# Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery [2024 – 2027]

C. Franco Mayorga[1], Sena Mursel[2], **Georgios Tsampras**[3], and Paolo Bocchini[4]

[1]Graduate Student Researcher, University of California San Diego, CA, USA
[2]Graduate Student Researcher, Lehigh University, PA, USA
[3]PI, Associate Professor, University of California San Diego, CA, USA
[4]Co-PI, Professor, Lehigh University, PA, USA

August 18, 2026
NIST | NSF | Disaster Resilience Research Grant Symposium

# TSAMPRAS RESEARCH GROUP

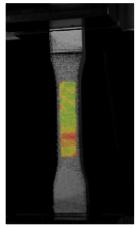
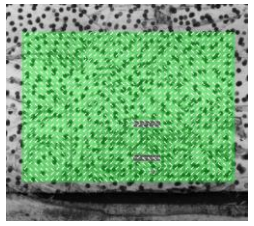
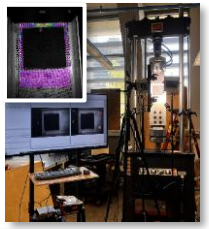
## Improvement of safety and resilience of our built environment & structural engineering education

U.S. National Science Foundation | NIST | Caltrans | INL Idaho National Laboratory



The Wolfinger Foundation | PCI Precast/Prestressed Concrete Institute

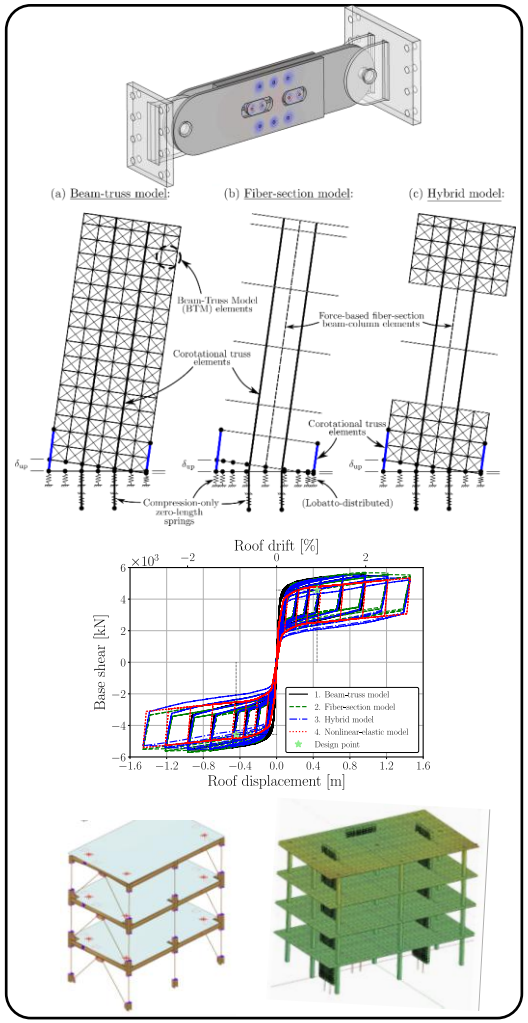
## Experimental



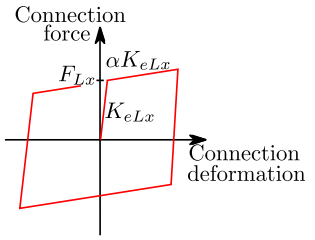


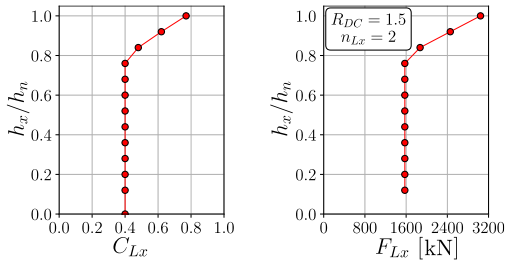

## Computational

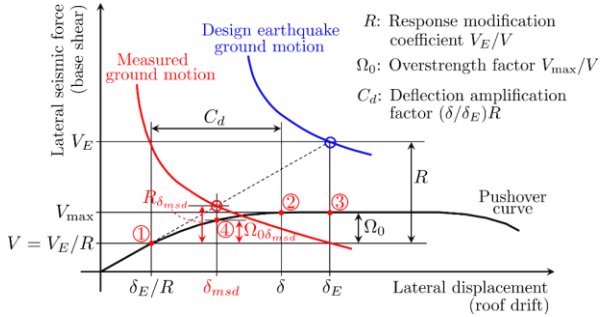



## Design

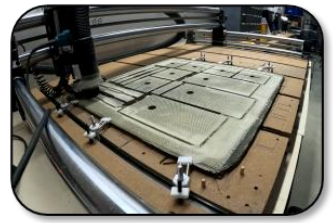
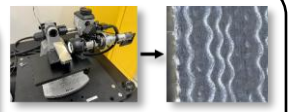
$$F_{Lx} = \frac{C_{Lx}}{R_{DC}} \frac{w_{px}}{n_{Lx}}$$




## Manufacturing

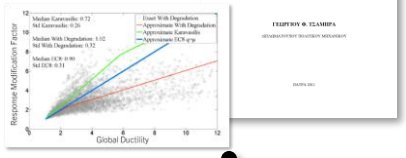








http://tsampras.ucsd.edu

# Past efforts related to design of high-performance buildings

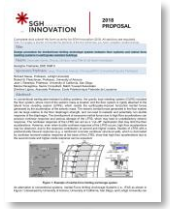




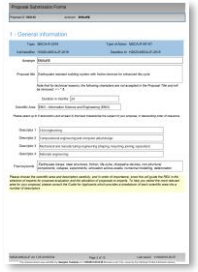

## 2011
**MSc Thesis**
Performance-Based Seismic Response Modification Factors of Planar Steel Moment Resisting Frames



## 2016
**PhD Thesis**
Force-Limiting Deformable Connections for Earthquake-Resistant Buildings




## 2018
**SGH Innovation**
**(not funded)**
Design procedure for inertial-force limiting anchorage system between floor systems and lateral force resisting systems in earthquake-resistant buildings.



## 2018
**Marie-Curie Program**
**(EPFL as host)**
**(not funded)**
Earthquake resistant building system with friction devices for enhanced life-cycle



## 2019
**UC San Diego Interview**
Future Research Topic 2: Development of a unified procedure for the design of lateral seismic force resisting systems and floor diaphragms

## 2020
**Disaster resilience research grant**
**(not-funded)**
Collaborative Research: Unified design methodology for high-performance earthquake-resilient buildings



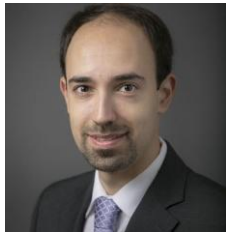



## 2022
**Disaster resilience research grant**
**(funded)**
Resilience-based design of buildings with accelerated post-earthquake functional recovery

## Our DRRG Project Starts
01/15/2024

# Our DDRG Collaborative Project Team

| Project | Group/Board | Organization | Member |
|---|---|---|---|
| Resilience-based design of buildings with accelerated post-earthquake functional recovery | Research Group | UC San Diego | PI, Georgios Tsampras |
| | | | GSR, Franco Mayorga |
| | | Lehigh University | Co-PI, Paolo Bocchini |
| | | | GSR, Sena Mursel |
| | Educational Outreach Group | Walgrove Elementary School | Coordinator, Andrea Kittelson |
| | | | STEAM Teachers |
| | Academic Advisory Board | Colorado State University | Advisor, Bruce R. Ellingwood |
| | Practicing Engineering Advisory Board | Maffei Structural Engineering | Advisor, Lawrence Burkett |
| | | Magnusson Klemencic Associates | Advisor, John D. Hooper |
| | | Mar Structural Design | Advisor, David Mar |
| | | Skidmore, Owings & Merrill (SOM) | Advisor, Mark Sarkisian |
| | Industry Advisory Board | Gripple Inc. | Advisor, Prasad Naik |

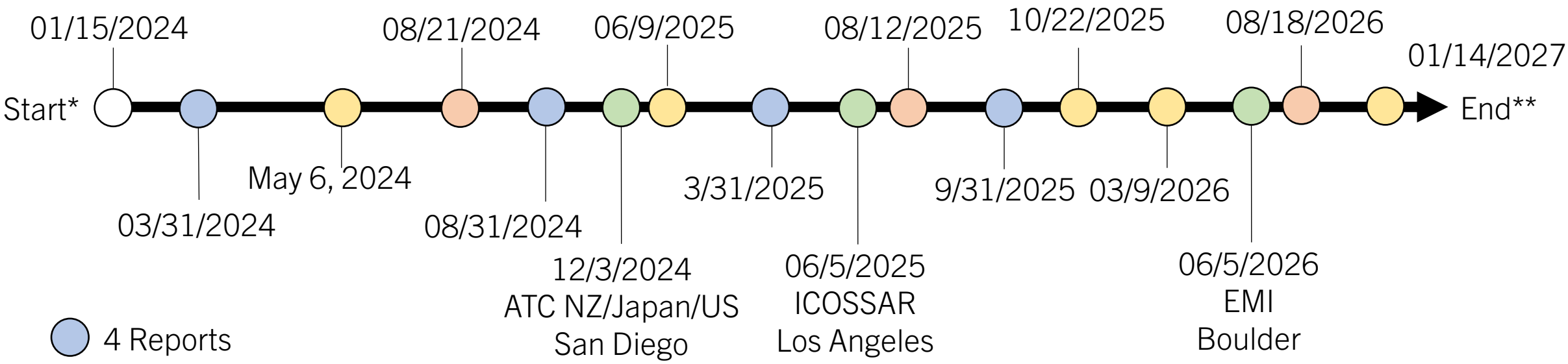




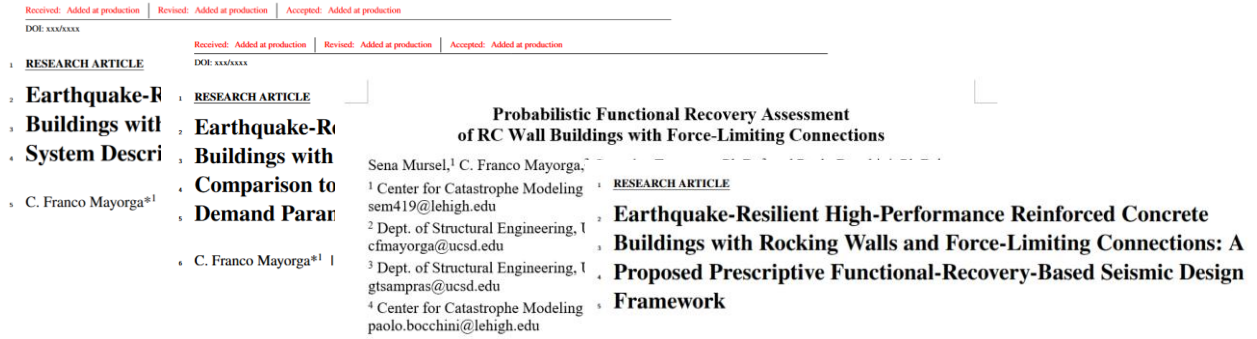





# Project Activities & Timeline




- 4 Reports
- 3 DRRG Symposiums
- 4 Advisory Board Meetings + 1 to be scheduled
- 3 Conference presentations


Probabilistic Functional Recovery Assessment of RC Wall Buildings with Force-Limiting Connections

Earthquake-Resilient High-Performance Reinforced Concrete Buildings with Rocking Walls and Force-Limiting Connections: A Proposed Prescriptive Functional-Recovery-Based Seismic Design Framework

