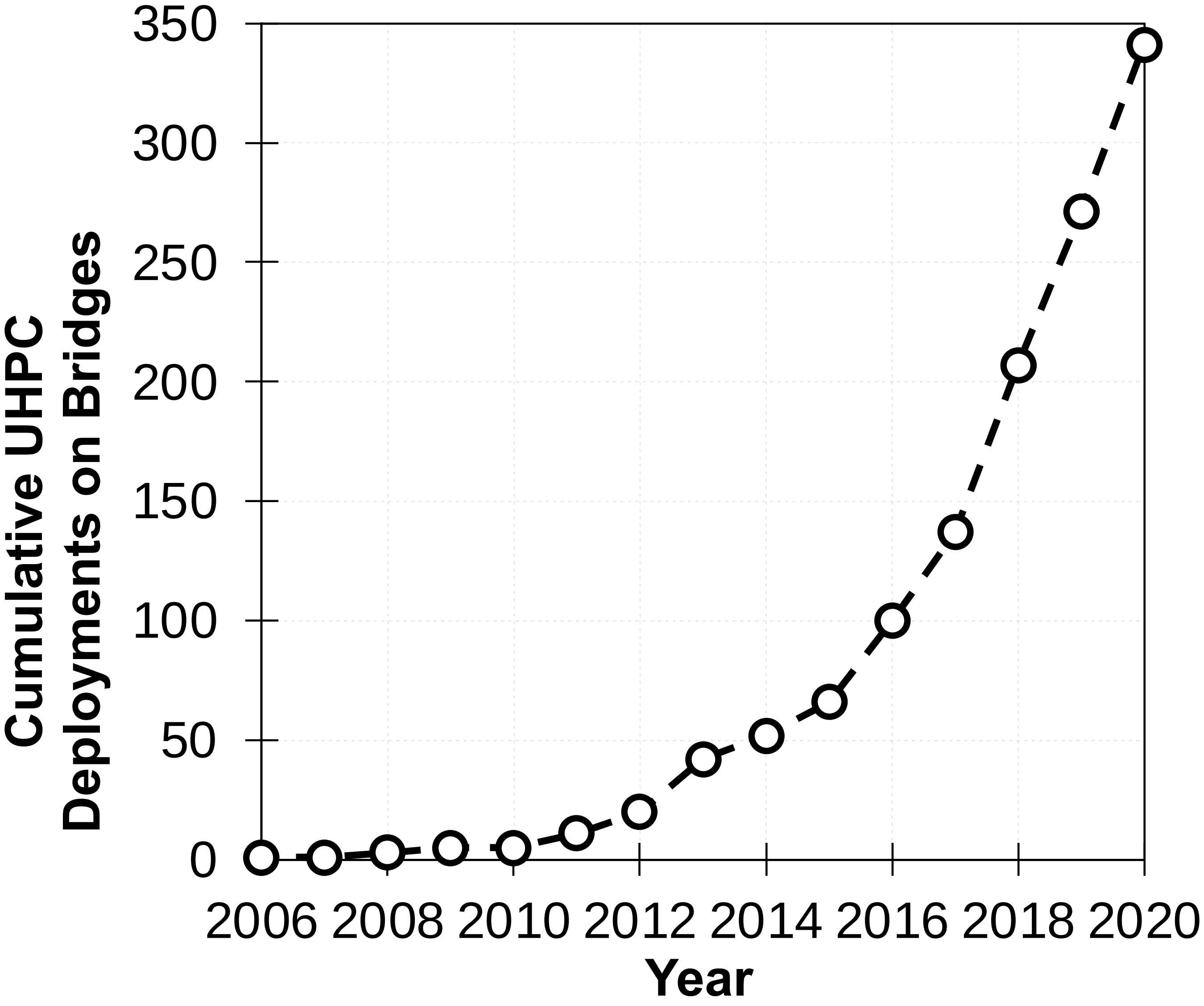
Reinforced HPFRCC
Rebar: 616 kg
Cost: $1,564



Frank et al. (2017)

GROWTH OF HPFRCCS: EXAMPLE UHPC IN BRIDGES



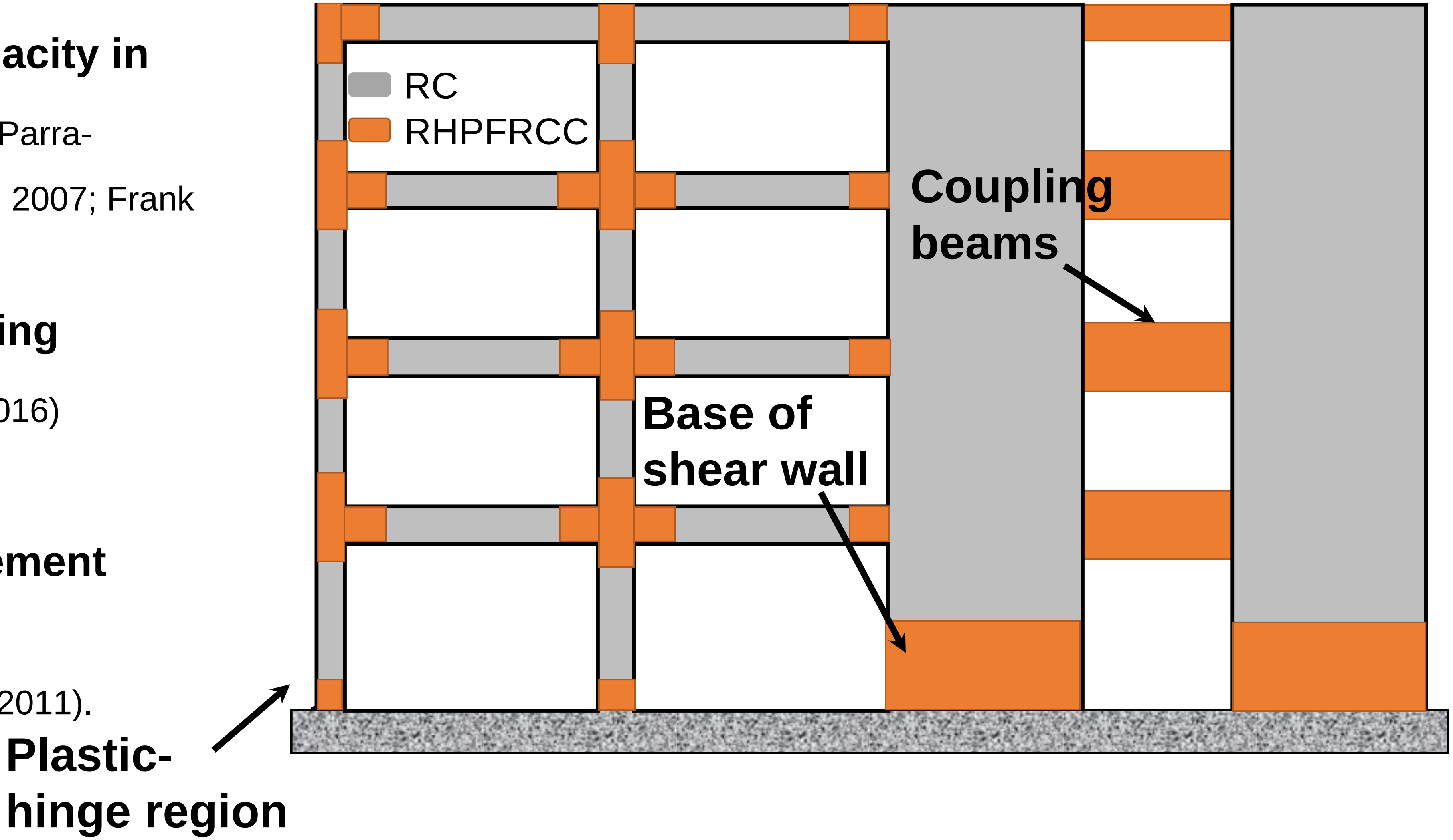


- UHPC has grown substantially in bridge construction
- What are the obstacles preventing growth in seismic design?

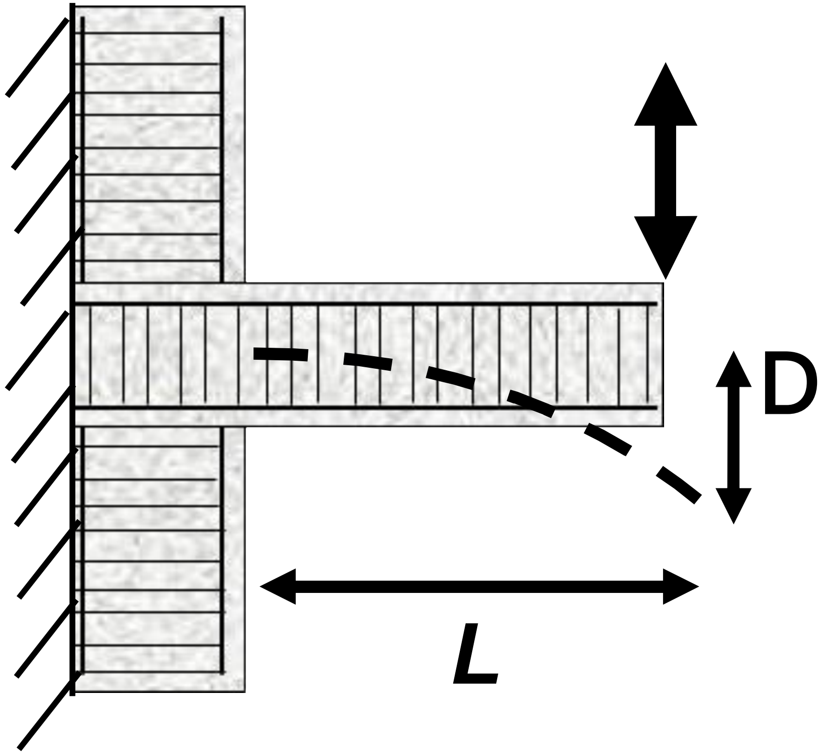
Adapted from FHWA (2020)

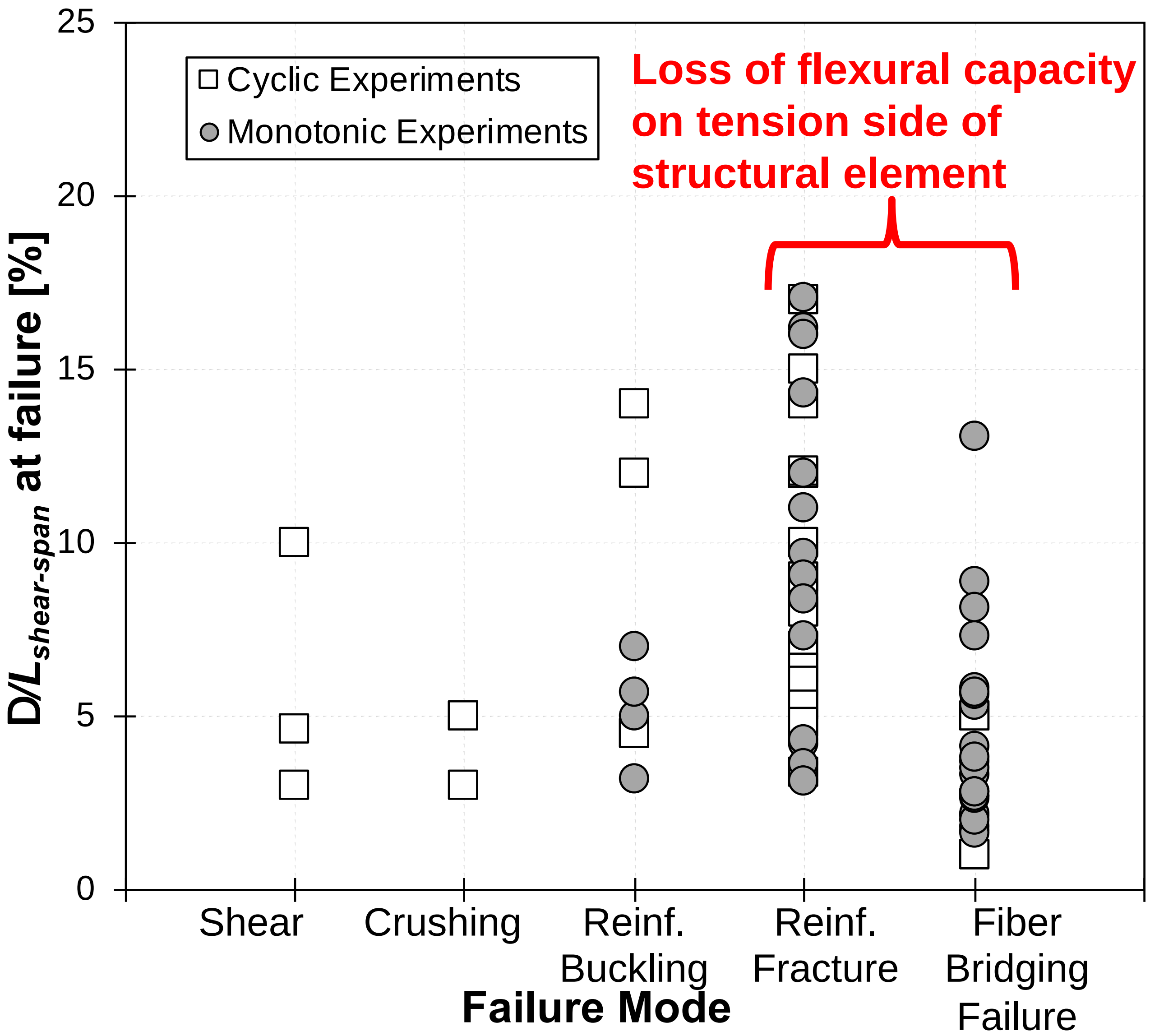
Representative Experimental Seismic Research

