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

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UC San Diego

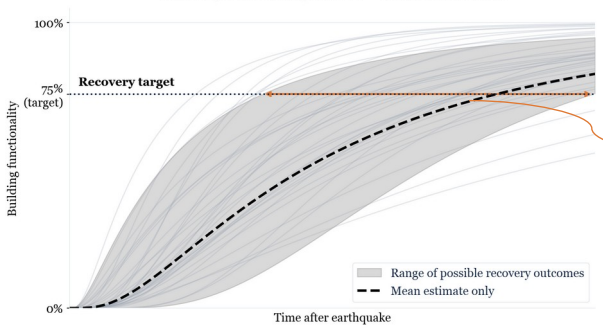


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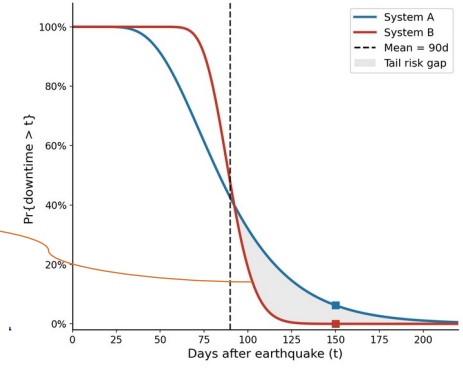
Project Overview & Motivation

- Buildings designed to life-safety standards regularly survive earthquakes structurally intact yet remain closed for weeks or months due to nonstructural damage.
- 1994 Northridge & 2011 Christchurch: buildings closed for months despite surviving structurally.
- Despite growing policy momentum e.g., FEMA P-2090, NIST/FEMA 2021 quantitative probabilistic frameworks for building-level functional recovery are still maturing.
- Existing frameworks produce mean recovery estimates and variability, tail risk, and worst-case outcomes may remain unquantified.



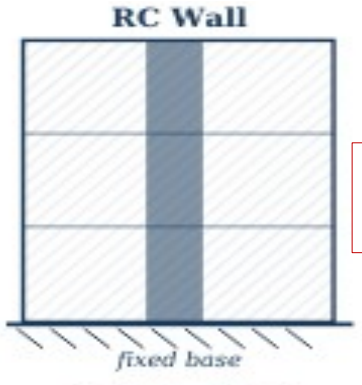


When can we achieve the **recovery target** and with what **level of confidence**?



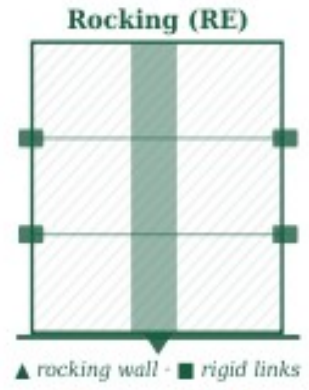
Research Question: How do FLCs influence not just typical **recovery speed**, but the **spread** and **predictability** of recovery outcomes?

Structural systems considered



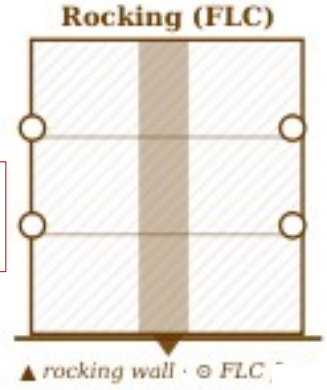
- **Conventional fixed-base wall. Absorbs seismic energy through cracking and yielding, transmitting high floor accelerations to all nonstructural components.**

Limitation: Large IDR



- **Post-tensioned rocking wall. Self-centering behavior reduces residual drift, but floor accelerations remain high so nonstructural damage is not reduced.**