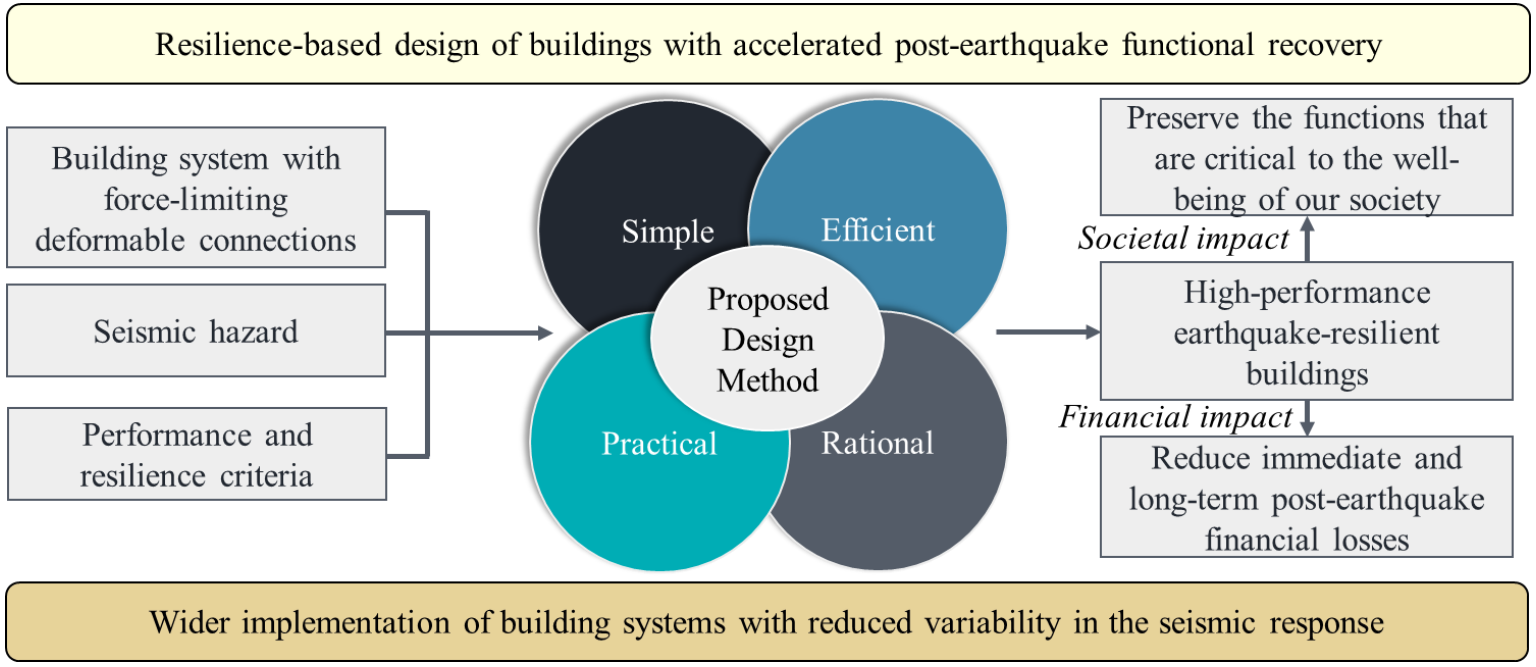
*Biweekly UC San Diego / Lehigh research meetings throughout the duration of the project

** 2 Graduate student dissertations, 4 journal manuscripts under preparation

# Project Overview

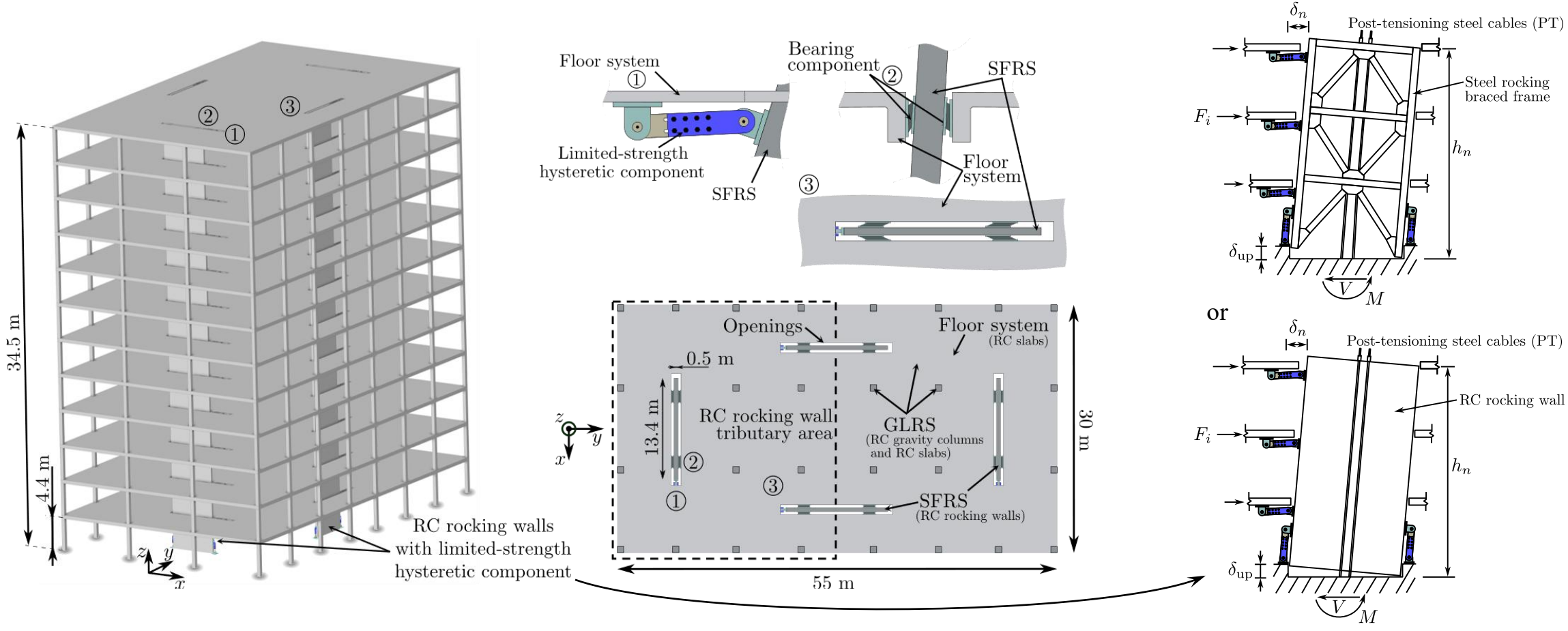
# Project Vision and Goal

- Vision: to advance the fundamental knowledge that will democratize the simple, efficient, rational, and practical design of high-performance buildings that even after earthquakes preserve the functions that are critical for the well-being of our society and reduce the immediate and long-term financial losses.
- Goal: to develop and validate a design method that will integrate performance and resilience criteria.



# Building system

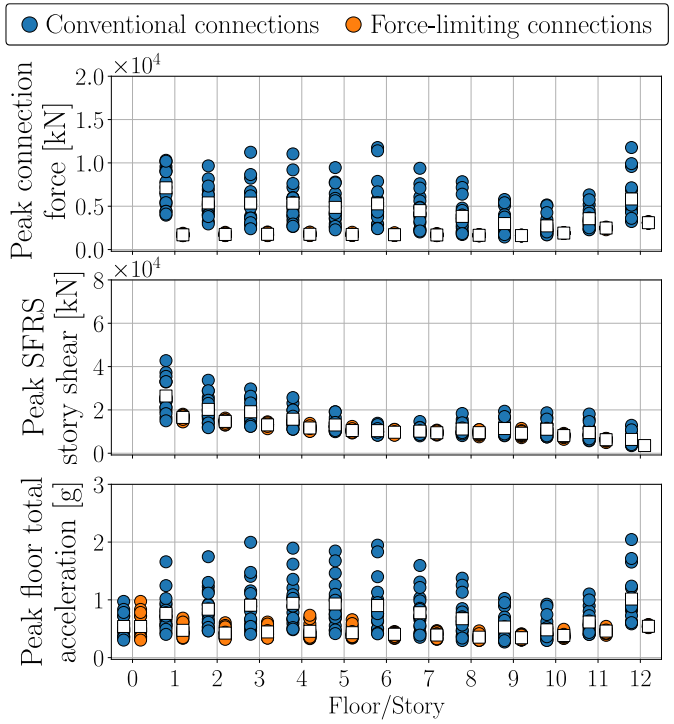
- The proposed research focuses on building systems that utilize practical reusable force-limiting deformable connections efficiently placed in the building seismic load path.



# Why buildings with force-limiting connections?

Research findings have shown these buildings:

- Limit the earthquake-induced horizontal forces transferred from the floor diaphragms to the vertical elements of the seismic force-resisting system.
- Reduce the higher-mode shear-dominant acceleration and force responses and their dispersion due to ground motion-to-ground motion variability.





1. Tsampras, G. 2016. "Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings," PhD Dissertation, Lehigh University, Bethlehem, PA, USA
2. Tsampras G., R. Sause, D. Zhang, R.B. Fleischman, J.I. Restrepo, D. Mar, J. Maffei. 2016. "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses." Earthquake Engineering & Structural Dynamics; 45(9): 1473–1494. https://doi.org/10.1002/eqe.2718.
3. Tsampras, G., R. Sause, R.B. Fleischman, J.I. Restrepo. 2017. "Experimental study of deformable connection consisting of buckling-restrained brace and rubber bearings to connect floor system to lateral force resisting system." Earthquake Engineering & Structural Dynamics, 46(8): 1287–1305. https://doi.org/10.1002/eqe.2856.
4. Tsampras, G., R. Sause, R.B. Fleischman, J.I. Restrepo. 2018. "Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system." Earthquake Engineering & Structural Dynamics; 47(4): 1032–1053. https://doi.org/10.1002/eqe.3004.
5. Zhang, Z., R.B. Fleischman, J.I. Restrepo, G. Guerrini, A. Nema, D. Zhang, U. Shakya, G. Tsampras, R. Sause. 2018. "Shake-table test performance of an inertial force-limiting floor anchorage system." Earthquake Engineering & Structural Dynamics, 47(10): 1987–2011. https://doi.org/10.1002/eqe.3047.
6. Mayorga, C.F., Tsampras G. 2024. "Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation." Earthquake Engineering & Structural Dynamics, 53(4):1465-1491. https://doi.org/10.1002/eqe.4073.
7. Lee K., Tsampras G., Mayorga C.F. (2024), Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions, ASCE Journal of Structural Engineering, DOI: 10.1061/JSENDH/STENG-13609
8. Tsampras G., Sause R. (2025), Reducing the magnitude and variability of seismic-induced acceleration and force responses in steel buildings with controlled rocking base mechanism and force-limiting connections, Resilient Cities and Structures, doi: 10.1016/j.rcns.2025.12.004

# Why buildings with force-limiting connections? (Cont'd)

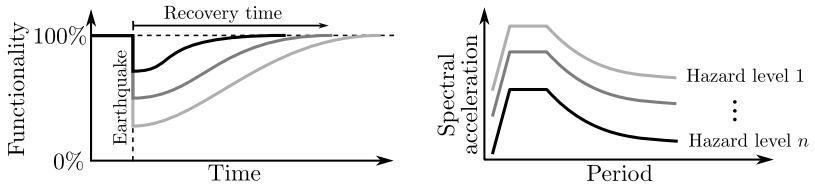
- Reduced magnitude of the building seismic responses → Reduced damage in the structural and nonstructural components → Improved post-disaster functionality.

- Reduced dispersion of the building seismic responses → Higher confidence in the response prediction → Higher confidence in building design reliability → Higher confidence in achieving resilience-based design objectives.

There is no simple and practical design method that provides the means for the holistic design of buildings with force-limiting connections for target performance and post-earthquake functional recovery levels.