1. **High deformation capacity in beams and columns** (Parra-Montesinos and Chompreda, 2007; Frank et al. 2015)
2. **High Shear and Bending deformations** (Zheng, 2016)
3. **Reduce transverse reinforcement requirement** (Lequesne, 2010)
4. **Structural fuse** (Oslen, 2011).



Alternative Failure Mechanisms in Flexure

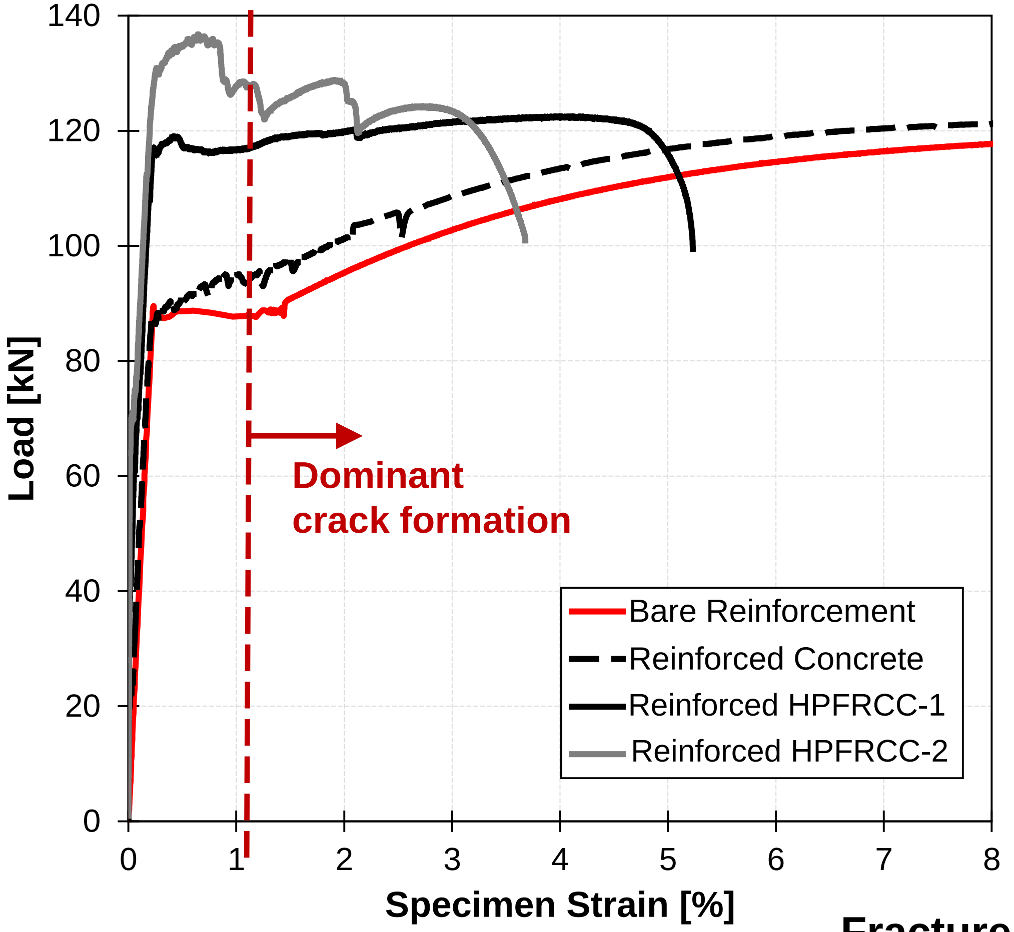




Adapted from Bandelt and Billington (2016), Shao and Billington (2019)

Tensile Response of Reinforced Elements

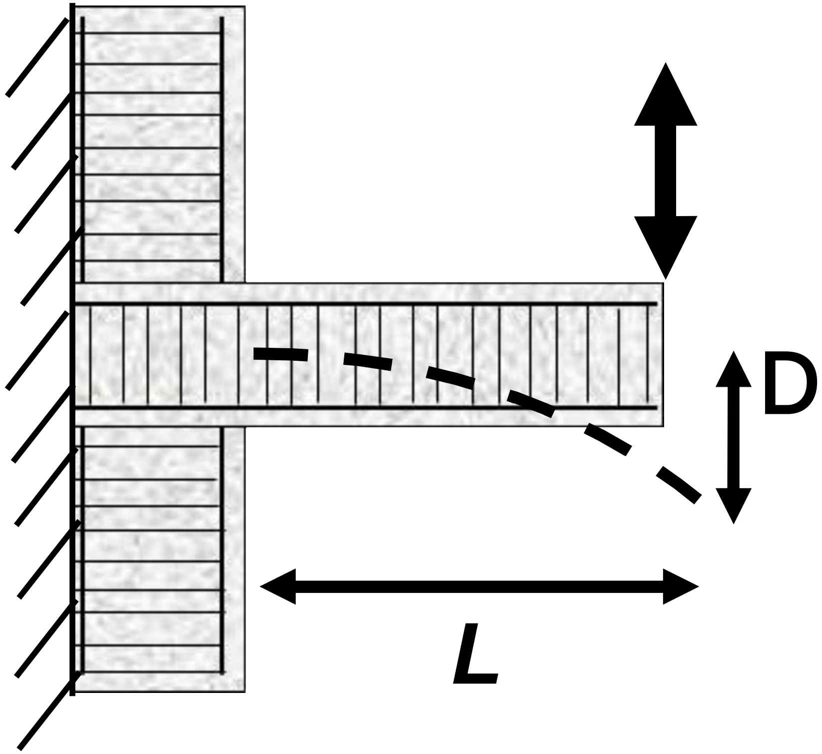
Reinforced HPFRCCs **restrain splitting cracks** better than reinforced concrete in tension stiffening experiments

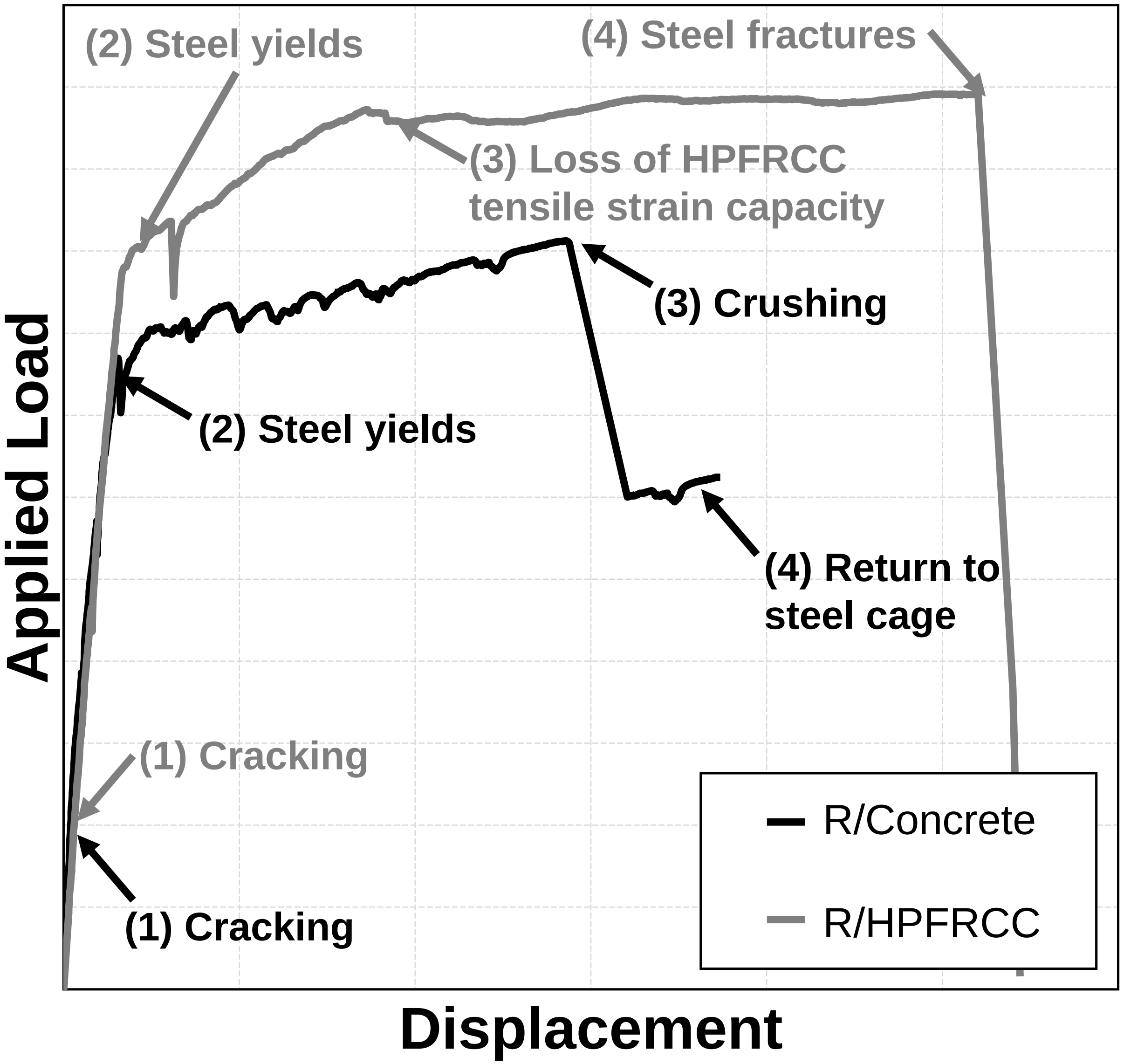


Material	Concrete
Fracture specimen strain	10.2%

Adapted from Moreno et al. (2014), Bandelt and Billington (2016)