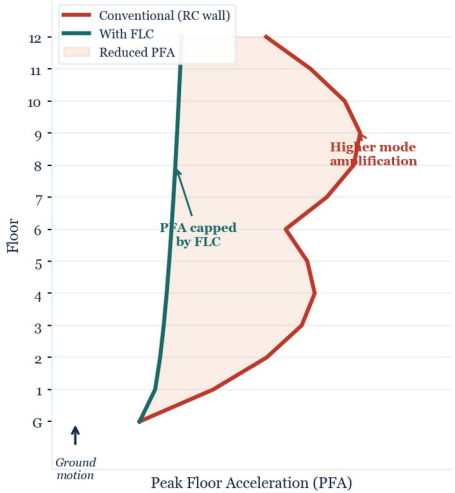
Limitation: Large forces

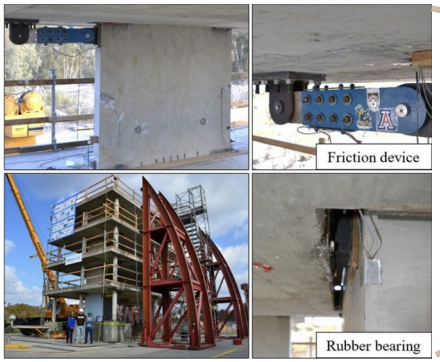


- **Rocking wall with force-limiting connections at each floor. FLC devices activate at a design threshold, capping floor accelerations and protecting acceleration-sensitive components.**

Structural systems considered

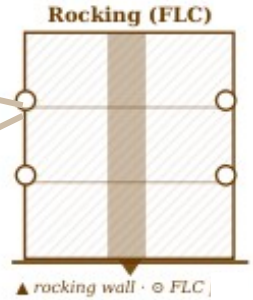
- A conventional RC shear wall resists lateral forces through stiffness. It absorbs seismic energy by **cracking and yielding** but transmits high floor accelerations to every nonstructural component.
- A rocking wall with FLC devices decouples the wall from the floor diaphragm. The **wall rocks at its base** (self-centering), and the FLC devices activate at a design force threshold; **capping the floor accelerations** that drive nonstructural damage.





- Friction device activates at design force that **limits force transfer to floor.**
- Two components: friction device (activates at FL, limits force) + rubber bearings (out-of-plane stability, post-elastic stiffness)

✓ FLC reduces PFA sensitivity from **46.9% → 2.2%** relative to conventional connections.



- Force-limiting connections
- Reduced force and acceleration demands
- Low IDR
- Low PFA
- Nonstructural damage reduced

Recovery Assessment Framework

An integrated PBEE-based probabilistic framework couples nonlinear structural simulations with a recovery engine to generate ensembles of functionality trajectories and evaluate distribution-based resilience metrics.

Category	Occupancy	T_{75} (days) Target
A	Medical	5 days
C	Commercial	60 days
D	Residential	180 days
E	Data center	60 days



Takeaway: Structural uncertainty propagates into recovery uncertainty; Step 4 translates nonlinear response into occupancy-specific recovery-based design guidance.

Case1: 12-story office building

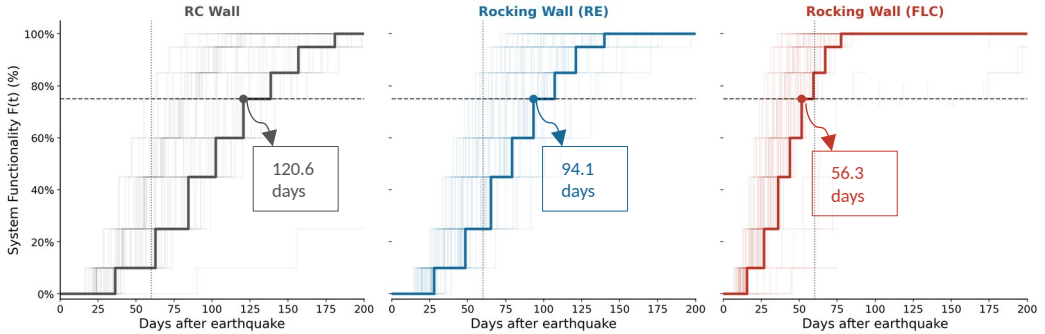
- Three systems:
  - RC wall,
  - Rocking Wall (RE),
  - Rocking Wall (FLC)
- Ground motions: 18 far-field records with
  - 0.5DBE
  - DBE
  - MCE hazard level.
- Component inventory:
  - Structural components
  - Drift-sensitive
  - Acceleration-sensitive nonstructural components