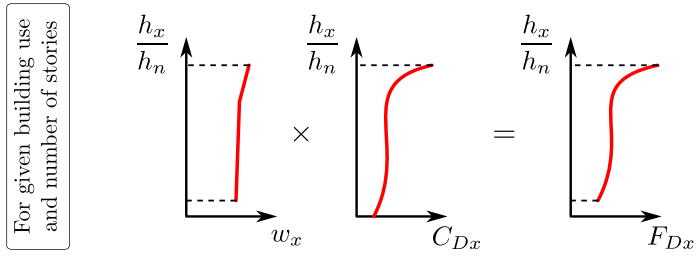
# Proposed Design Methodology used by Structural Engineers

1. The owner defines the functional-recovery-based target performance limits:

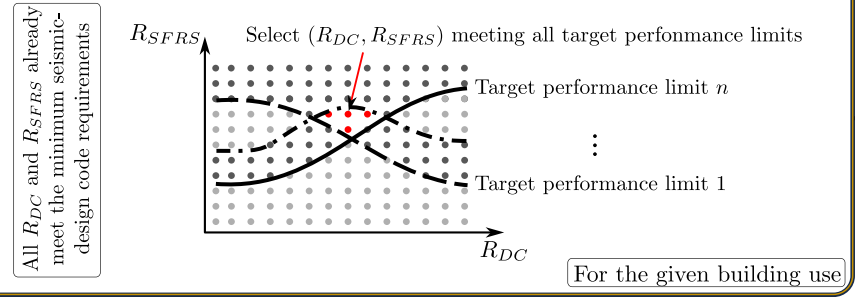



Example: **Probability** that a **target % of functionality** is restored within **a determined recovery time** after an **earthquake of a given hazard level**

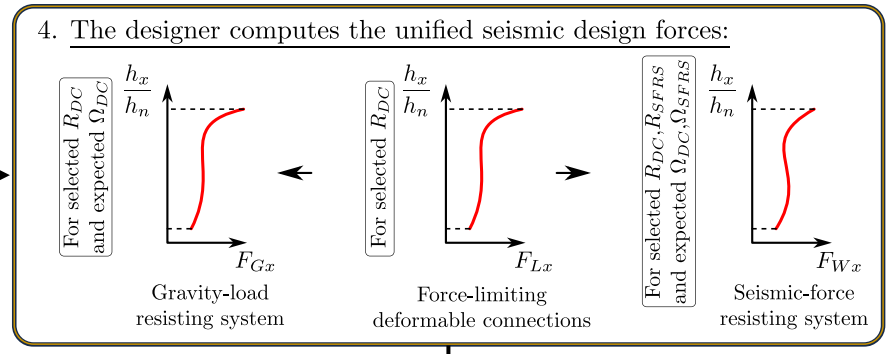
2. The designer computes the linear-elastic seismic design forces:



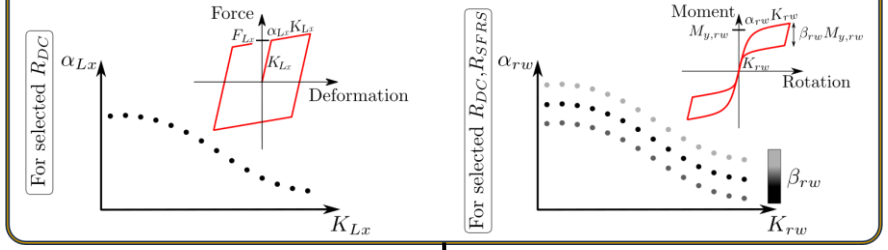

3. The designer selects the response modification factors $R_{DC}$ and $R_{SFRS}$:




4. The designer computes the unified seismic design forces:

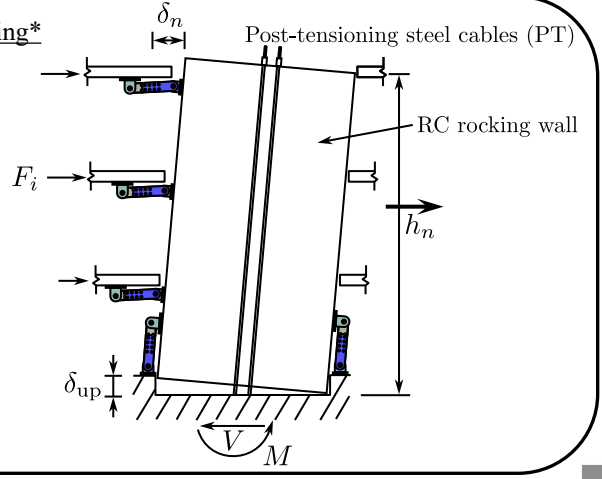



5. The designer accesses the recommended combinations of design variables:

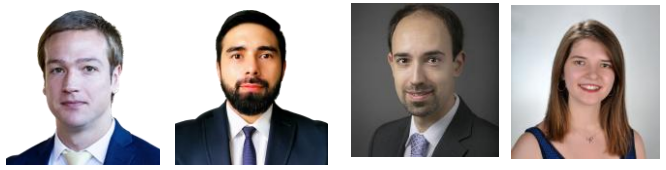



6. Structural detailing*

*Complete design examples for dissemination purposes will be developed



# Research Tasks



**Structural performance and design**

i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

**Recovery Assessment**

i. Assessment of functional recovery.
ii. Recovery Modeling Framework.
iii. Impeding Factors and Repair Delays.
iv. Functional Recovery Trajectories.
v. Resilience Metrics.
vi. Sensitivity Analysis of Component Damage.

**Objective:** Identify design parameters that satisfy functional recovery targets for a given occupancy, hazard level, and building archetype.

# Building Archetypes

Structural performance and design

i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

Recovery Assessment

i. Damage Simulation.
ii. Assessment of functional recovery.
iii. Recovery Modeling Framework.
iv. Impeding Factors and Repair Delays.
v. Functional Recovery Trajectories.
vi. Resilience Metrics.
vii. Sensitivity Analysis of Component Damage.

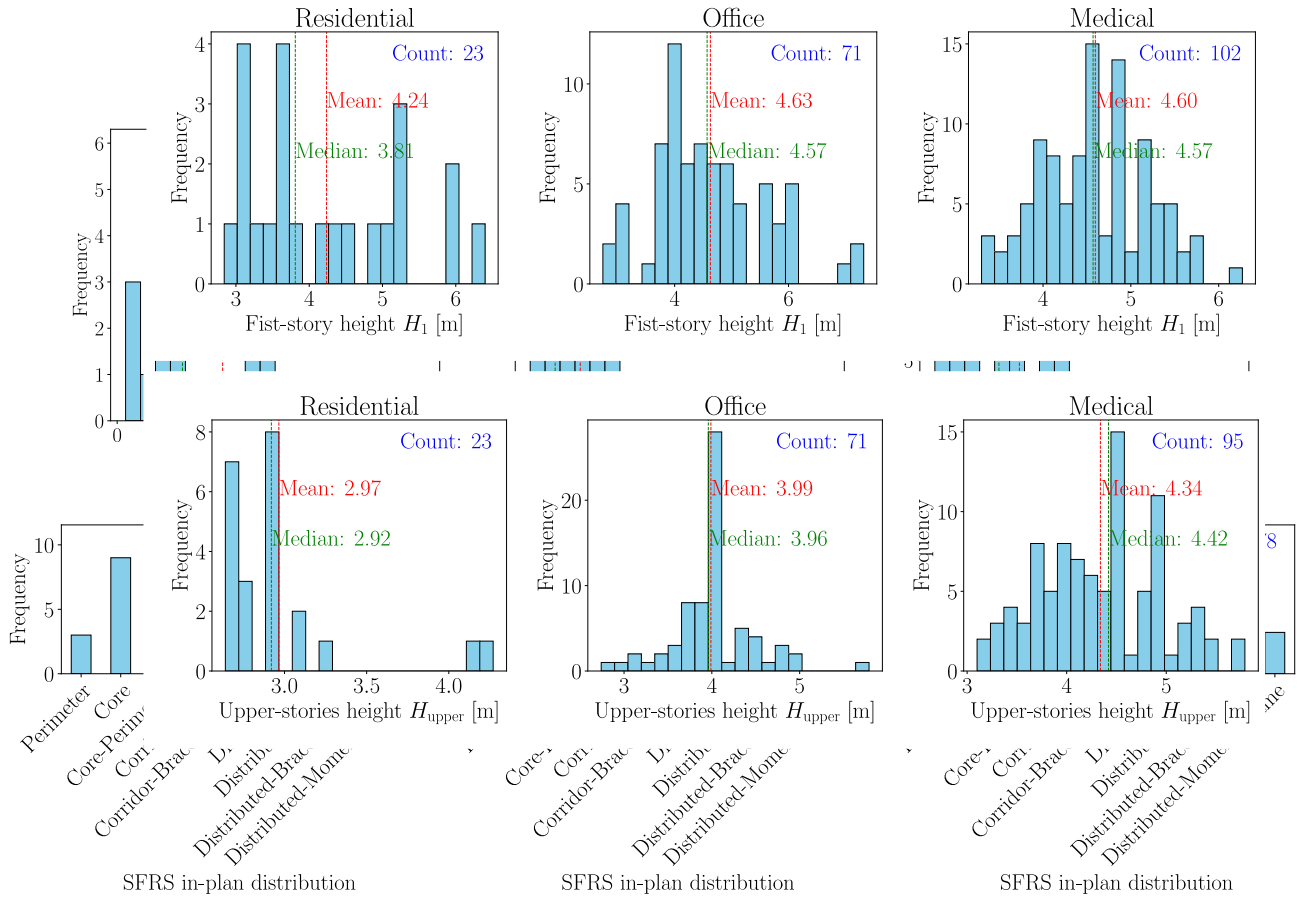
# Building Archetypes

Center for Engineering Strong-Motion Data (CESMD) building statistics.

- Plan dimensions , story heights, and number of stories were informed by CESMD building distributions.




California Department of Conservation

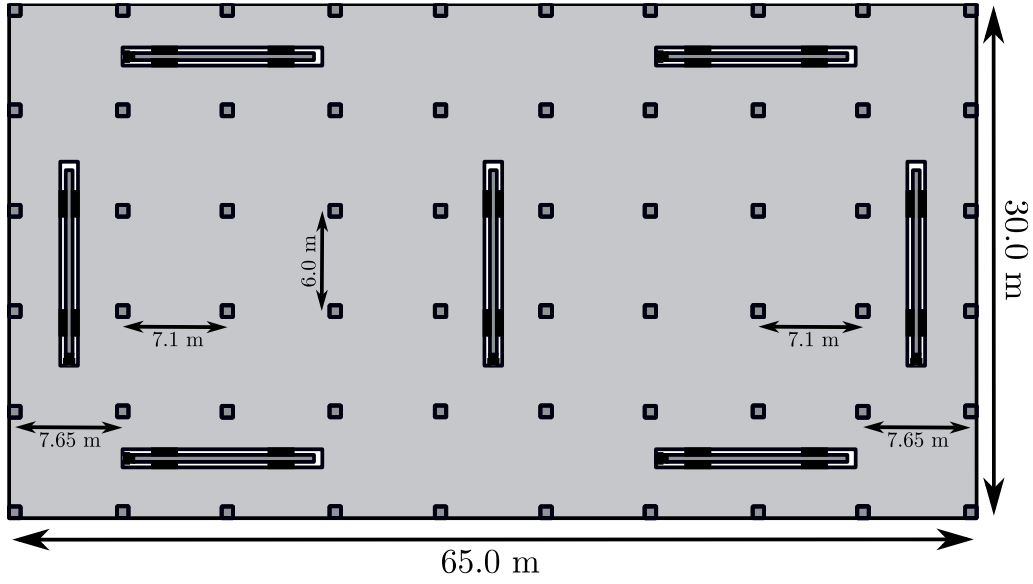


# Building Archetypes

Center for Engineering Strong-Motion Data (CESMD) building statistics and prior studies of buildings with force-limiting connections informed the archetype characteristics.

- Plan dimensions , story heights, and number of stories were informed by CESMD building distributions.

| Building archetype | Number of stories | Building use | First-story height [m] | Upper-story height [m] |
|---|---|---|---|---|
| 1 | 3 | Residential | 3.8 | 2.9 |
| 2 | | Office | 4.6 | 4.0 |
| 3 | | Medical | 4.6 | 4.4 |
| 4 | | Data center | 4.6 | 4.3 |
| 5 | 6 | Residential | 3.8 | 2.9 |
| 6 | | Office | 4.6 | 4.0 |
| 7 | | Medical | 4.6 | 4.4 |
| 8 | | Data center | 4.6 | 4.3 |
| 9 | 9 | Residential | 3.8 | 2.9 |
| 10 | | Office | 4.6 | 4.0 |
| 11 | | Medical | 4.6 | 4.4 |
| 12 | | Variable | 4.3 | 4.0 |
| 13 | 12 | Residential | 3.8 | 2.9 |
| 14 | | Office | 4.6 | 4.0 |
| 15 | | Medical | 4.6 | 4.4 |
| 16 | | Mixed | 4.3 | 4.0 |
| **Common properties:** | $30.0 \times 65.0$ m floor plan / Perimeter SFRS distribution | | | |



(Same plan dimensions for all uses)

# Unified force distribution for design

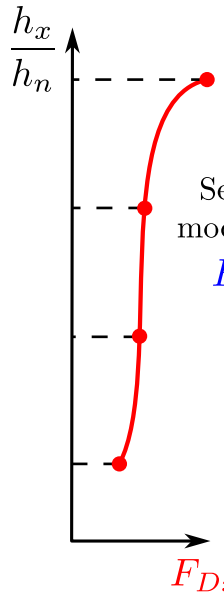
Structural performance and design

i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

Recovery Assessment

i. Damage Simulation.
ii. Assessment of functional recovery.
iii. Recovery Modeling Framework.
iv. Impeding Factors and Repair Delays.
v. Functional Recovery Trajectories.
vi. Resilience Metrics.
vii. Sensitivity Analysis of Component Damage.