Failure Mechanisms in Reinforced Components

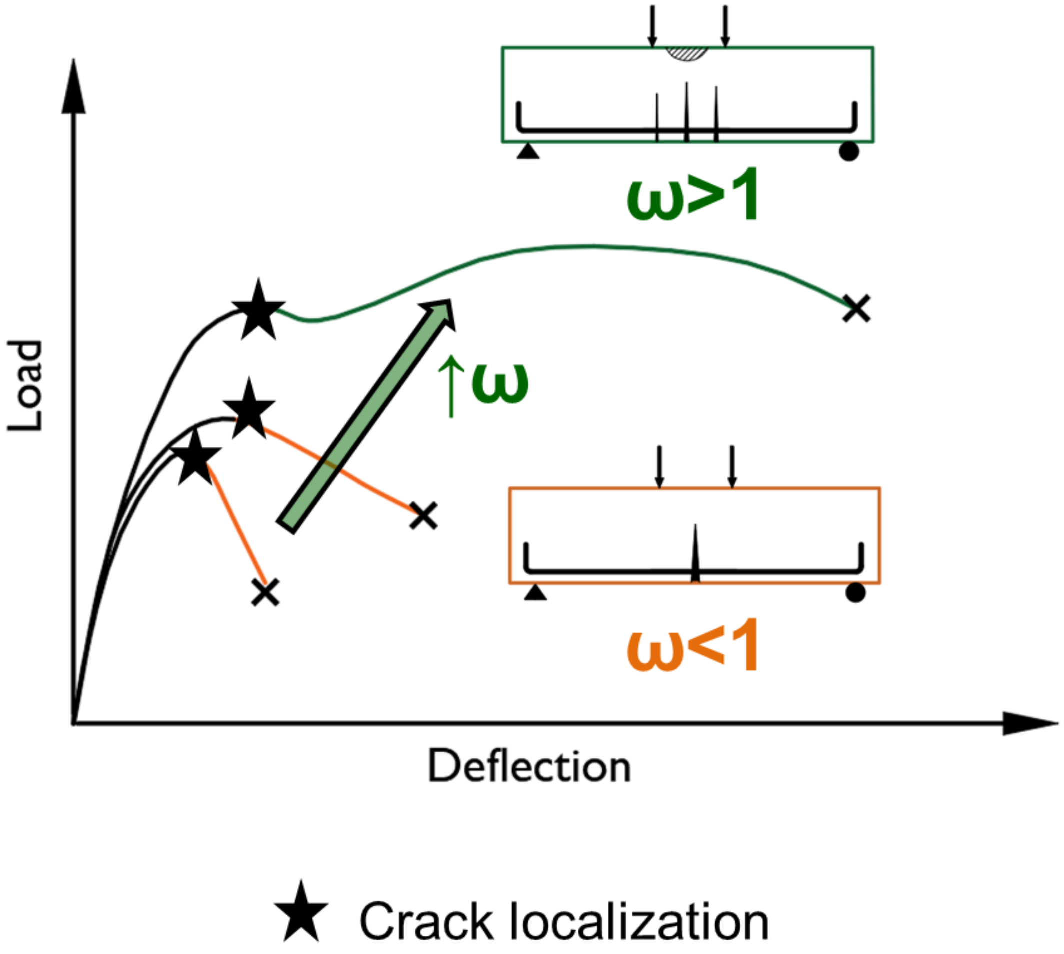


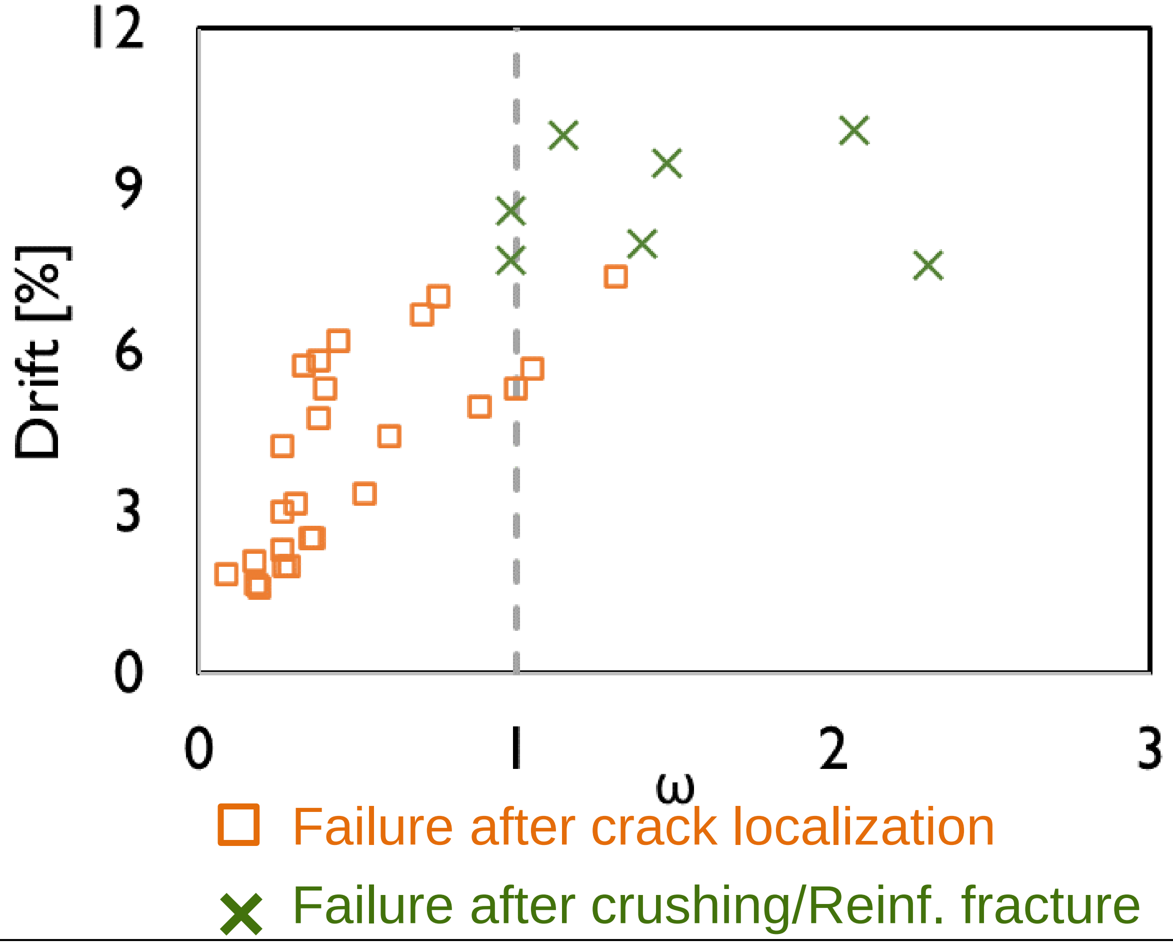


Adapted from Bandelt and Billington (2016)

Failure Path in Reinforced Components

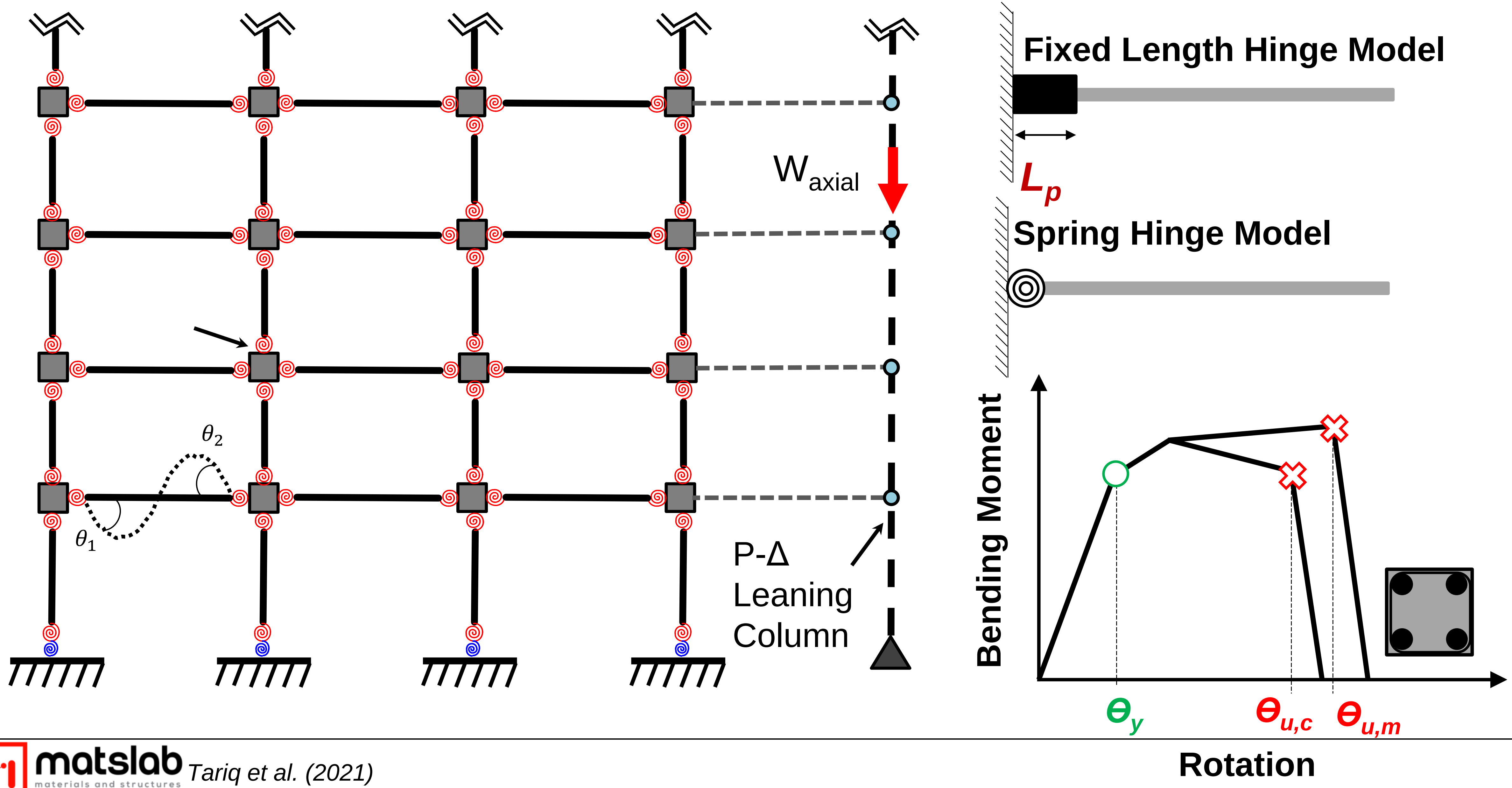
$$\omega = \frac{\text{Steel strain-hardening capacity}}{\text{HPFRCC tensile capacity}}$$





Adapted from Shao and Billington (2019)