	Component	FEMA ID	EDP	Floors	Qty /Floor	Total Qty	DS Columns	RC	RE	FLC
Structural	RC Shear Wall	B1043.001	IDR	1–12	6	72	4 (DS1–4)	✓	—	—
	Rocking Wall	Custom	θ roof	1–12	6	72	4 (DS1–4)	—	✓	✓
	Gravity Columns	B1041.001	IDR	1–12	60	720	4 (DS1–4)	✓	✓	✓
	Slab-Col. Conn.	B1049.031	IDR	1–12	60	720	4 (DS1–4)	✓	✓	✓
	RC Flat Slab	B1049.001	IDR	1–12	20	240	4 (DS1–4)	✓	✓	✓
NS — DRIFT	Curtain Wall	B2022.001	IDR	1–12	20	240	4 (DS1–4)	✓	✓	✓
	Partitions	C1011.001a	IDR	1–12	20	240	4 (DS1–4)	✓	✓	✓
	Stairs	B1031.001	IDR	1–12	2	24	3 (DS1–3)	✓	✓	✓
NS — ACCE	Susp. Ceilings	C3032.002b	PFA	1–12	700	8,400	3 (DS1–3)	✓	✓	✓
	HVA	D3041.011c	PFA	1–12	1,000	12,000	3 (DS1–3)	✓	✓	✓
	Spri	011.021a	PFA	1–12	120	1,440	3 (DS1–3)	✓	✓	✓
	tors	1014.011	PFA	12	2	2	4 (DS1–4)	✓	✓	✓
	Plumbing	D2021.011a	PFA	1–12	11	132	2 (DS1–2)	✓	✓	✓
	brace	D2021.011a	PFA	1–12	11	132	1 (DS1)	✓	✓	✓

Recovery Trajectories & Percentile Curves

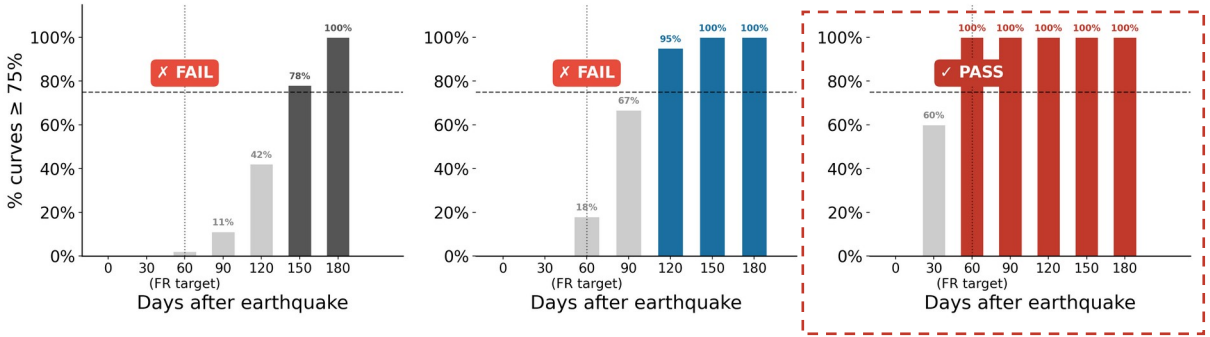
- 25th percentile curves.
- RC Wall reaches 75% functionality at 120.6 days · Rocking RE at 94.1 days · Rocking FLC at 56.3 days (25th pct)
- Only Rocking FLC meets the Commercial FR target of 75% functionality by Day 60.



★ Why 75% 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).
- ATC-138 does not prescribe a functionality threshold.
- FEMA P-2090 / NIST SP-1254 (2021) defines recovery objectives but not a quantitative functionality level.

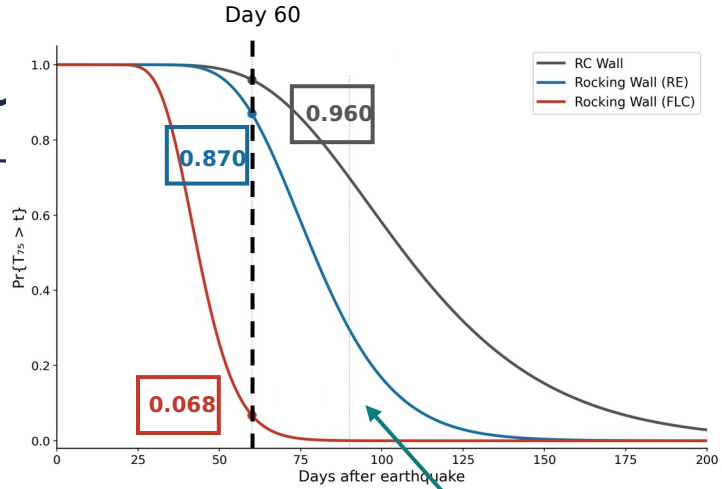
Target: Reaching to 75% functionality by