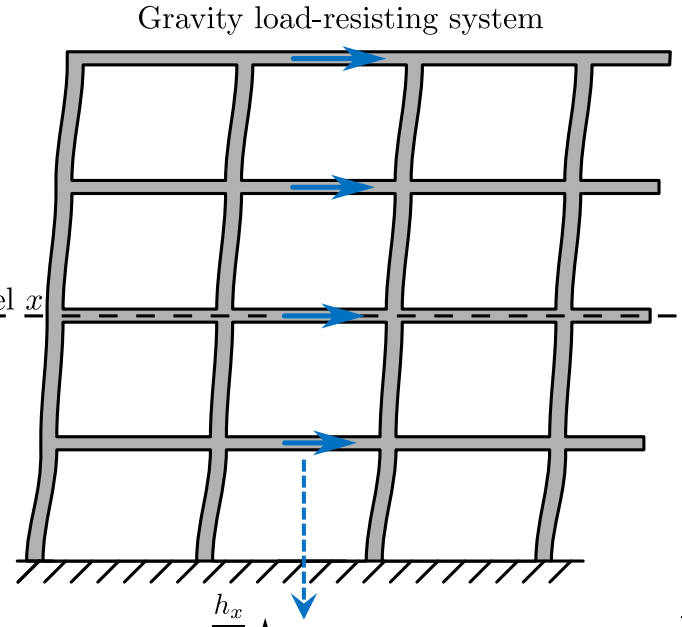
# Unified Seismic Design Forces




Seismic response modification factors

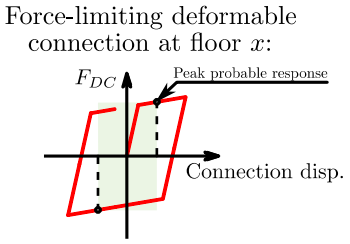
$R_{DC}$, $R_{SFRS}$

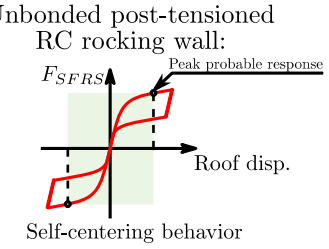
(Linear-elastic design forces)

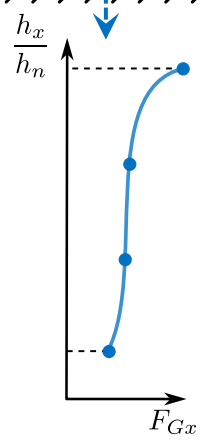


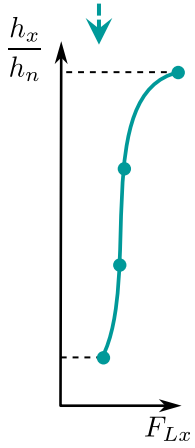

Force-limiting deformable connections

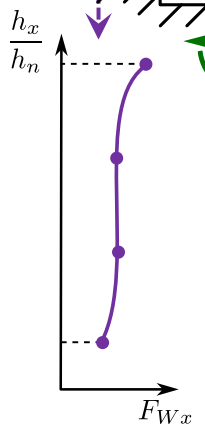
Seismic force-resisting system



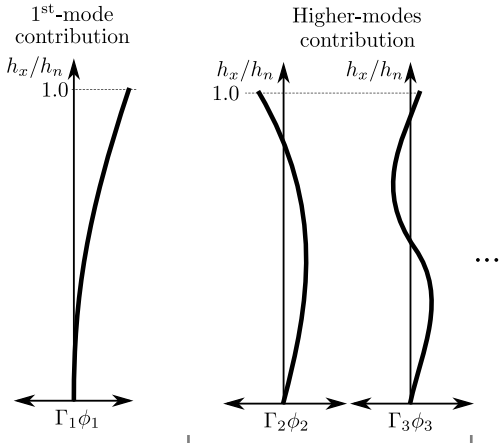




$$V_{Wb} = \sum_{x=1}^{n} F_{Wx}$$

$$M_{Wb} = \frac{\sum_{x=1}^{n} F_{Lx,1m} \times h_x}{R_{SFRS}}$$

$$F_{Dx} = \sqrt{(F_{Dx,1m})^2 + (F_{Dx,hm})^2}$$




$$F_{Gx} = n_{DC} \cdot \Omega_{DC} \cdot F_{Lx}$$

(capacity design forces)

$$F_{Lx} = \frac{F_{Dx}}{R_{DC}}$$

$$F_{Wx} = \sqrt{\left(\frac{F_{Lx,1m} \times \Omega_{SFRS}}{R_{SFRS}}\right)^2 + (F_{Lx,hm} \times \Omega_{DC})^2}$$

(capacity design forces)

# Linear-Elastic Seismic Design Forces



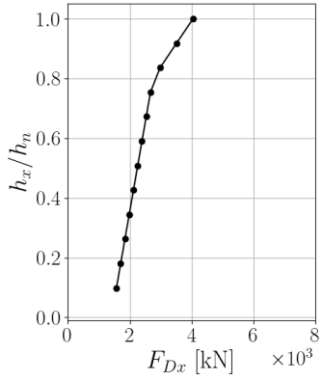

Mayorga, C. F., and G. Tsampras. 2025. "**Assessment of Seismic Design Provisions for Floor Diaphragms and Higher-Mode Responses Using Data from Instrumented Buildings in California**." Earthquake Spectra, 41(5): 3826–3857. https://doi.org/10.1177/87552930251377781

## 1. Based on ASCE/SEI 7-22




Equations from Section 12.10.3 Alternative Design Provisions for Floor Diaphragms.

$F_{Dx1}$




## 2. Based on continuum models

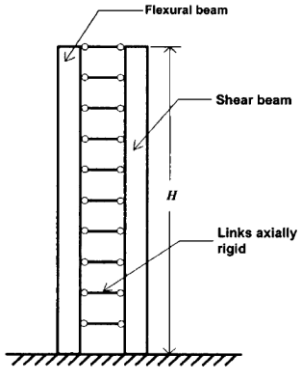
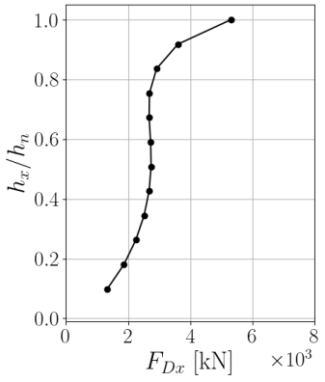
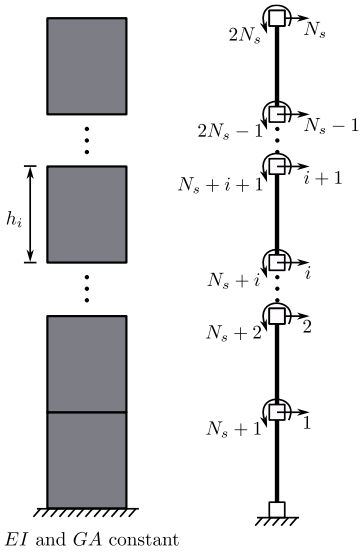



**Fig. 1.** Simplified model to estimate dynamic properties of multistory buildings

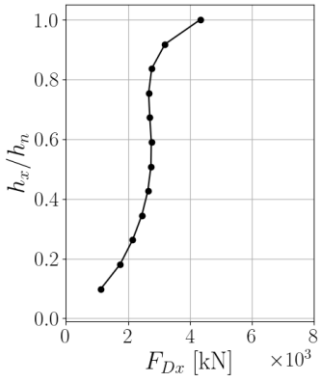
$F_{Dx2}$




## 3. Based on discrete models




$F_{Dx3}$





1. ASCE/SEI 7-22. 2021. "Minimum Design Loads and Associated Criteria for Buildings and Other Structures." American Society of Civil Engineers. https://doi.org/10.1061/9780784415788.
2. Miranda, E. and S. Taghavi. 2005. "Approximate Floor Acceleration Demands in Multistory Buildings. I: Formulation." Journal of Structural Engineering, 131:203–211. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:2(203).
3. Chopra, A.K. 2023. "Dynamics of Structures: Theory and Applications to Earthquake Engineering." 6th ed. Pearson.

# Numerical models for earthquake simulations and damage limit state

## Need for accuracy and computational efficiency

Structural performance and design

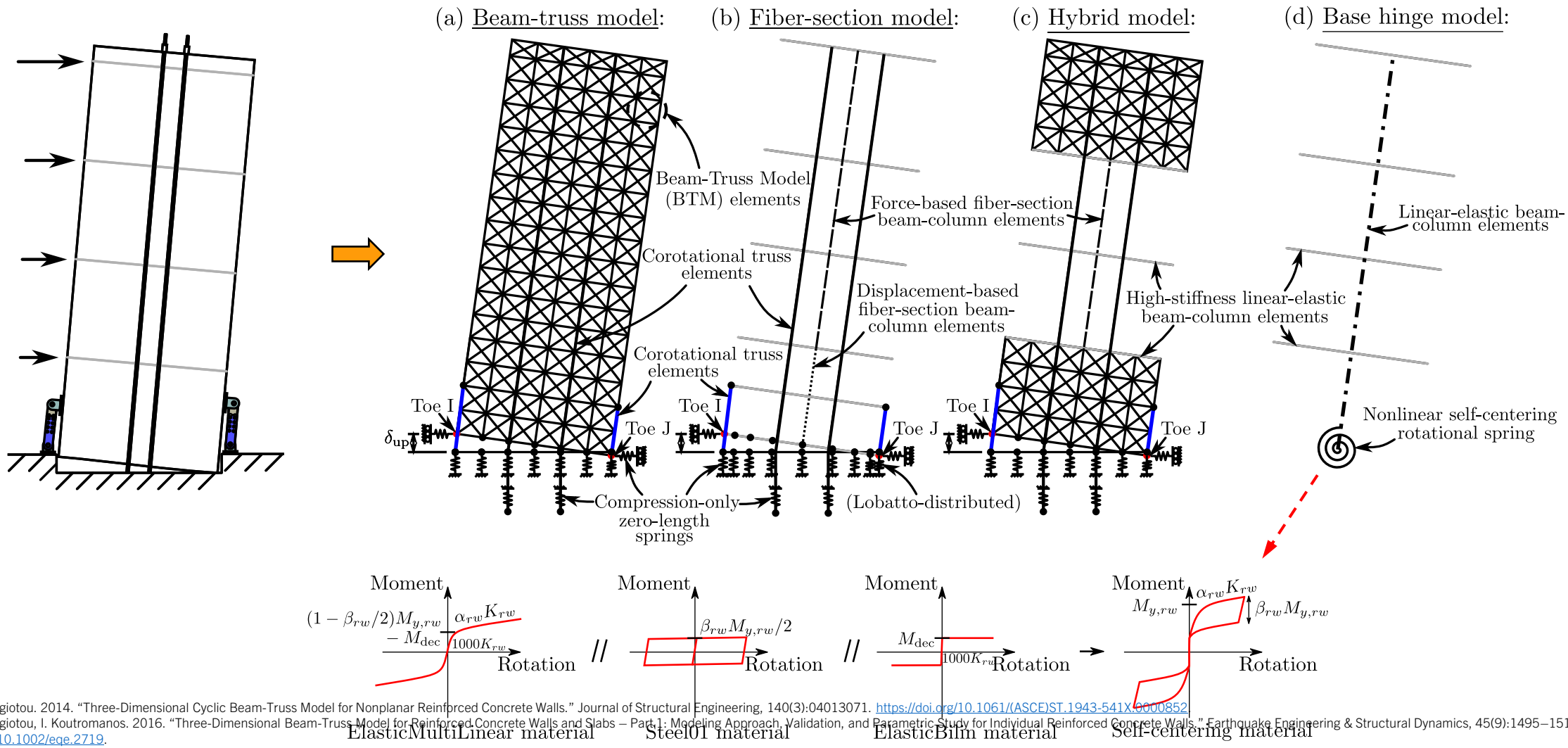
i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

Recovery Assessment

i. Damage Simulation.
ii. Assessment of functional recovery.
iii. Recovery Modeling Framework.
iv. Impeding Factors and Repair Delays.
v. Functional Recovery Trajectories.
vi. Resilience Metrics.
vii. Sensitivity Analysis of Component Damage.

# Nonlinear Numerical Models

Unbonded post-tensioned RC rocking wall with base friction devices.