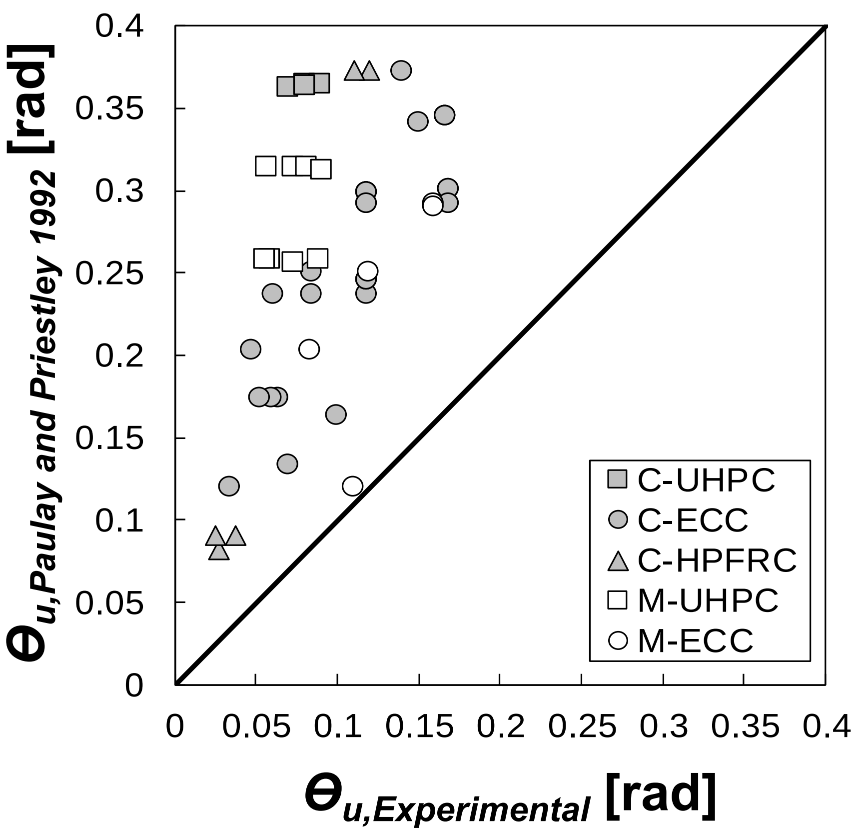
SEISMIC SYSTEM ANALYSIS

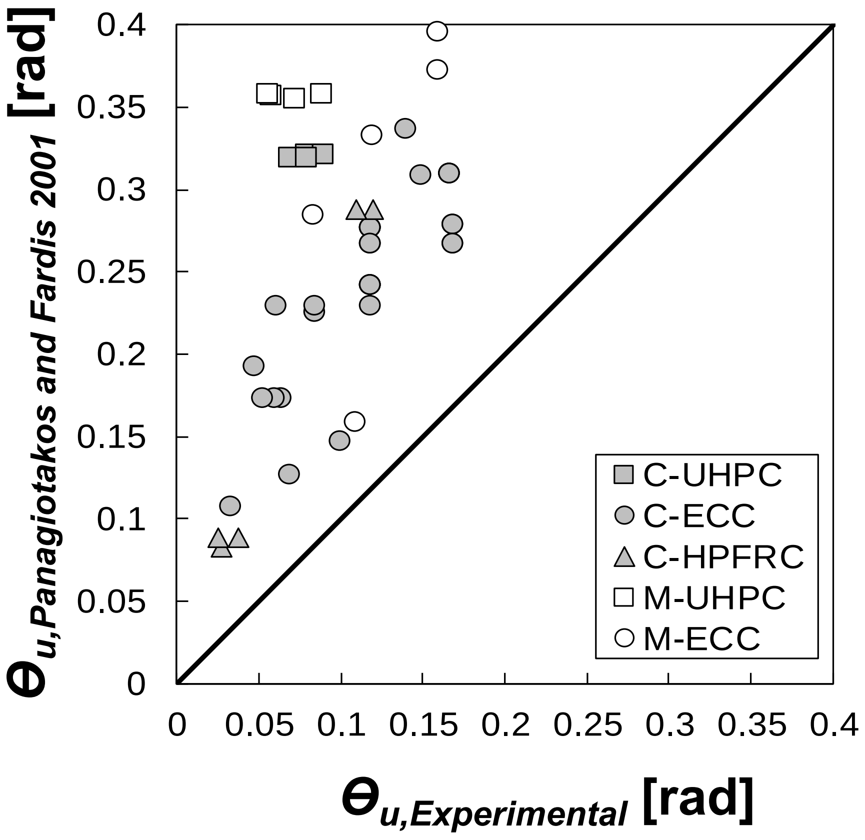


R/C Hinge Models don't work with R/HPFRCCs

- Traditional R/C rotational capacity predictions don't work with R/HPFRCCs

- Need to account for failure modes, ductility, distribution of damage





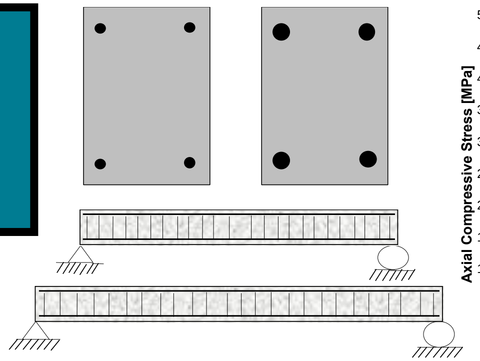
RC Model Development

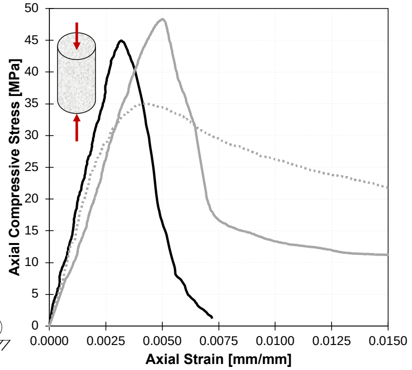
- Can we follow the process for model development from our knowledge for reinforced concrete?

- Challenges for UHPC and HPFRCCs
  - Limited existing experiments
  - Time to create larger experimental database
  - Rapidly changing advances in material properties

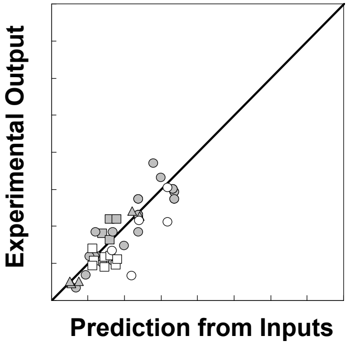
Execute Experiments

Repeat across variables





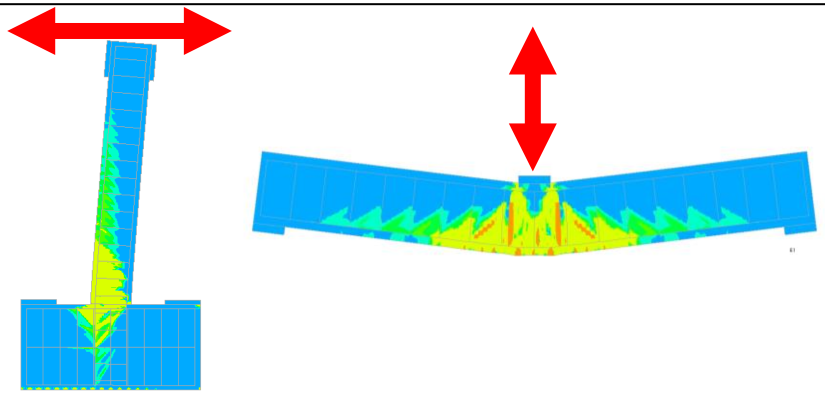
Model Fit



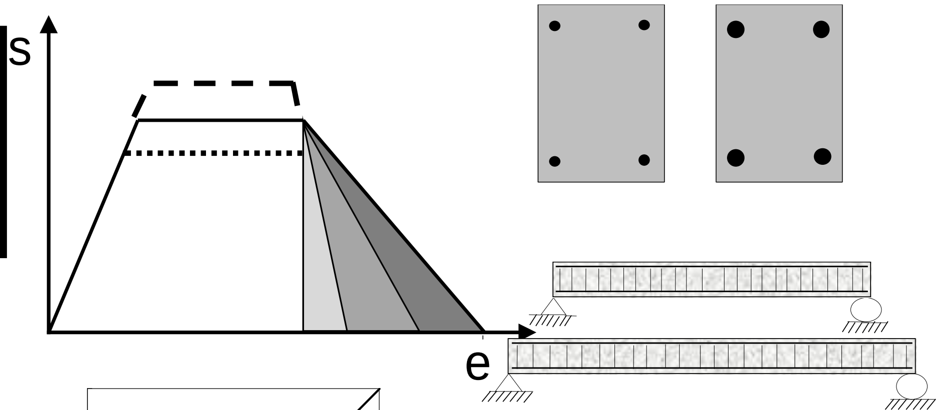
Pokhrel and Bandelt (2019)

An Alternative Approach for R/HPFRCCs

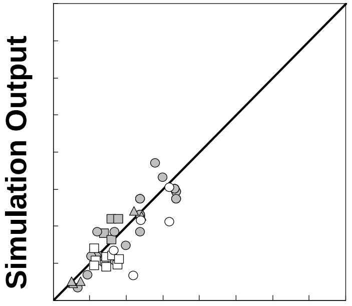
Execute Simulations



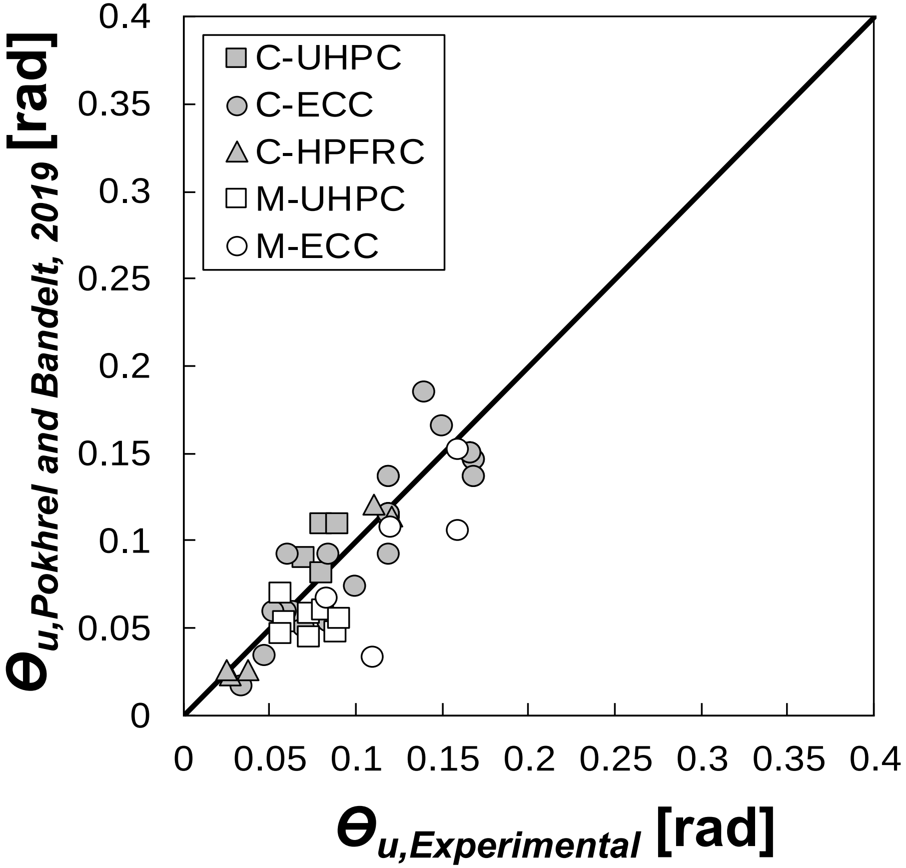
Repeat across variables



Model Fit

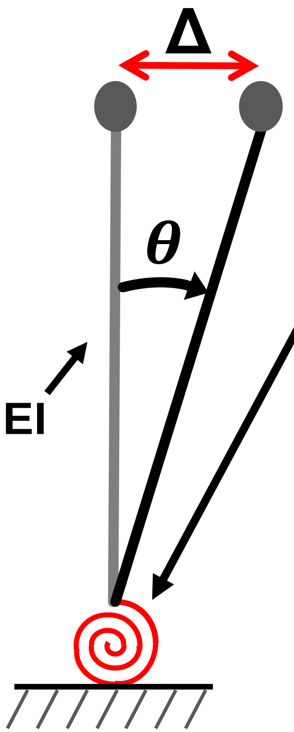


Validate with Separate Experiments

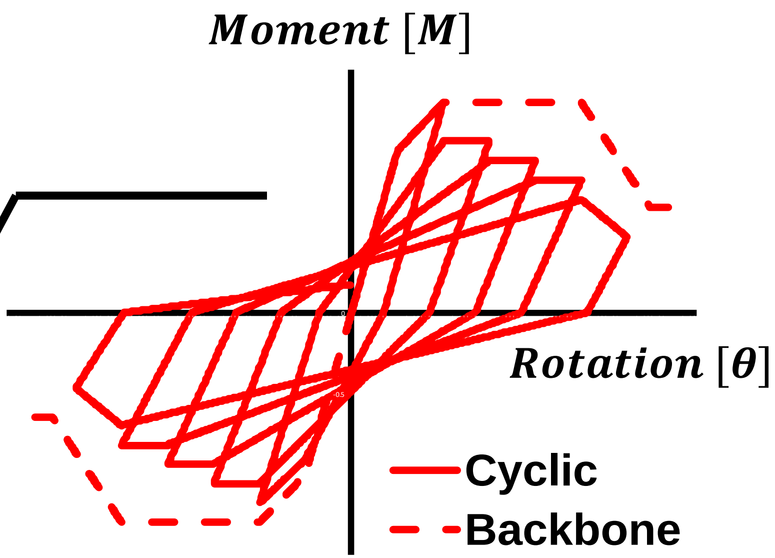


Pokhrel and Bandelt (2019)