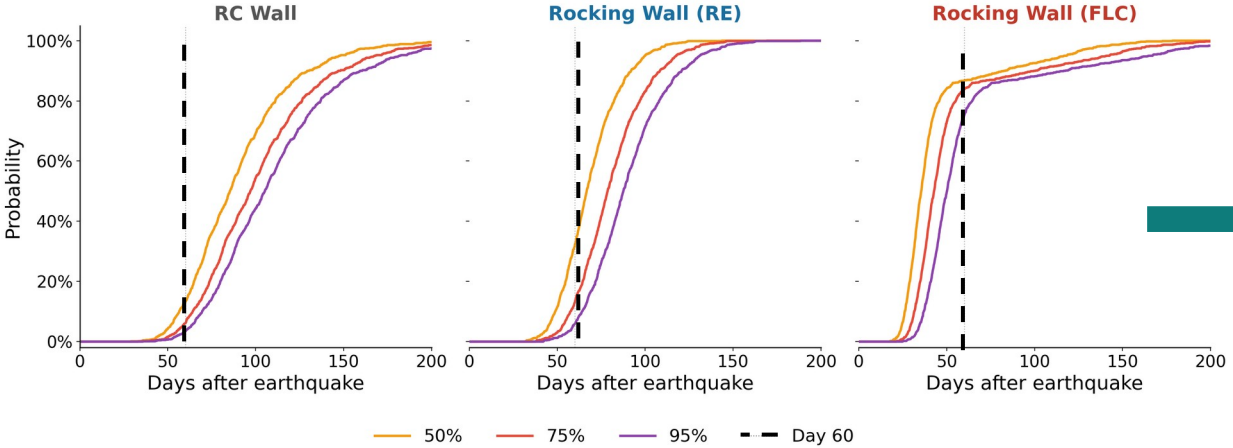


Target reached

Probabilistic functionality cu

- P(F≥75%) at Day 60: RC Wall = 4.0% · Rocking RE = 13.0% · Rocking FLC = 93.2%
- At the Commercial FR deadline, FLC has a ~20× higher probability of meeting the target than RC Wall
- The tight spread of FLC curves reflects predictability; not just faster recovery, but more reliable recovery.

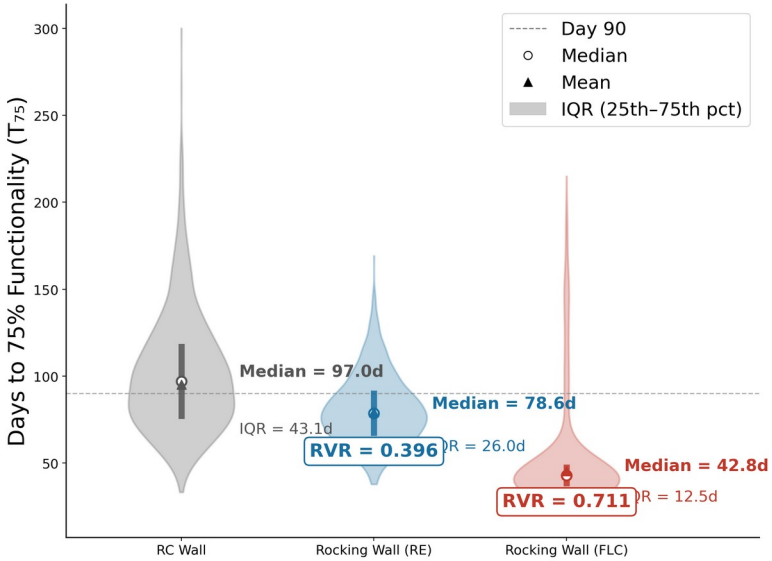




System	P(F>=50%)	P(F>=75%)	P(F>=95%)
RC Wall	7.3%	**4.0%**	2.1%
Rocking Wall (RE)	24.5 %	**13.0 %**	6.4%
Rocking Wall (FLC)	97.7 %	**93.2 %**	83.8%

Recovery Variability Ratio and Impedance Time Fraction

- Recovery Variability Ratio: $\mathrm{RVR_p} = 1 - \frac{\mathrm{IQR(T_P)_i}}{\mathrm{IQR(T_P)_{REF}}}$, where $\mathrm{IQR(T_P)_i}$ corresponds to interquartile range for time to reach $p\%$ function for different designs.
- Impeding Time Fraction: $\mathrm{ITF} = t_{\mathrm{imp}}/t_{\mathrm{total}}$, where t_{imp} is impeding time.