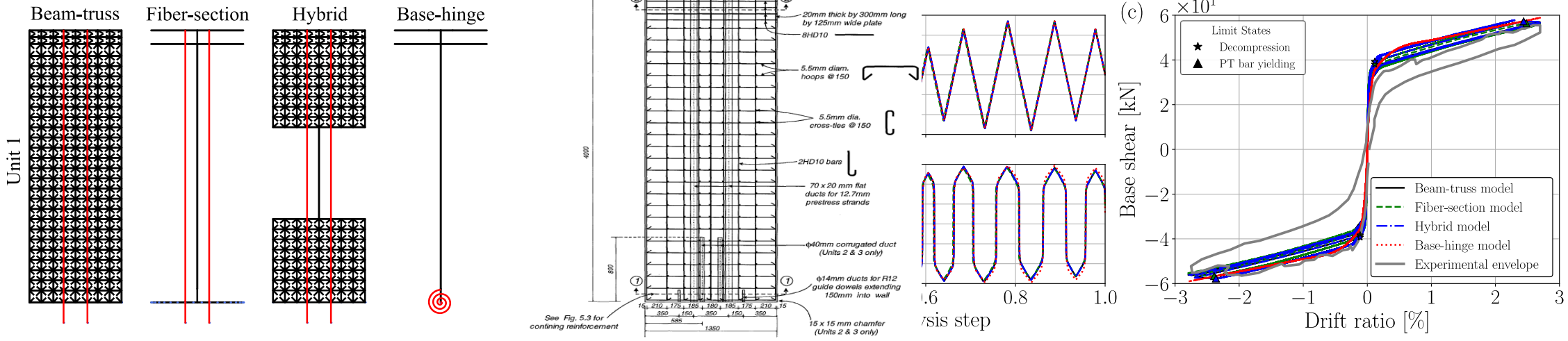
1. Lu, Y., M. Panagiotou. 2014. "Three-Dimensional Cyclic Beam-Truss Model for Nonplanar Reinforced Concrete Walls." Journal of Structural Engineering, 140(3):04013071. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000852.
2. Lu, Y., M. Panagiotou, I. Koutromanos. 2016. "Three-Dimensional Beam-Truss Model for Reinforced Concrete Walls and Slabs – Part 1: Modeling Approach, Validation, and Parametric Study for Individual Reinforced Concrete Walls." Earthquake Engineering & Structural Dynamics, 45(9):1495–1513. https://doi.org/10.1002/eqe.2719.
3. Kurama, Y.C. 1997. "Seismic Analysis, Behavior, and Design of Unbonded Post-Tensioned Precast Concrete Walls." Ph.D. dissertation, Lehigh University, Bethlehem, PA.
4. Spieth, H.A., A.J. Carr, A.G. Murahidy, D. Arnolds, M. Davies, J.B. Mander. 2004. "Modelling of Post-Tensioned Precast Reinforced Concrete Frame Structures with Rocking Beam-Column Connections." Proceedings of the 2004 NZSEE Conference.

# Example assessment against experiments

Numerical validation.

| Specimen | Project | Scale | Height $h_w$ [m] | Width $b_w$ [m] | Aspect ratio $h_w/l_w$ | Total post-tensioning bar area [m$^2$] | Initial post-tensioning ratio $f_{psi}/f_{psu}$ | Total axial load ratio $P/(A_g f'_c)$ |
|---|---|---|---|---|---|---|---|---|
| Unit 1 | UOC 808 (Rahman and Restrepo (2000); Restrepo and Rahman (2007)) | 1/2 | 4.000 | 0.125 | 2.96 | $2.000 \times 10^{-4}$ | 0.500 | 0.030 |
| TW3 | CMS-93-07880 and CMS-96-12165 (Perez et al., 2004) | 5/12 and 1/2 for wall width | 9.906 | 0.152 | 3.90 | $4.839 \times 10^{-3}$ | 0.553 | 0.233 |
| 4S-Bld | NEES-2011-1083 (Zhang et al., 2018) | 1/2 | 9.220 | 0.203 | 4.32/5.34* | $1.690 \times 10^{-3}/1.020 \times 10^{-3}$ | 0.610/0.420 | 0.103/0.101 |

*For the 4S-Bld Specimen, pairs of reported values correspond to the EW and NS walls, respectively.

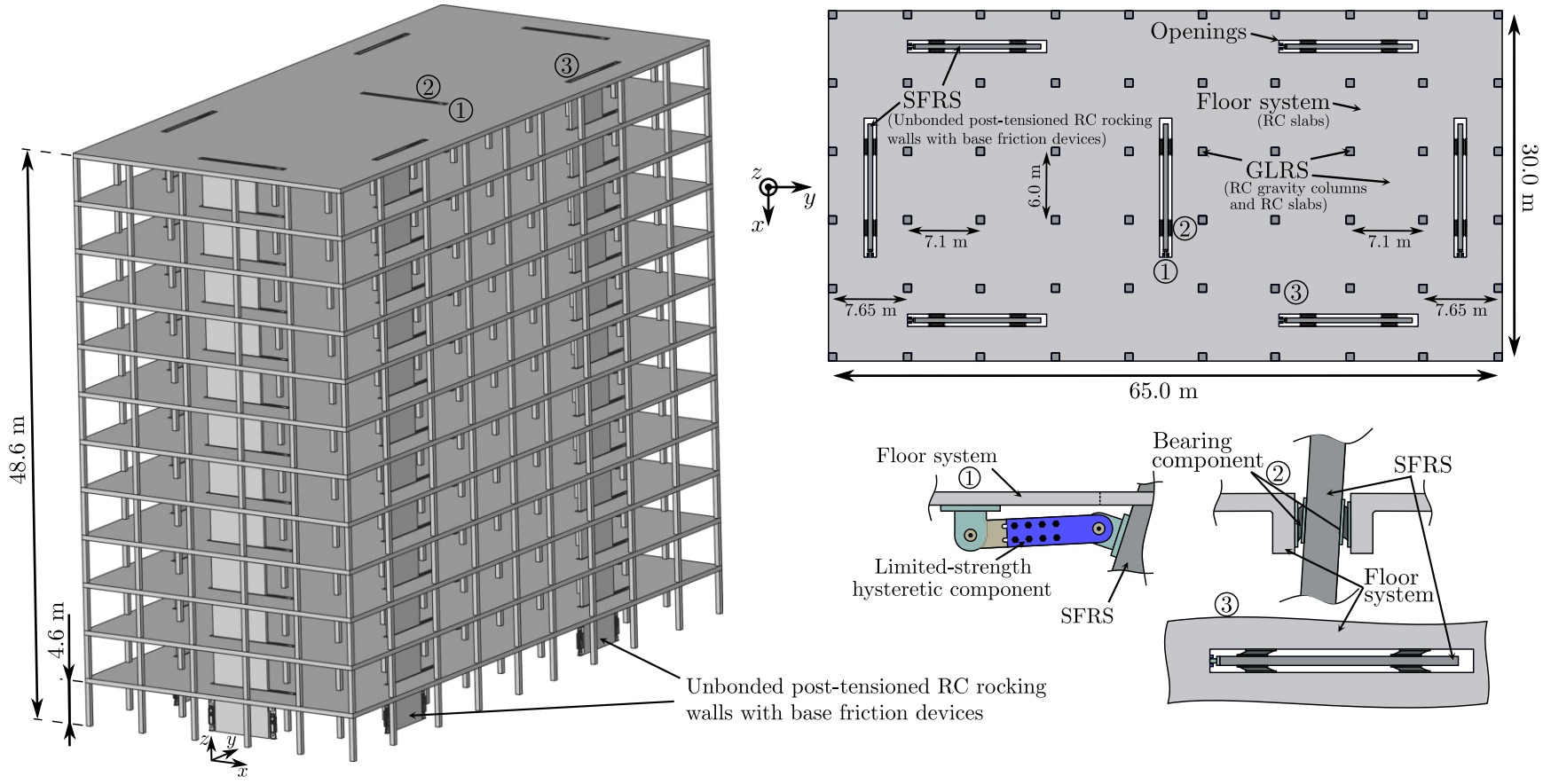



Source: Rahman and Restrepo (2000)


1. Rahman, A. M., and J. I. Restrepo-Posada. 2000. "Earthquake Resistant Precast Concrete Buildings: Seismic Performance of Cantilever Walls Prestressed Using Unbonded Tendons." University of Canterbury, Department of Civil Engineering. https://hdl.handle.net/10092/10702.
2. Restrepo, J. I., and A. Rahman. 2007. "Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators." Journal of Structural Engineering, 133(11): 1560–1570. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:11(1560).
3. Perez, F. J., S. Pessiki, and R. Sause. 2004. "Experimental and Analytical Lateral Load Response of Unbonded Post-Tensioned Precast Concrete Walls." Precast/Prestressed Concrete Institute. https://doi.org/10.15554/pci.rr.seis-008.
4. Zhang, Z., R. B. Fleischman, J. I. Restrepo, G. Guerrini, A. Nema, D. Zhang, U. Shakya, G. Tsampras, and R. Sause. 2018. "Shake-Table Test Performance of an Inertial Force-Limiting Floor Anchorage System." Earthquake Engineering & Structural Dynamics, 47(10): 1987–2011. https://doi.org/10.1002/eqe.3047.

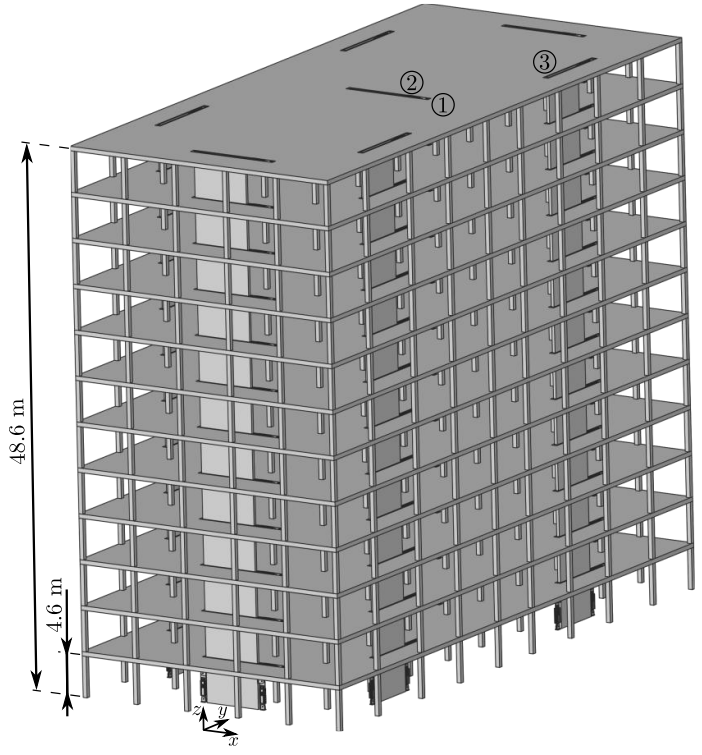
# Nonlinear Numerical Models

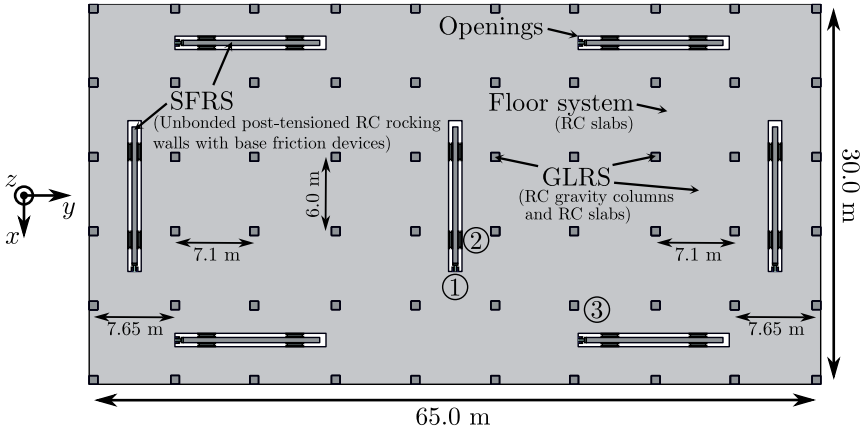
Case study: 12-story office building with unbonded post-tensioned RC rocking walls, base friction devices, and force-limiting connections.