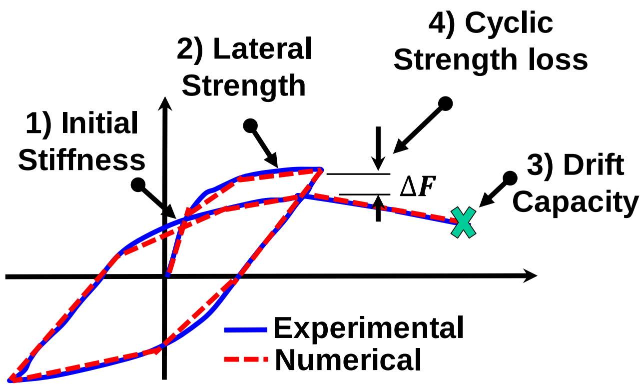
Seismic Component Analysis



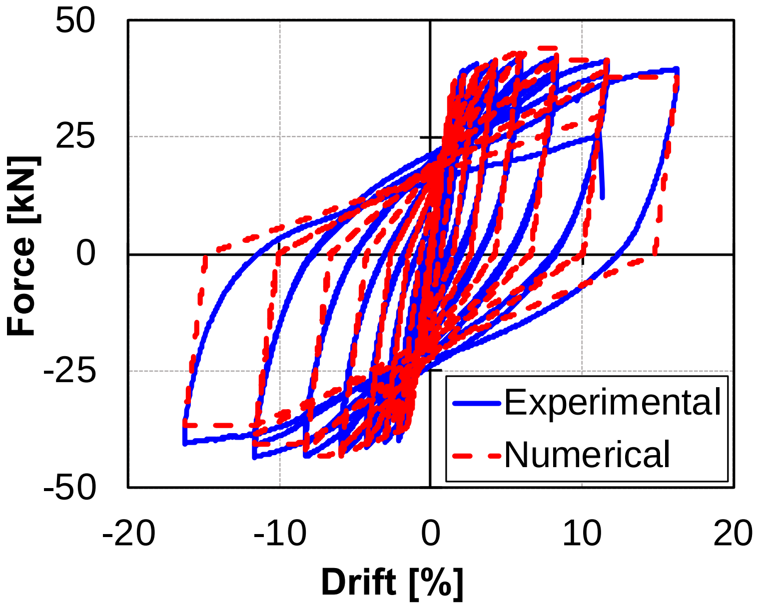
Nonlinear Spring



Rotational Model

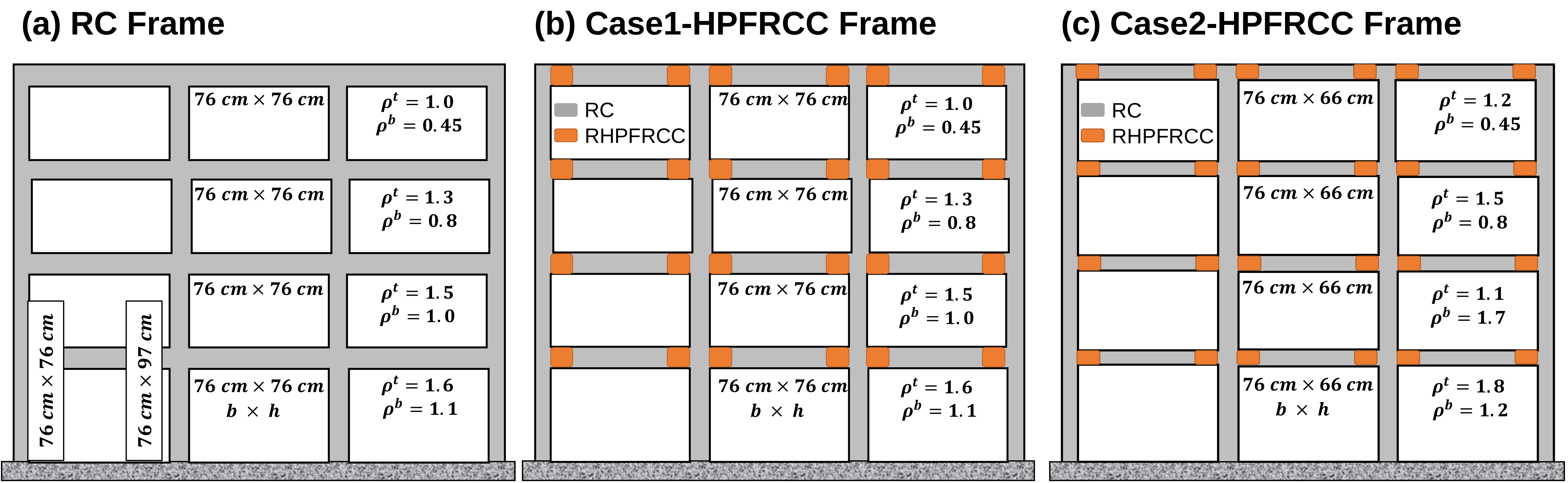


Target Objective



Comparison to Experiments

DESIGN ILLUSTRATION OF 4 STORY FRAME



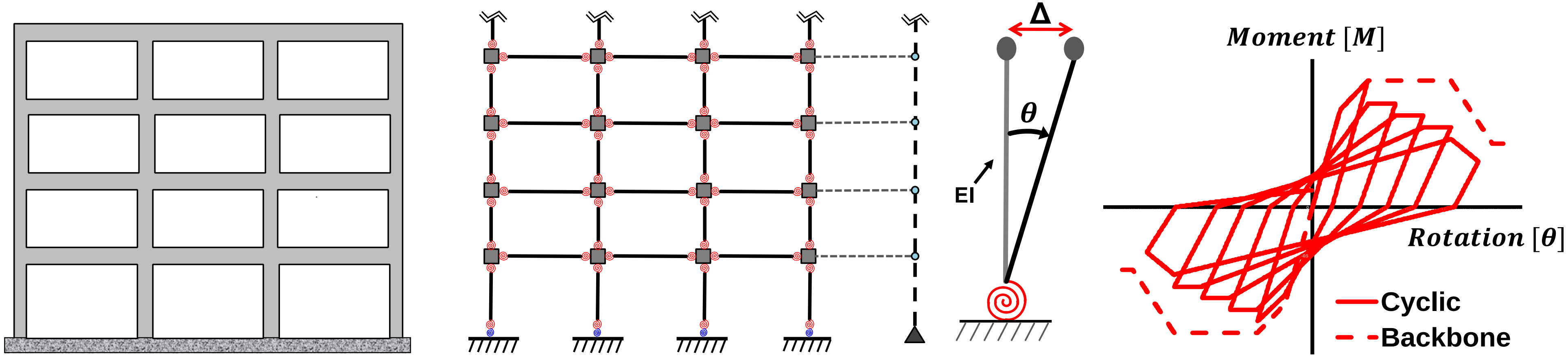
Code confirming R/C structure

Replace concrete with HPFRCC in beam regions and no other Changes.

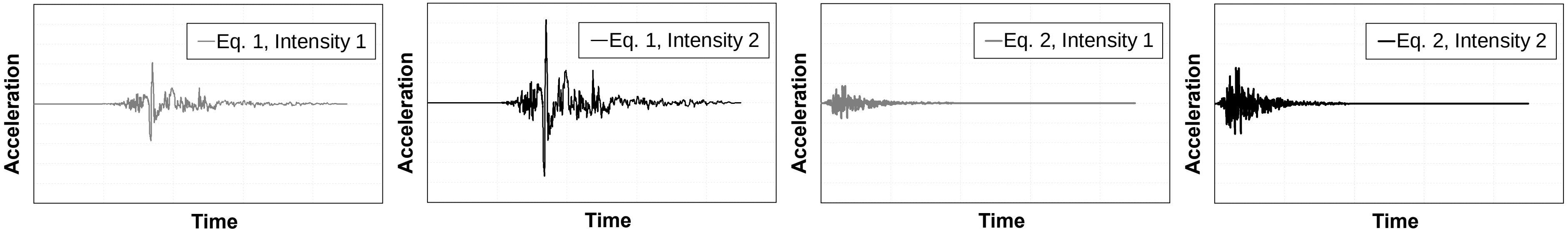
Replace concrete with HPFRCC in beam regions. Resize members to maintain strong-column weak-beam.

Seismic System Analysis

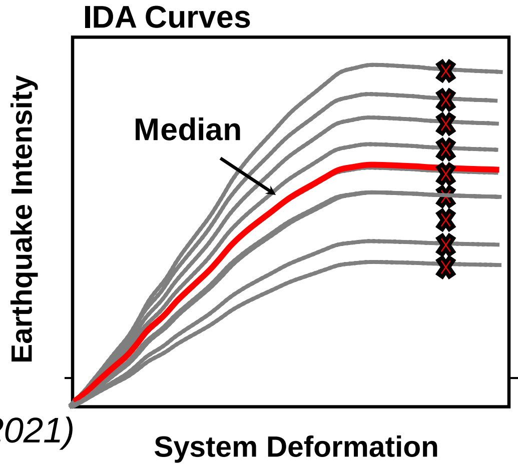
Develop System Model



Subject Model to Earthquake Records

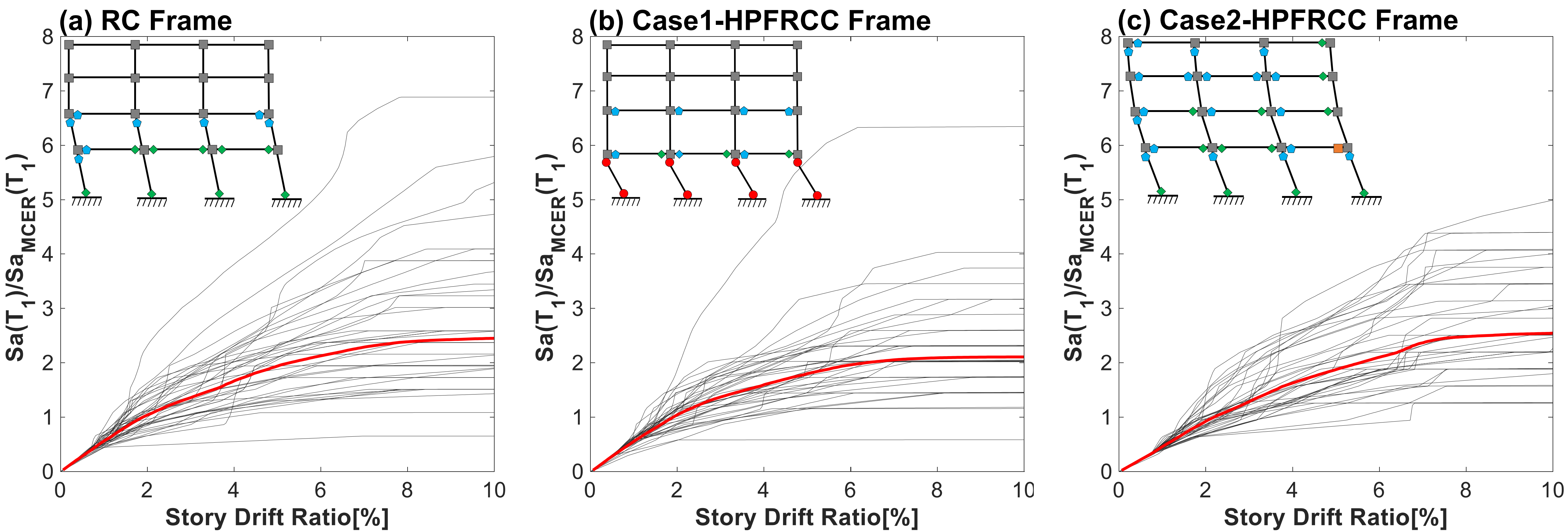


Observe Response



Tariq et al. (2021)