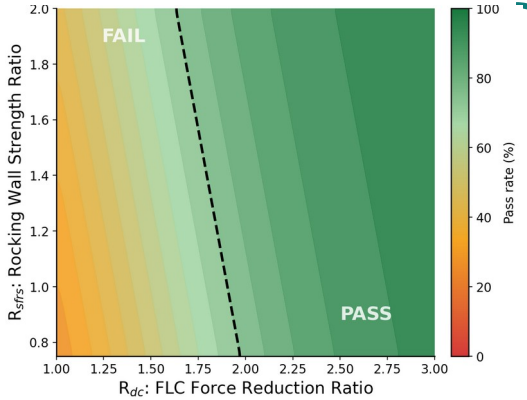


71% Reduction in recovery variability

Not only the repair time but also impeding times due to administrative delays are substantially decreased.

Parametric analysis for design

- ~~Design variables:~~
  - **Rdc: controlling the ductility and force reduction from the deformable connection**
  - **Rsfrs: controlling the seismic-force-resisting system**
  - Other FLC and rocking-wall properties
- Analysis space:
  - 4 occupancy types × 4 archetypes × 4 hazard levels × multiple design combinations
  - Criterion: P(F≥75% @ T_target) ≥ 0.75: probabilistic pass/fail per design point

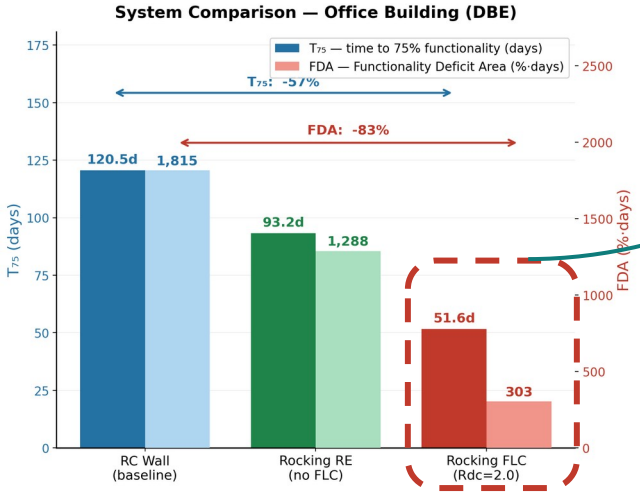


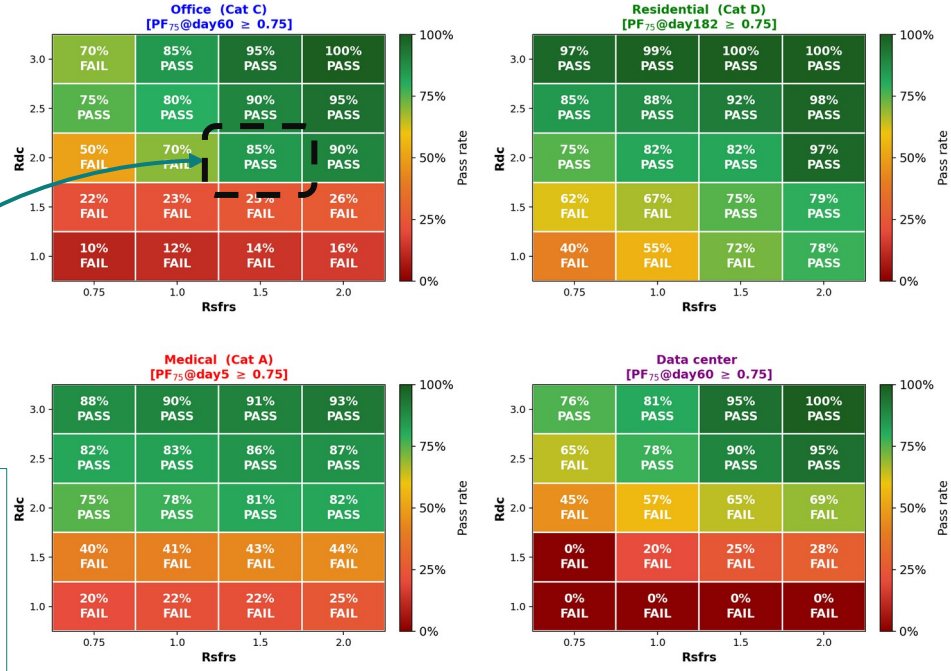
Category	Occupancy	T_{75} Target
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Objective: Identify design parameters that satisfy functional recovery targets for a given occupancy, hazard level, and building archetype.