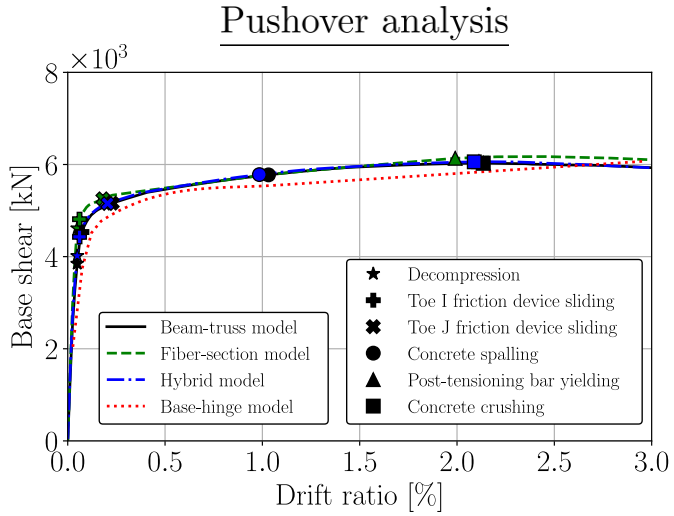


# Nonlinear Numerical Models

Case study: 12-story office building with unbonded post-tensioned RC rocking walls, base friction devices, and force-limiting connections.



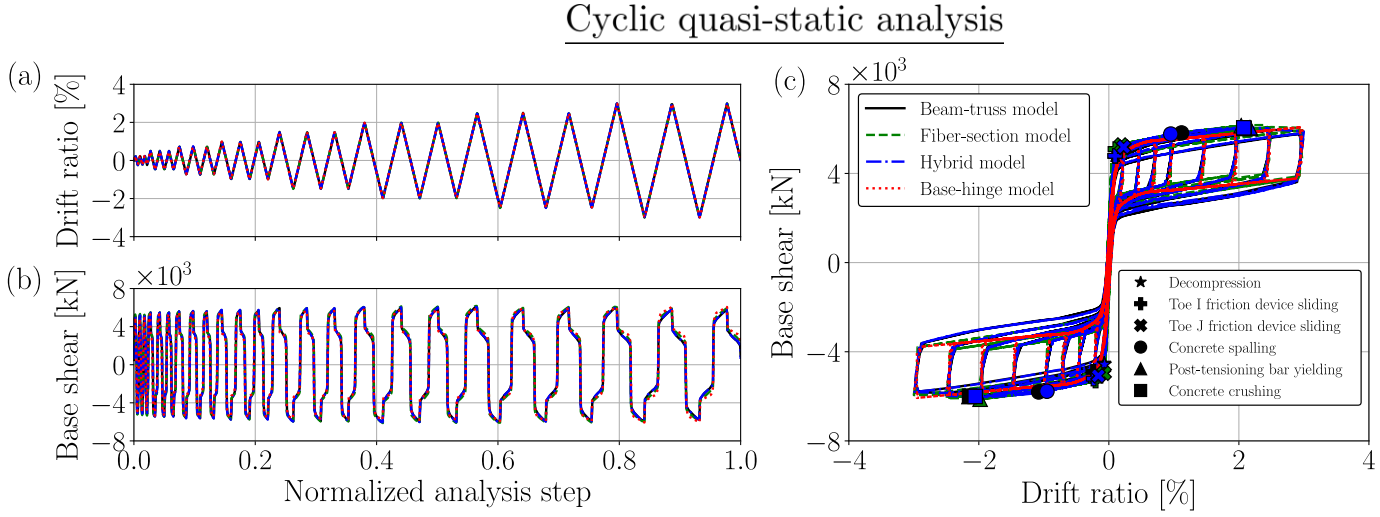




$h_w = 48.6$ m  $A_p = 0.00230$ m$^2$ $(\times 5)$

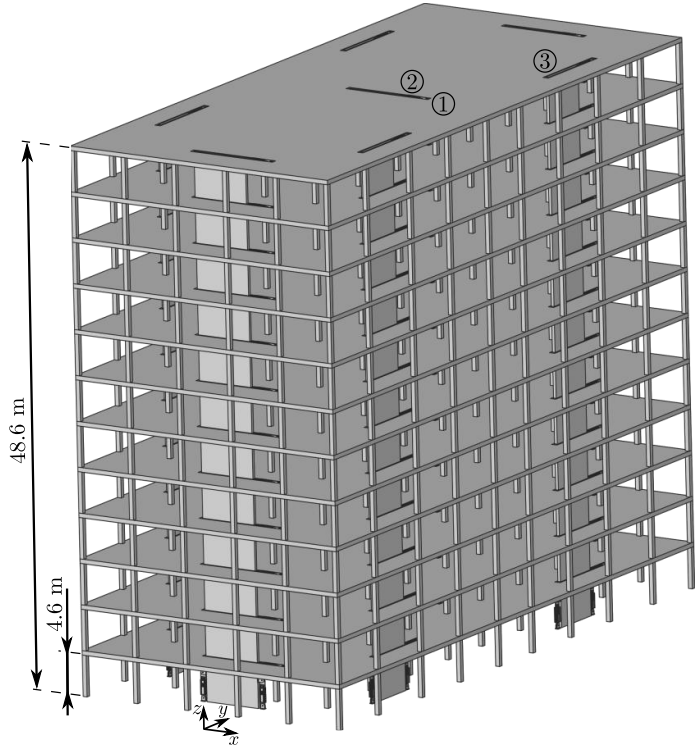
$l_w = 14.4$ m  $f_{pi}/f_{pu} = 65.0\%$

$b_w = 0.55$ m  $\beta_{rw} = 0.5$



# Nonlinear Numerical Models

The base-hinge model balances accuracy and computational efficiency considering the required limits states need to be captured in this project.

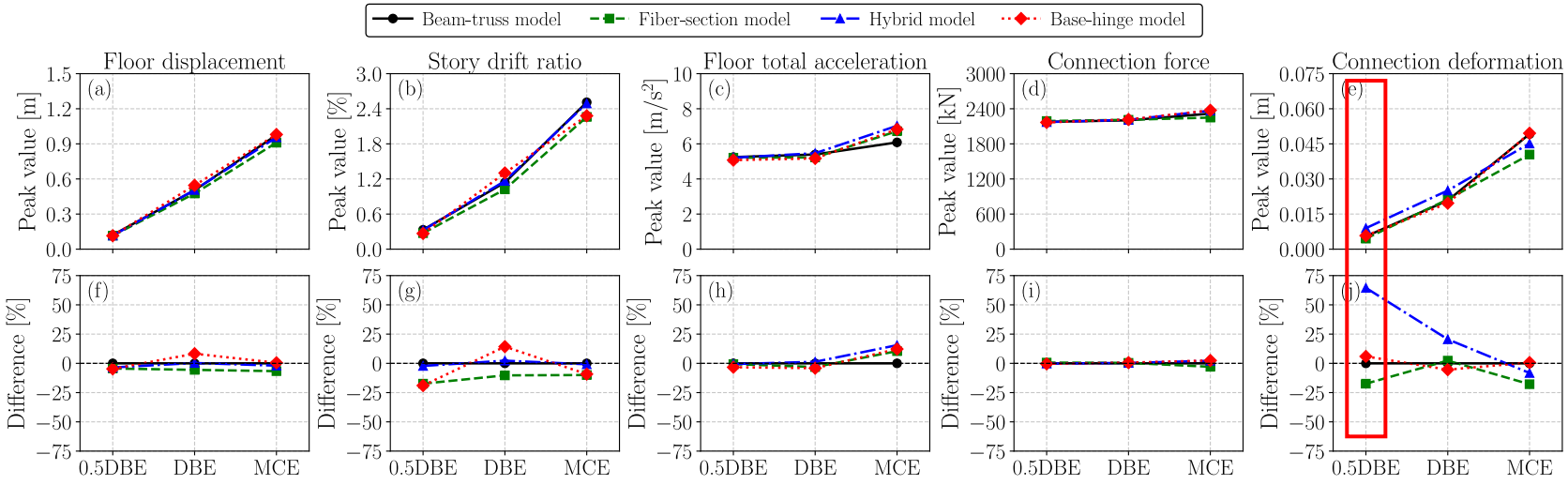



$h_w = 48.6$ m  $A_p = 0.00230$ m$^2$ $(\times 5)$

$l_w = 14.4$ m  $f_{pi}/f_{pu} = 65.0\%$

$b_w = 0.55$ m  $\beta_{rw} = 0.5$

Numerical earthquake simulations




(2D numerical models)

Speedups relative to Beam-truss model results

| Earthquake intensity | Beam-truss Time [min] | Fiber-section Time [min] | Fiber-section Speedup [-] | Hybrid Time [min] | Hybrid Speedup [-] | Base-hinge Time [min] | Base-hinge Speedup [-] |
|---|---|---|---|---|---|---|---|
| 0.5 DBE | 645.2 | 27.2 | 23.7 | 129.9 | 5.0 | 19.0 | 34.0 |
| DBE | 471.4 | 27.2 | 17.3 | 162.4 | 2.9 | 18.4 | 25.6 |
| MCE | 421.1 | 28.8 | 14.6 | 185.6 | 2.3 | 18.6 | 22.6 |
| Average | **512.6** | 27.7 | 18.5 | 159.3 | 3.4 | 18.7 | **27.4** |

# Parametric earthquake numerical simulations

Structural performance and design

i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

Recovery Assessment

i. Damage Simulation.
ii. Assessment of functional recovery.
iii. Recovery Modeling Framework.
iv. Impeding Factors and Repair Delays.
v. Functional Recovery Trajectories.
vi. Resilience Metrics.
vii. Sensitivity Analysis of Component Damage.

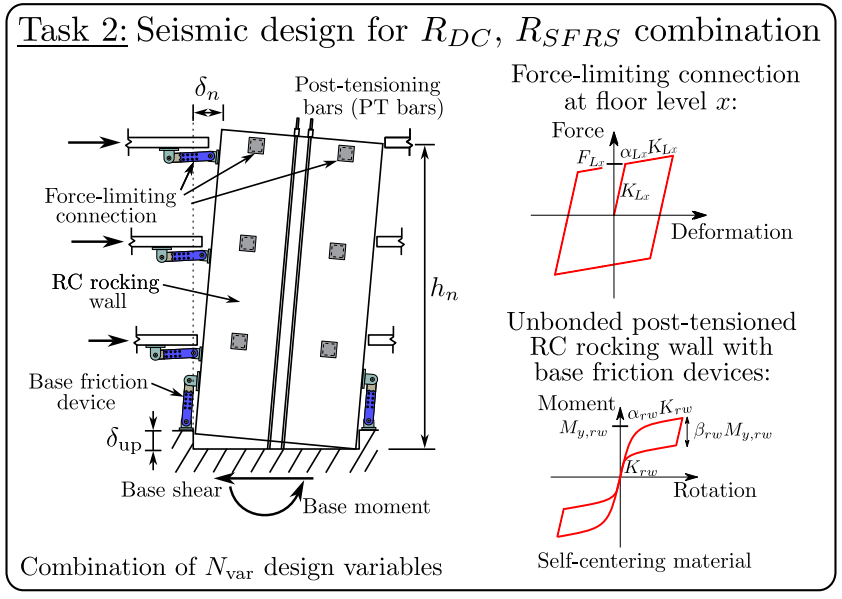
# Parametric Analysis of seismic response

TACC
TEXAS ADVANCED COMPUTING CENTER

Systematic parametric analysis to compute engineering demand parameters.

Computed engineering demand parameters are used as input to the recovery assessment framework.

- **Parametric analysis:** 16 building archetypes, 40 ground motions, 4 earthquake-intensity levels, 2 response modification factors, and 5 component-level design variables.
- **16,588,800 nonlinear numerical earthquake simulations**. (Nonlinear simulations performed on TACC Stampede3)




| Parameter | Definition | Values |
|---|---|---|
| **Earthquake intensity level** | | |
| $r_{SF_{gm}}$ | Ground-motion intensity factor applied to the DBE earthquake level | {0.50, 0.75, 1.00, 1.50} |
| **Seismic response modification factors** | | |
| $R_{DC}$ | Connection response modification factor | {1.00, 1.50, 2.00, 2.50, 3.00} |
| $R_{SFRS}$ | SFRS response modification factor | {0.75, 1.00, 1.50, 2.00} |
| **Rocking-wall design-variable factors** | | |
| $r_{K_{rw}}$ | Factor applied to the reference rocking-wall elastic stiffness, $K_{rw}^{\text{ref}}$ | {0.75, 1.00, 1.25} |
| $r_{\alpha_{rw}}$ | Factor applied to the reference rocking-wall post-elastic stiffness ratio, $\alpha_{rw}^{\text{ref}}$ | {0.75, 1.00, 1.25} |
| $r_{\beta_{rw}}$ | Factor applied to the reference base friction-device contribution to the rocking-wall base moment strength, $\beta_{rw}^{\text{ref}}$ | {0.25, 0.50, 1.00, 1.50} |
| **Force-limiting-connection design-variable factors** | | |
| $r_{K_{Lx}}$ | Factor applied to the reference connection elastic stiffness, $K_{Lx}^{\text{ref}}$ | {0.75, 1.00, 1.25} |
| $r_{\alpha_{Lx}}$ | Factor applied to the reference connection post-elastic stiffness ratio, $\alpha_{Lx}^{\text{ref}}$ | {0.50, 1.00, 1.50} |

# Recovery Assessment

Structural performance and design

i. Building archetypes.
ii. Unified force distribution.
iii. Numerical models for earthquake simulations.
iv. Definition of Damage Limit States.
v. Ground Motion Selection and Scaling.
vi. Parametric earthquake numerical simulations.