Seismic System Analysis

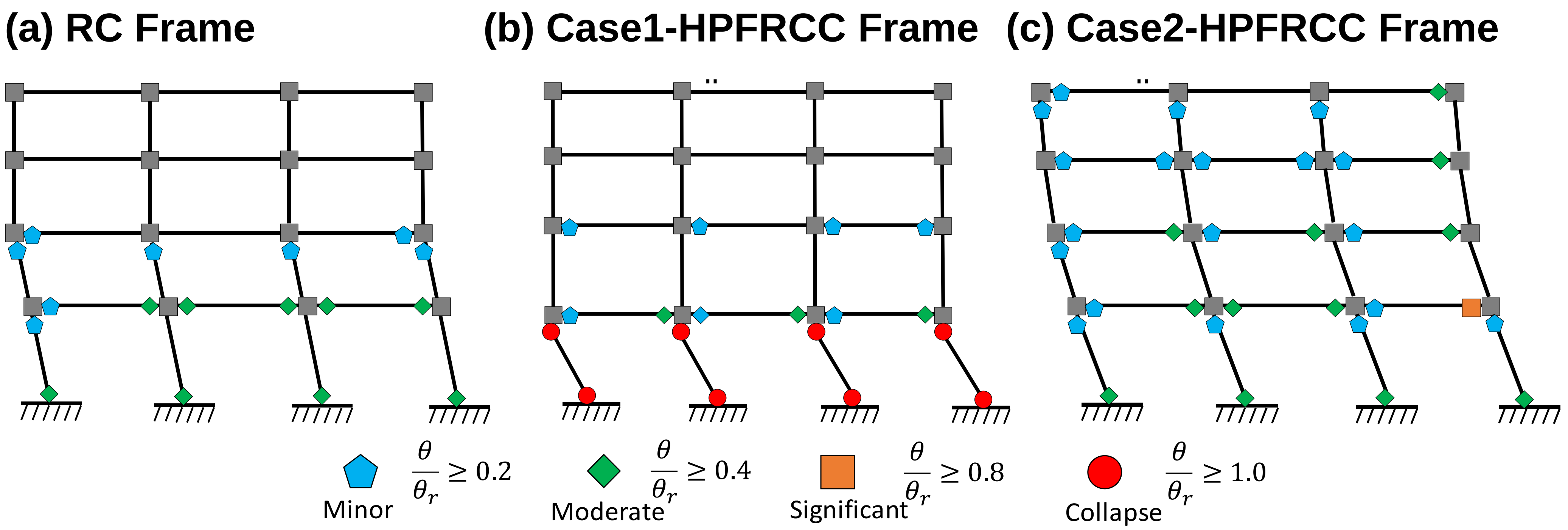


Y-axis: Earthquake intensity
X-axis: System deformation

matslab materials and structures laboratory at NJIT

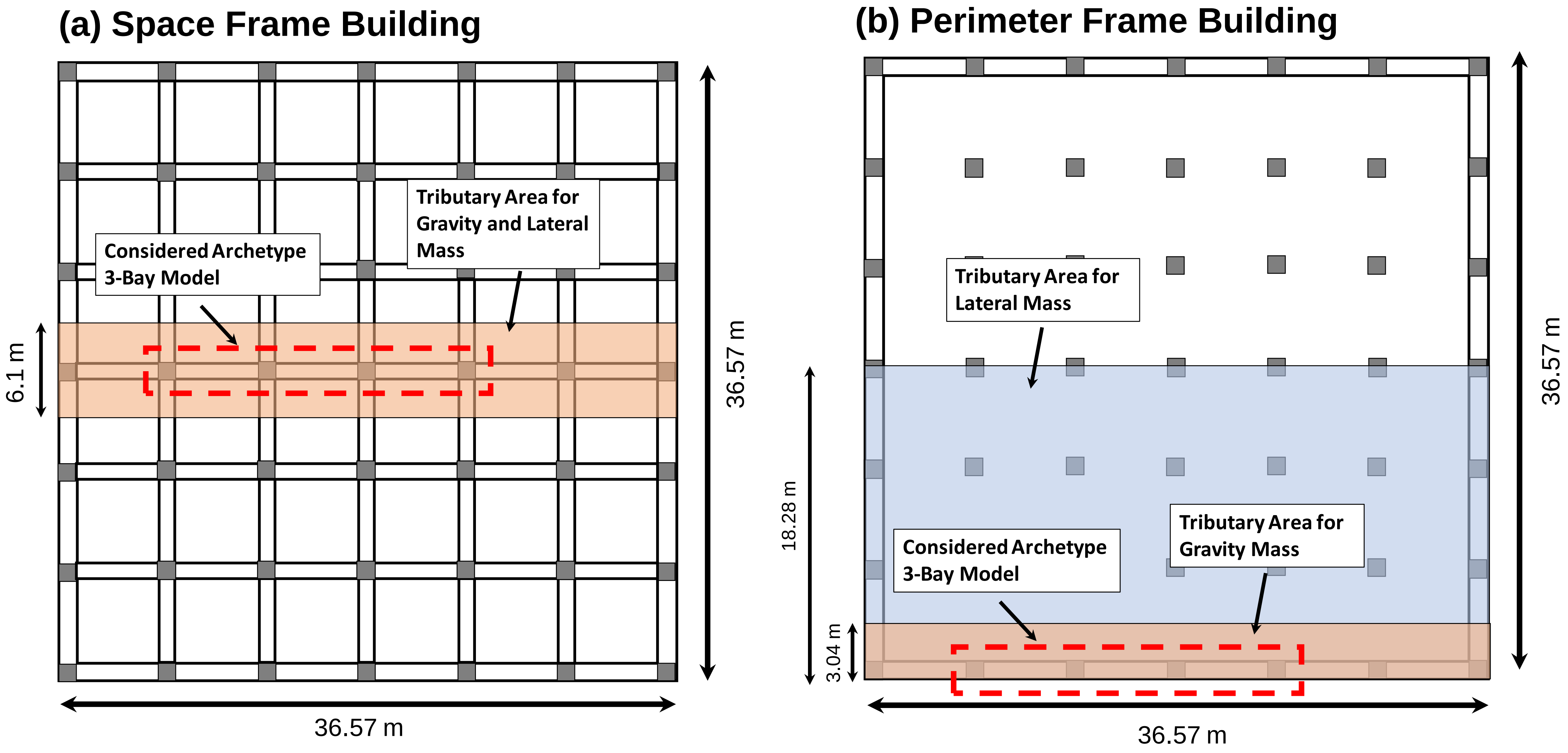
Tariq et al. (2021)

Seismic System Analysis



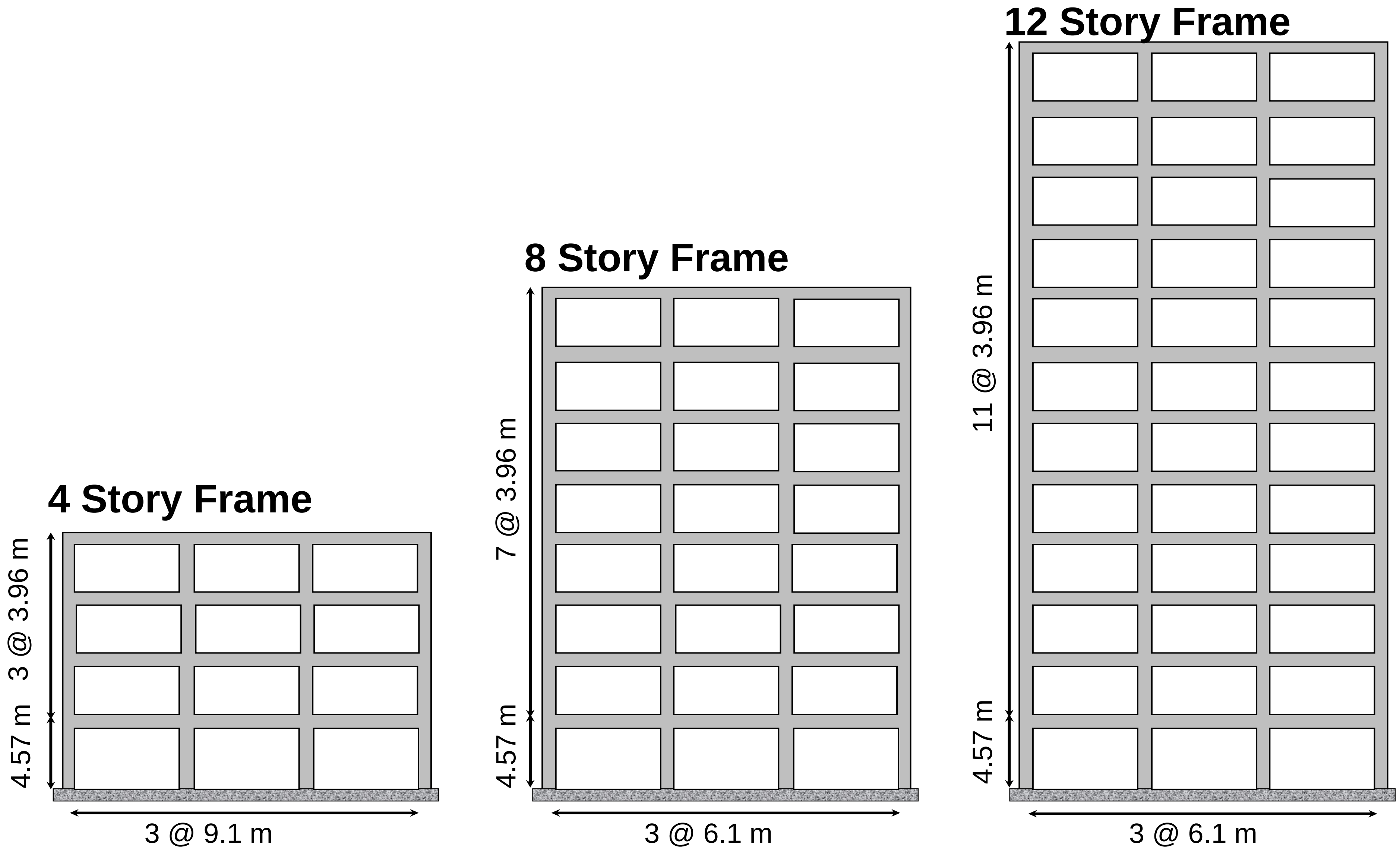
- When increase in M_n was not considered, **structure was 47% more likely to collapse compared to R/C** under maximum considered earthquake
- When re-engineered to account for unique material properties, structure was **38% less likely to collapse compared to R/C under MCE**

FRAME CONFIGURATIONS



Haselton et al. (2007); Tariq et al. (2023)

FRAME CONFIGURATIONS

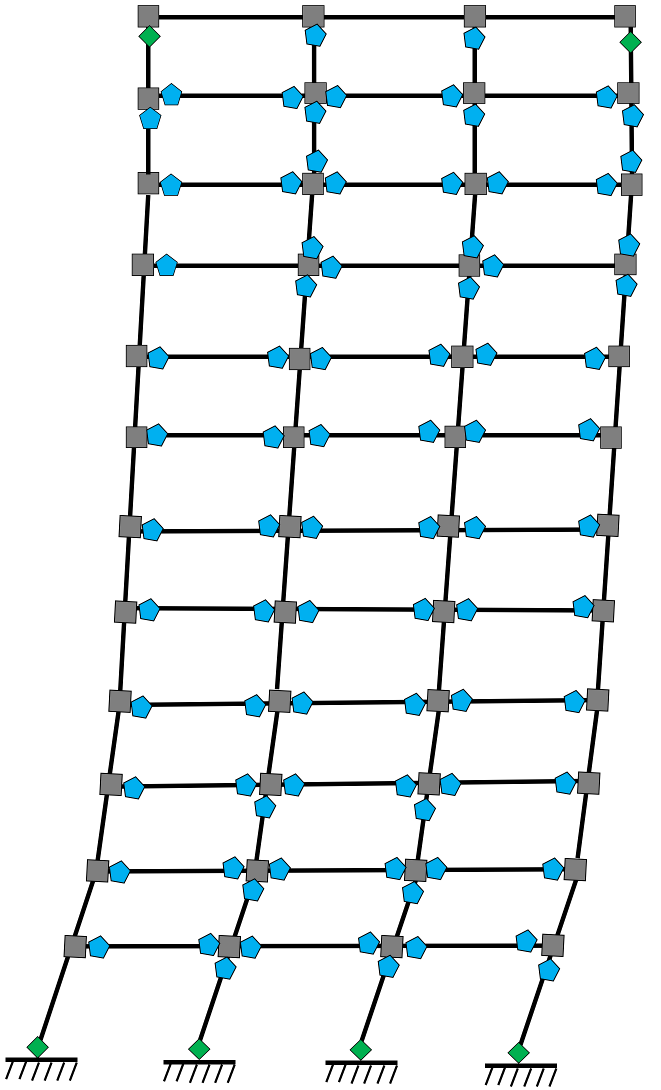


Haselton et al. (2007); Tariq et al. (2023)