Parametric analysis for design

- 8 design parameters define the FLC building configuration.
- Recovery performance evaluated for 4 occupancies (office, residential, medical, data center).
- Functional recovery targets depend on occupancy type.
- Recovery metrics used to identify acceptable



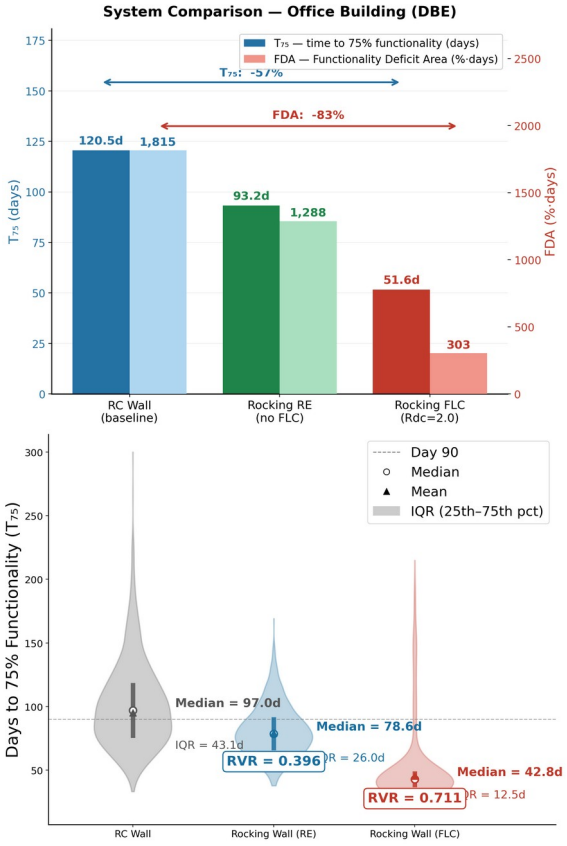


Each design configuration is evaluated based on the probability of meeting the target recovery objective.

Takeaway: Recovery targets can be used as explicit design constraints to identify acceptable regions of the parameter space.

Conclusions

- **A probabilistic framework was developed to translate structural response into functionality trajectories, recovery metrics, and occupancy-specific recovery targets.**
  - Integrates nonlinear analysis, component fragilities, and recovery simulation.
  - Produces distributions of recovery outcomes rather than single estimates.
  - Enables explicit quantification of recovery uncertainty through distribution-aware metrics.
- **Force-limiting connections substantially accelerate functional recovery**
  - Acceleration-sensitive damage is significantly reduced.
  - Time to 75% functionality decreases from 120.5 days to 51.6 days.
  - FLC is the only configuration that satisfies the 60-day commercial recovery target.
- **Force-limiting connections improve recovery predictability.**
  - Recovery outcomes become substantially more predictable.
  - Recovery Variability Ratio indicates a 71% reduction in recovery-time variability.
  - Probabilistic functionality curves show a much higher likelihood of meeting recovery objectives.
- **Recovery objectives can be incorporated directly into structural design.**



Thank you!

Component Damage State Distribution

- Plumbing, Elevators, HVAC, Sprinklers, Ceilings: FLC: 58–100% no damage vs. 10–16% for RC Wall
- Stairs, Partitions, Curtain Wall: Drift-sensitive: slight improvement in FLC
- Structural components: slight improvement in FLC

- **FLC benefits are primarily concentrated in acceleration-sensitive systems, which are the primary drivers of recovery delay and impeding time.**