Recovery Assessment

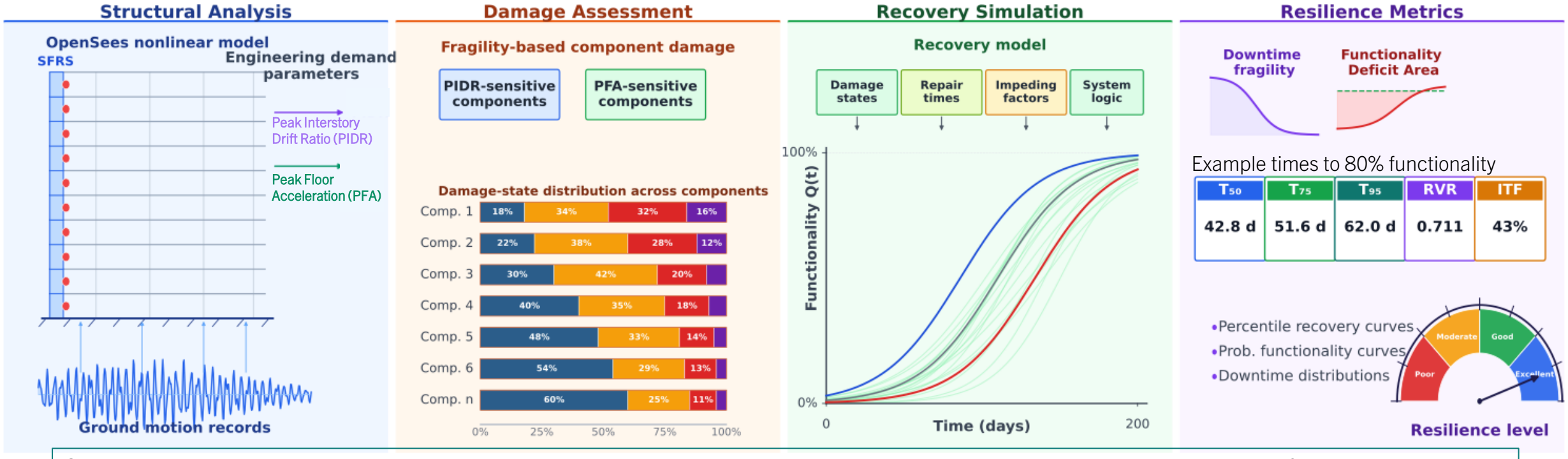
i. Damage Simulation.
ii. Assessment of functional recovery.
iii. Recovery Modeling Framework.
iv. Impeding Factors and Repair Delays.
v. Functional Recovery Trajectories.
vi. Resilience Metrics.
vii. Sensitivity Analysis of Component Damage.

# Recovery Assessment Framework

An integrated performance-based probabilistic framework with a recovery engine that uses as input the computed engineering demand parameters to generate ensembles of functionality trajectories and evaluate distribution-based resilience metrics.

| Category | Occupancy | $T_{80}$ (days) Target |
|---|---|---|
| A | Medical | 5 days |
| C | Commercial | 180 days |
| D | Residential | 180 days |
| E | Data center | 30 days |

75% probability of not exceeding the listed time to reach 80% functionality ($T_{80}$).

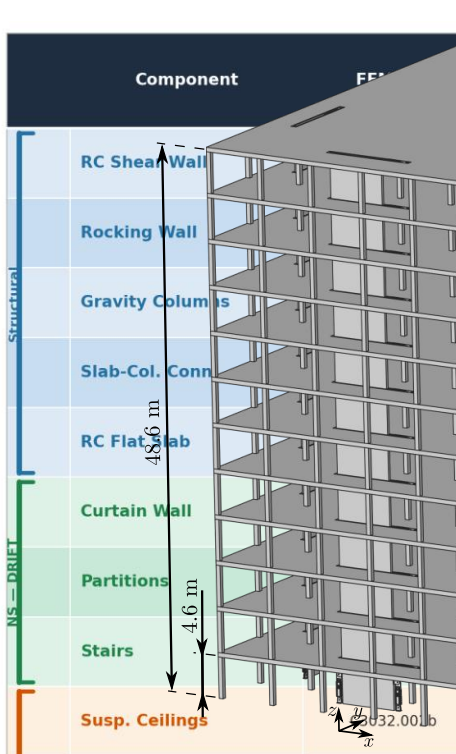



Structural uncertainty propagates into recovery uncertainty; last step translates nonlinear response into occupancy-specific recovery-based design guidance.

# Case Study - Selected Results

## 12-story office building (Commercial)

- Three systems:
  - RC wall,
  - Rocking Wall (RE),
  - Rocking Wall (FLC)
- Ground motions: 18 far-field records with
  - 0.5DBE
  - DBE
  - MCE hazard level.
- Component inventory:
  - Structural components
  - Drift-sensitive
  - Acceleration-sensitive nonstructural components




| Component | | | | | | | DS Columns | RC | RE | FLC |
|---|---|---|---|---|---|---|---|---|---|---|
| Structural | RC Shear Wall | | | | | | 4 (DS1–4) | ✓ | — | — |
| | Rocking Wall | | | | | | 4 (DS1–4) | — | ✓ | ✓ |
| | Gravity Columns | | | | | | 4 (DS1–4) | ✓ | ✓ | ✓ |
| | Slab-Col. Conn. | | | | | | 4 (DS1–4) | ✓ | ✓ | ✓ |
| | RC Flat Slab | | | | | | 4 (DS1–4) | ✓ | ✓ | ✓ |
| NS — DRIFT | Curtain Wall | | | | | | 4 (DS1–4) | ✓ | ✓ | ✓ |
| | Partitions | | | | | | 4 (DS1–4) | ✓ | ✓ | ✓ |
| | Stairs | | | | 12 | 2 | 24 | 3 (DS1–3) | ✓ | ✓ | ✓ |
| NS — ACC | Susp. Ceilings | D3032.001b | PFA | 1–12 | 700 | 8,400 | 3 (DS1–3) | ✓ | ✓ | ✓ |
| | HVAC Ducting | D3041.011c | PFA | 1–12 | 1,000 | 12,000 | 3 (DS1–3) | ✓ | ✓ | ✓ |
| | Sprinklers | D4011.021a | PFA | 1–12 | 120 | 1,440 | 3 (DS1–3) | ✓ | ✓ | ✓ |
| | Elevator | D1014.011 | PFA | 12 | 2 | 2 | 4 (DS1–4) | ✓ | ✓ | ✓ |
| | pipe | 011a | PFA | 1–12 | 11 | 132 | 2 (DS1–2) | ✓ | ✓ | ✓ |
| | Plumbing bra | D2021.011a | PFA | 1–12 | 11 | 132 | 1 (DS1) | ✓ | ✓ | ✓ |

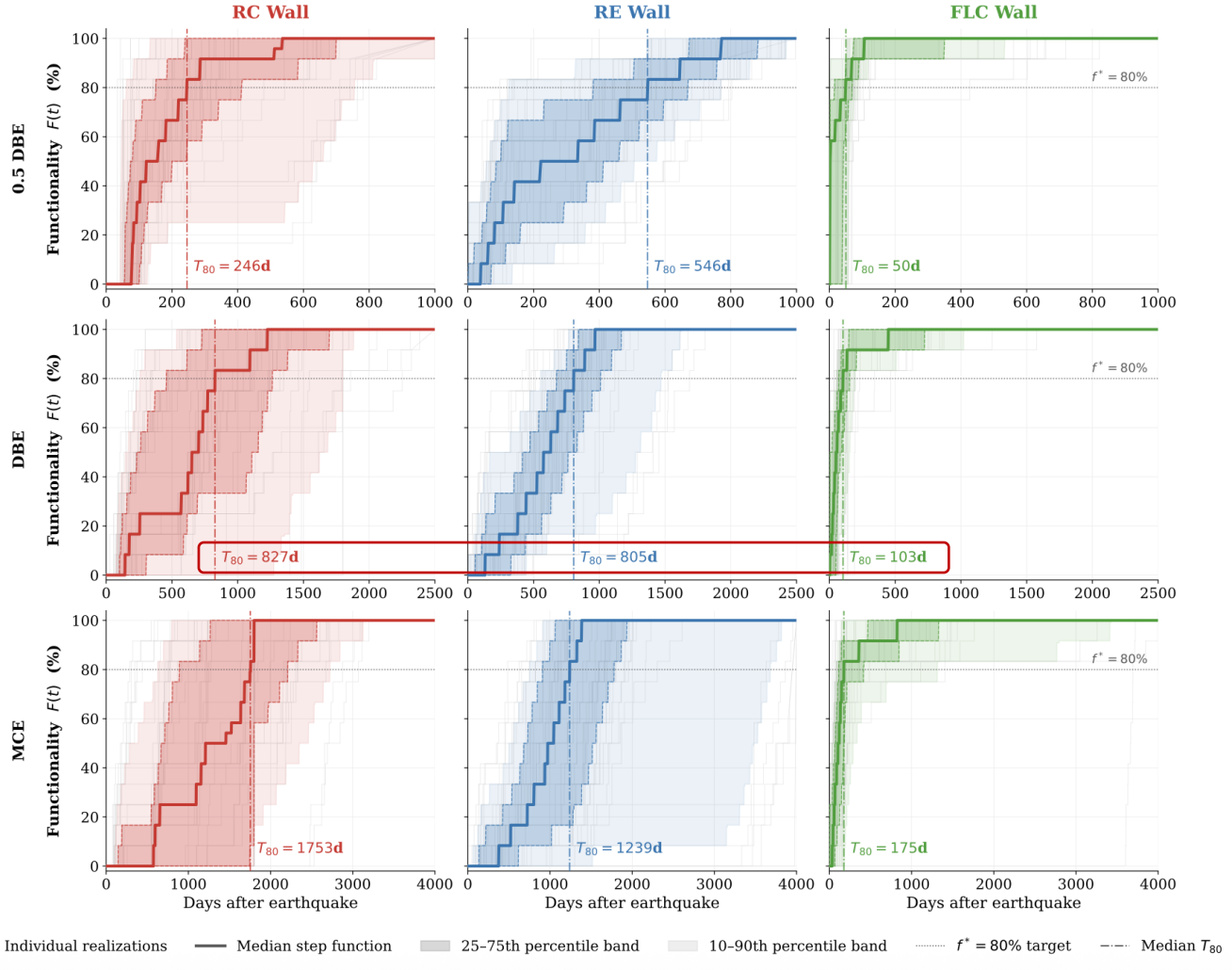
- N = 18,000 MC realizations per configuration/hazard level
- Total replacement value $56.4M
- 50 occupants/floor

# Recovery Trajectories & Percentile Curves

- RC Wall reaches 80% functionality at 827 days · Rocking RE at 805 days · Rocking FLC at 103 days (median at DBE level)
- Only Rocking FLC meets the Commercial FR target of 80% functionality by Day 180.