Performance of Frame Configurations

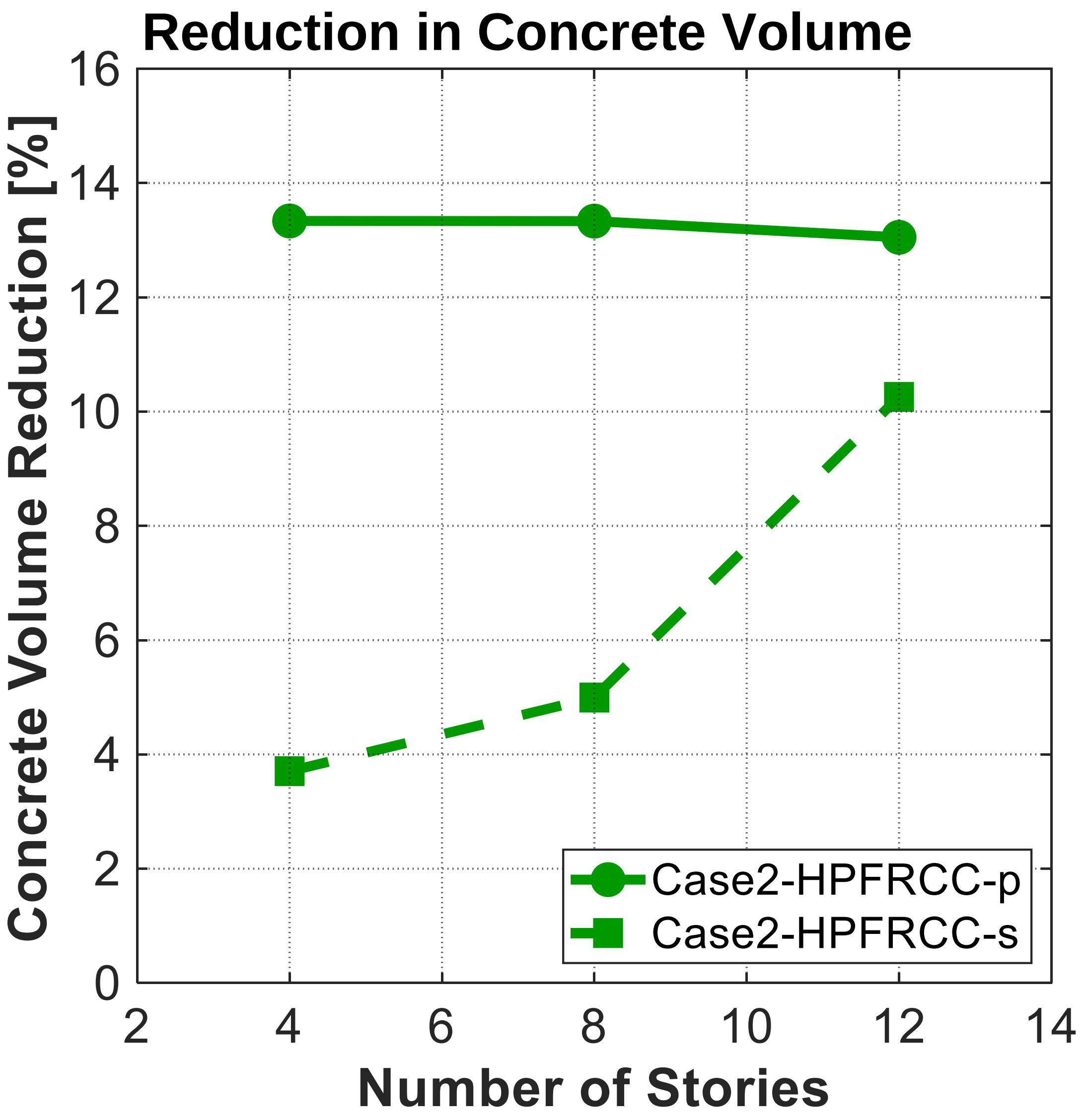
- The **probability of collapse** given a 2% in 50-year earthquake **(*P[C|2/50]*) was 20% lower**, on average, in R/HPFRCC frames

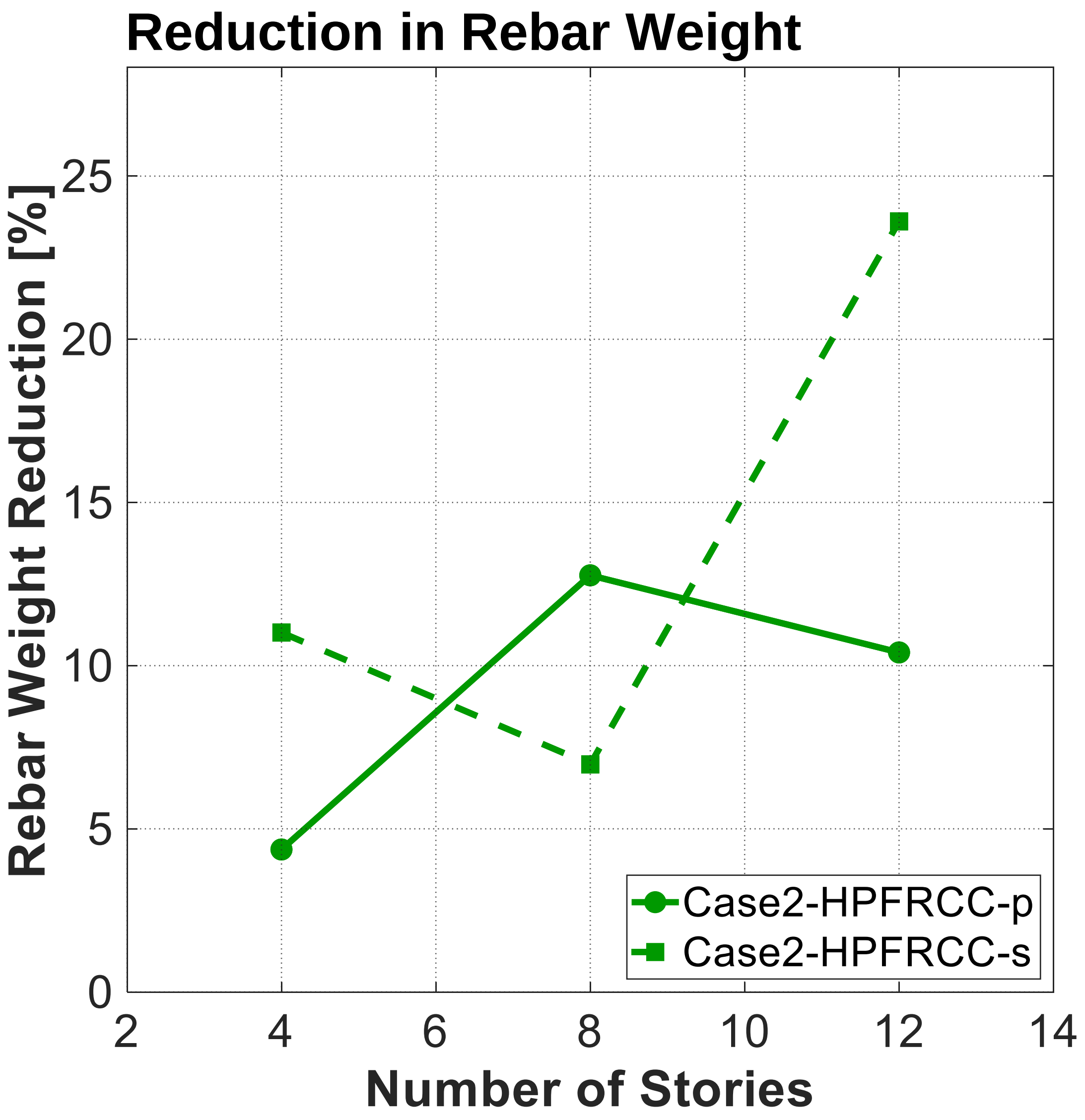
- The **mean annual frequency of collapse was (λ_{col}) 26% lower**, on average in R/HPFRCC frames



Tariq et al. (2023)

CONCRETE VOLUME AND REINFORCEMENT TONNAGE





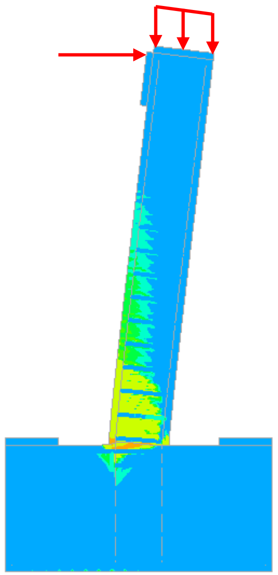
Tariq et al. (2023)

LIMITATIONS OF WORK TO DATE

- Limited experimental data on members with axial loading
- System-level analysis of structures with materials in components beyond beams
- Other variables
  - Effectiveness of various materials
  - Cost

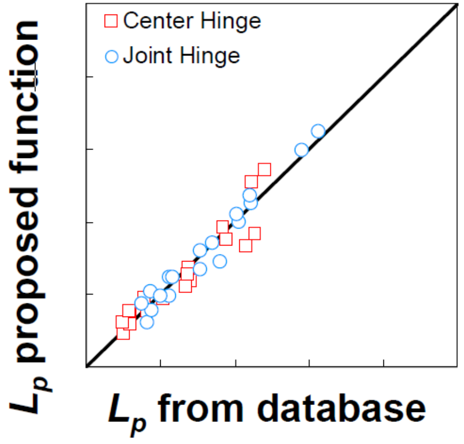
ONGOING PROJECT SUMMARY

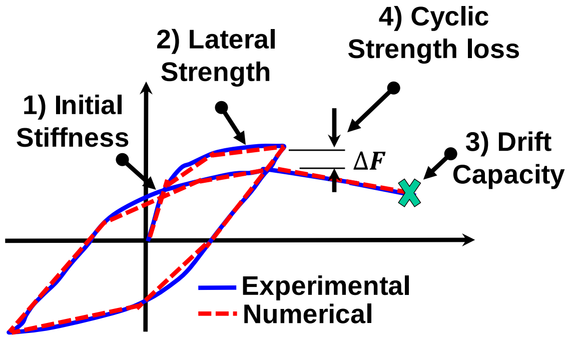
Objective 1
Investigate elements under combined loads