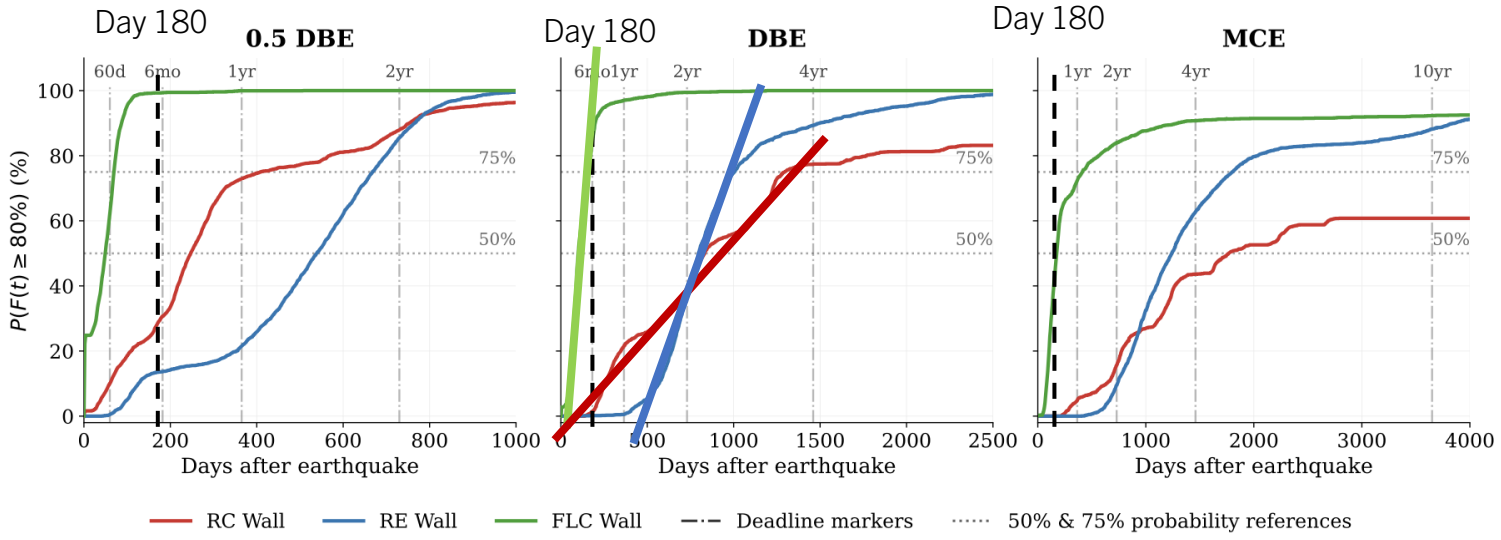
**Why 80% functionality?**

- Based on discussions with researchers and practitioners involved in functional recovery initiatives.
- Consistent with ongoing efforts to develop functional recovery provisions (e.g., proposed Appendix A to ASCE 7).



# Probabilistic functionality curves

- P(F≥80%) at Day 180: RC Wall = 2% · Rocking RE = 1% · Rocking FLC = 84%
- The higher slope of FLC system curves reflects predictability; not just faster recovery, but more reliable recovery.




| System | P(F>= 80%) |
|---|---|
| RC Wall | 2% |
| Rocking Wall (RE) | 1% |
| Rocking Wall (FLC) | 84% |

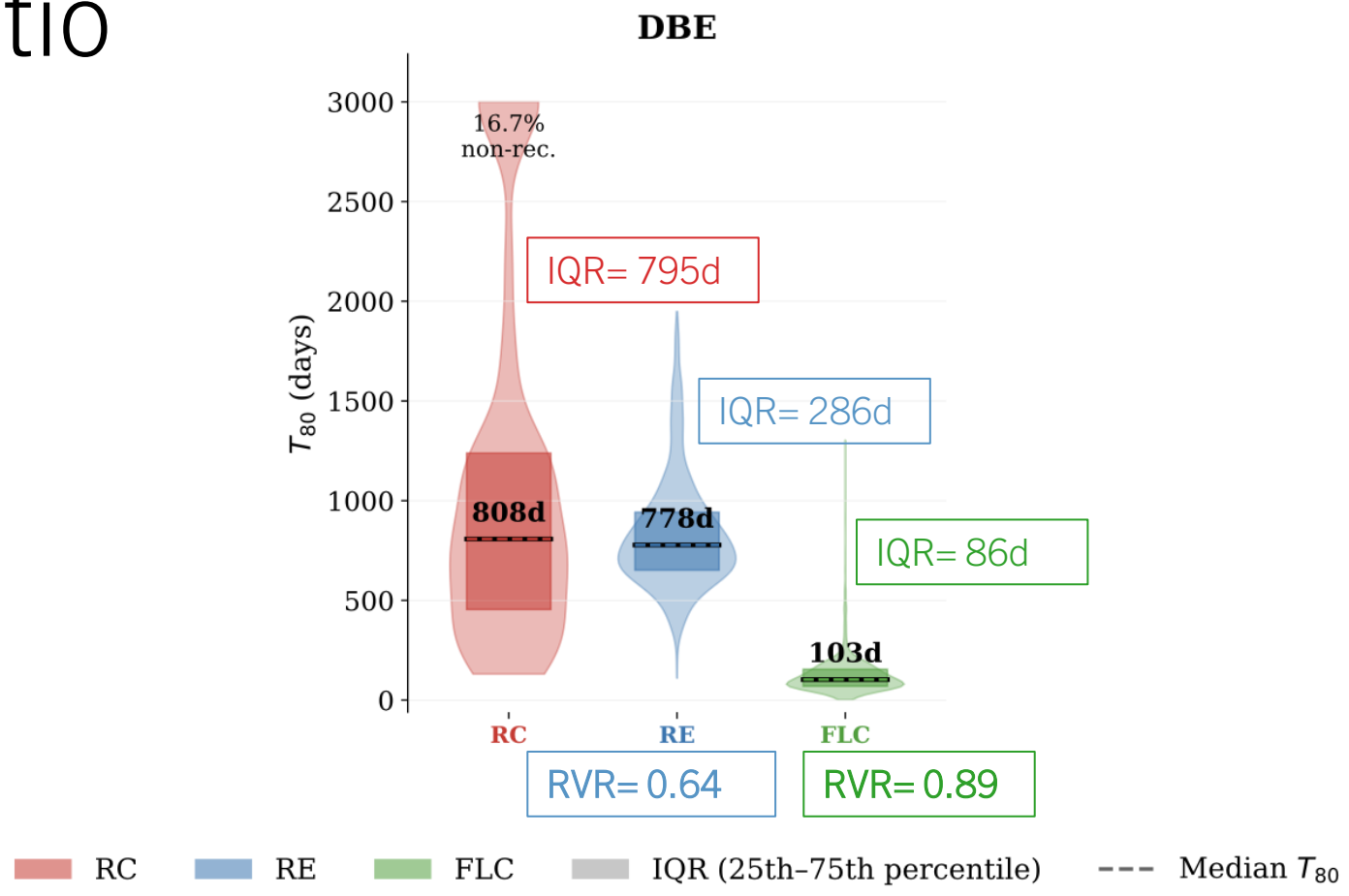
# Recovery Variability Ratio

$RVR_{80} = 1 - \frac{IQR(T_{80})_i}{IQR(T_{80})_{REF}}$, where

$IQR(T_{80})_i$ corresponds to interquartile range for time to reach $80\%$ function for different designs

*where* $i \in$ [*RC, RE, FLC*] *and REF* $\equiv$ *RC*

☛ RVR ranges from 0 to 1, where 0 indicates no reduction in recovery variability relative to the reference system, and 1 indicates complete elimination of variability.




**89% Reduction** in recovery variability

# Example correlation of recovery targets with design variables for DBE level earthquakes

| Category | Occupancy | $T_{80}$ Target |
|---|---|---|
| A | Medical | 5 days |
| C | Commercial | 180 days |
| D | Residential | 180 days |
| E | Data center | 30 days |

**Objective:** Identify design parameters that satisfy functional recovery targets for a given occupancy, hazard level, and building archetype.

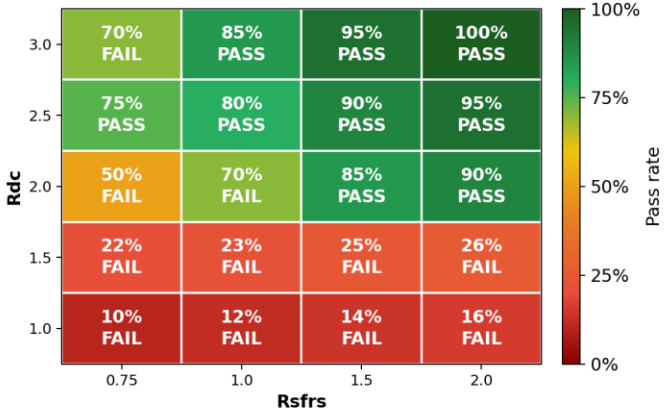
Analysis space:

- 16 archetypes (4 occupancies x 4 story numbers
- 40 ground motions,
- 4 earthquake-intensity levels,
- 2 response modification factors
- 5 component-level design variables

**Recovery target**: $P(F \geq 80\% \text{ @ } T_{80}) \geq 0.75$: probabilistic pass/fail per design point

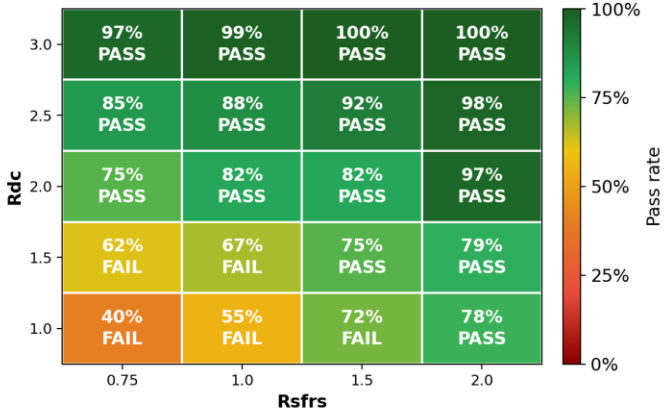
Office (Cat C)

$P(F \geq 80\% \text{ @ } T80) \geq 0.75$



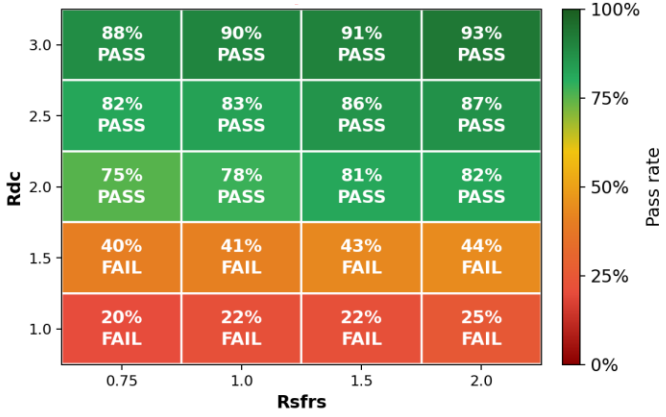

Residential (Cat D)

$P(F \geq 80\% \text{ @ } T80) \geq 0.75$



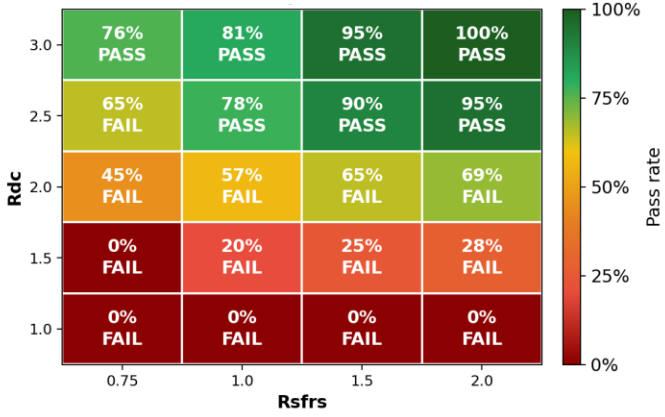

Medical (Cat A)

$P(F \geq 80\% \text{ @ } T80) \geq 0.75$




Data center (Cat E)

$P(F \geq 80\% \text{ @ } T80) \geq 0.75$



# Preliminary conclusions

- It is possible to design buildings with floor-to-wall force limiting connections and controlled base rocking mechanism considering performance and recovery objectives.
- Recovery performance becomes an achievable explicit design constraint rather than a post-analysis metric.
- The proposed system design results in faster recovery times with higher confidence / less variability compared to conventional RC and Rocking wall buildings.

# Ongoing Work

- Functional-recovery-based design relationships considering the design variables, building archetypes and earthquake intensity levels.
- Systematic procedure for selecting response modification factors and associated design variables using the functional-recovery-based design relationships and owner-defined target performance limits.
- Validate the proposed methodology through independent building designs.

August 18, 2026
NIST | NSF | Disaster Resilience Research Grant Symposium

# Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery [2024 – 2027]



Georgios Tsampras, gtsampras@ucsd.edu


Paolo Bocchini, paolo.bocchini@lehigh.edu


Franco Mayorga, cfmayorg@ucsd.edu


Sena Mursel, sem419@lehigh.edu


Thank you!

http://tsampras.ucsd.edu
http://www.paolobocchini.com