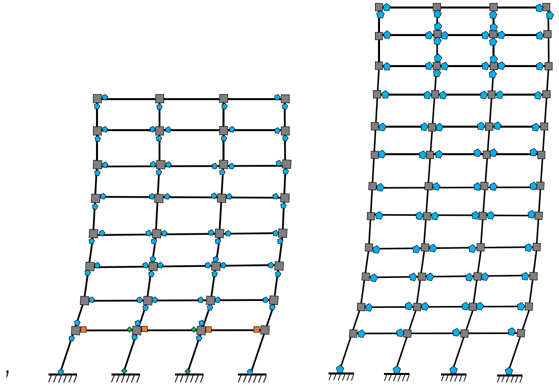
We are here

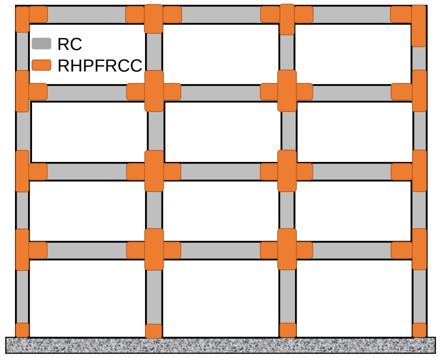
Objective 2
Develop plastic hinge and rotational capacity functions and integrate models



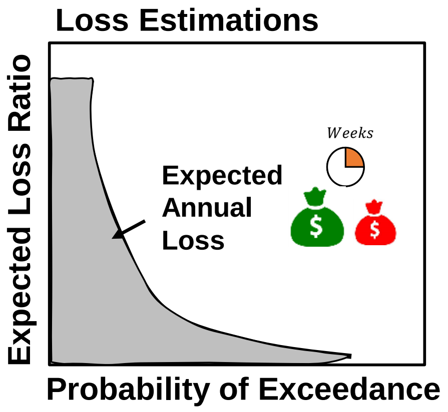


Objective 3
Assess system level performance and develop design approaches

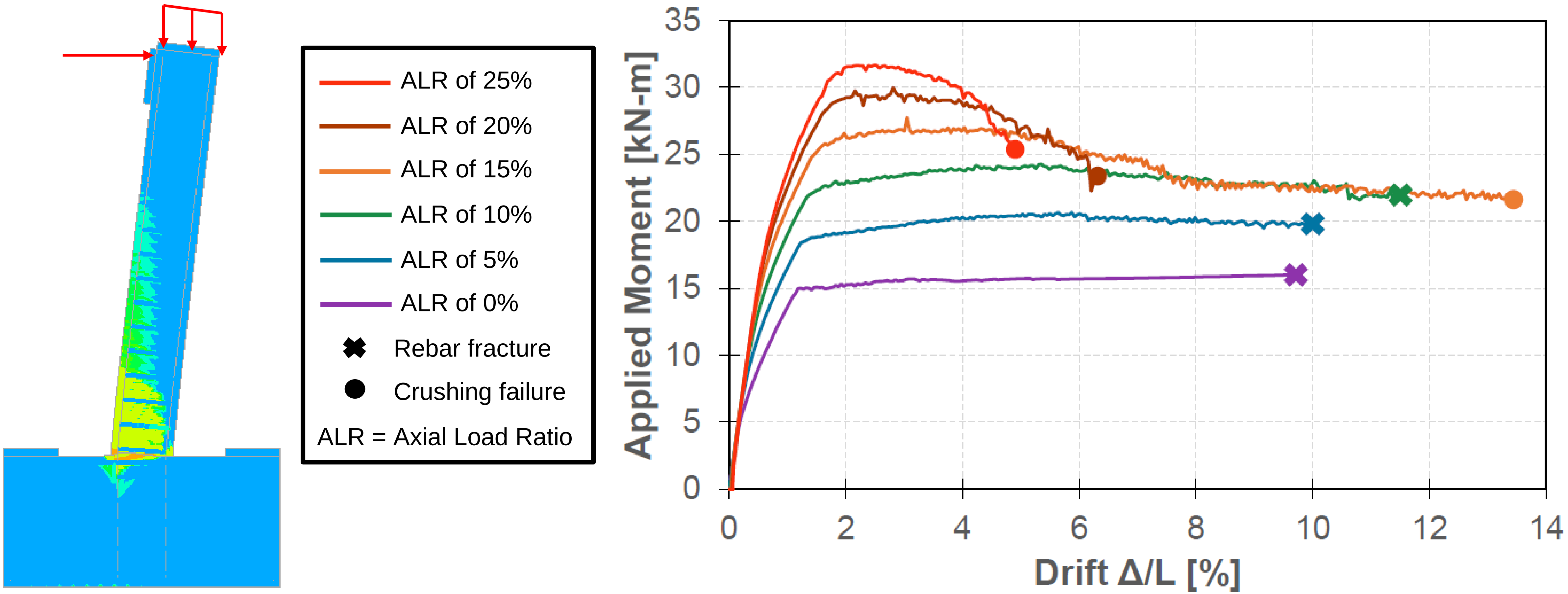




Objective 4
Assess system level losses and life-cycle costs

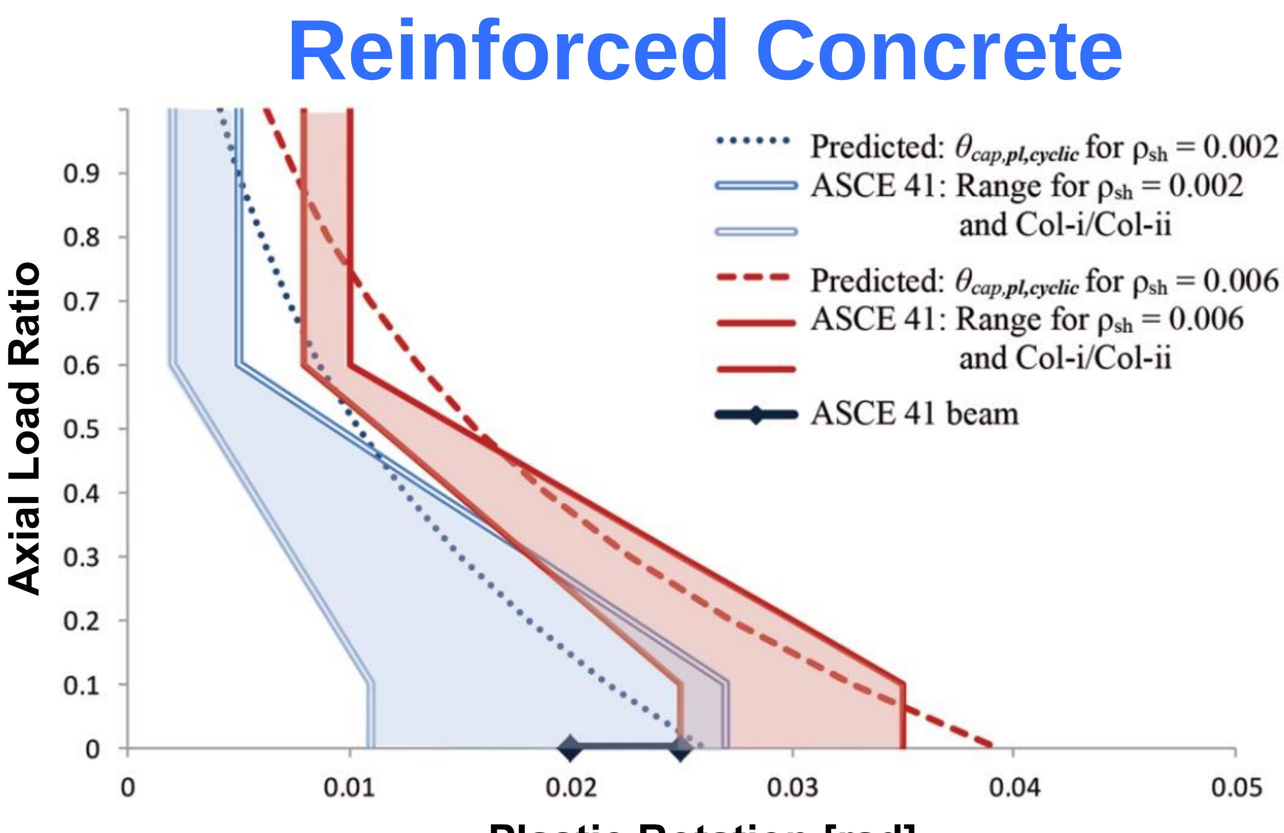


Preliminary Insights – Axial Load Effects

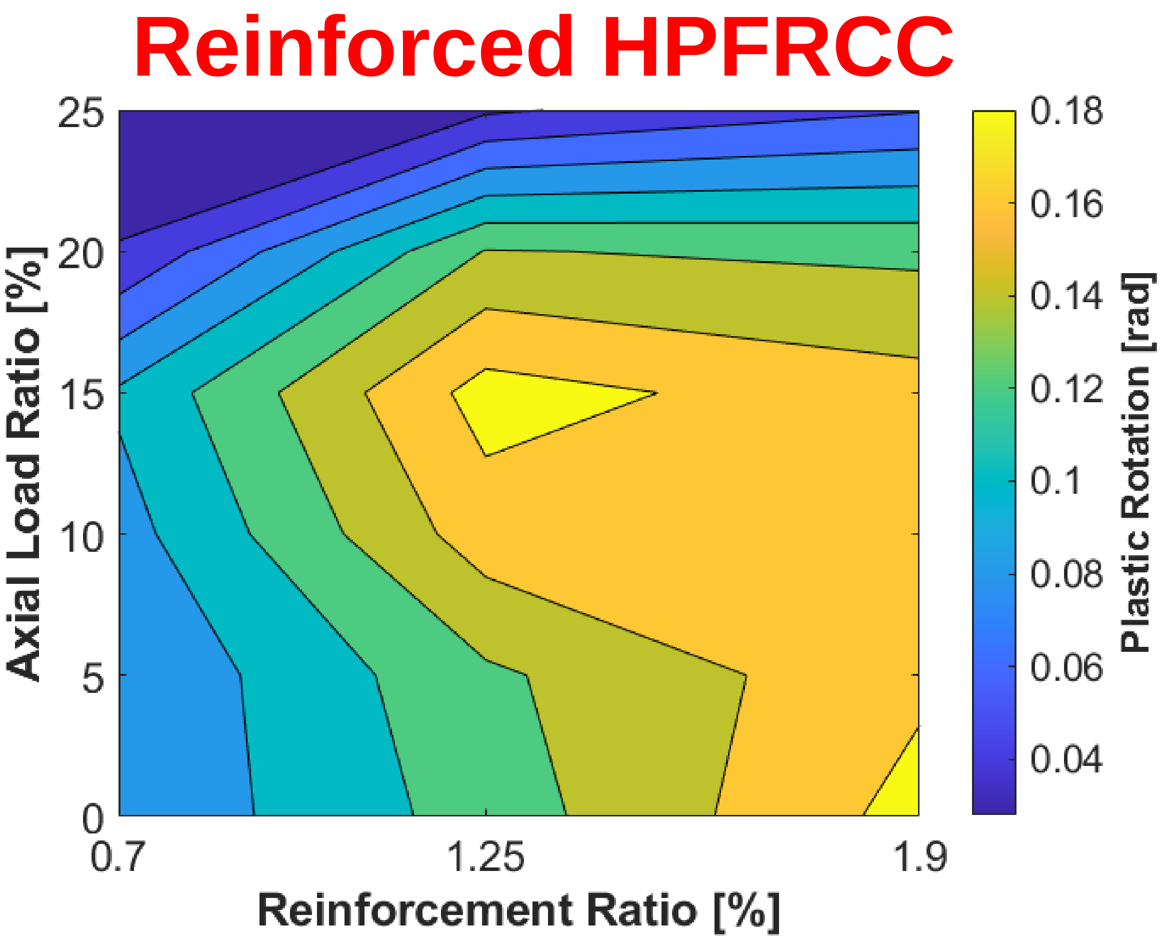


- Axial loading relieves tensile strains in reinforcement
- Axial load can increase deformation capacity

Preliminary Insights – Rotational Capacity



(Haselton et al. 2016)



- In reinforced concrete, axial load ratio is assumed to reduce rotational capacity
- In reinforced HPFRCCs, axial load ratio can increase rotational capacity

SUMMARY

- UHPC and other HPFRCCs have **unique failure modes** necessitating a need for **new models in seismic analysis and design**

- There is **significant potential to improve life safety and reduce damage** through these materials when properly engineered

- **New on-going work** to understand a **broader set of seismic systems** with UHPC and other HPFRCCs

THANK YOU!

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NJIT

New Jersey's Science & Technology University

Acknowledgements

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