UNIVERSITY OF WATERLOO

CANADIAN WOOD CONSTRUCTION RESEARCH NETWORK

NSERC Alliance Project ‘Next-generation Wood Construction’

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Functional Recovery Assessment of CLT shear-wall and Glulam Moment-resisting Frame (CLTW-GMRF) System

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Supervisor: Dr. Solomon Tesfamariam (Professor, University of Waterloo)

Outline

- Introduction.
- Development and Assessment of CLTW-GMRF System.
- Damage Fragility and Consequence Functions.
- Assessment Methodology.
- Results.
- Conclusion.
- References.

Introduction

FEMA P-58 Seismic Loss Assessment Methodology

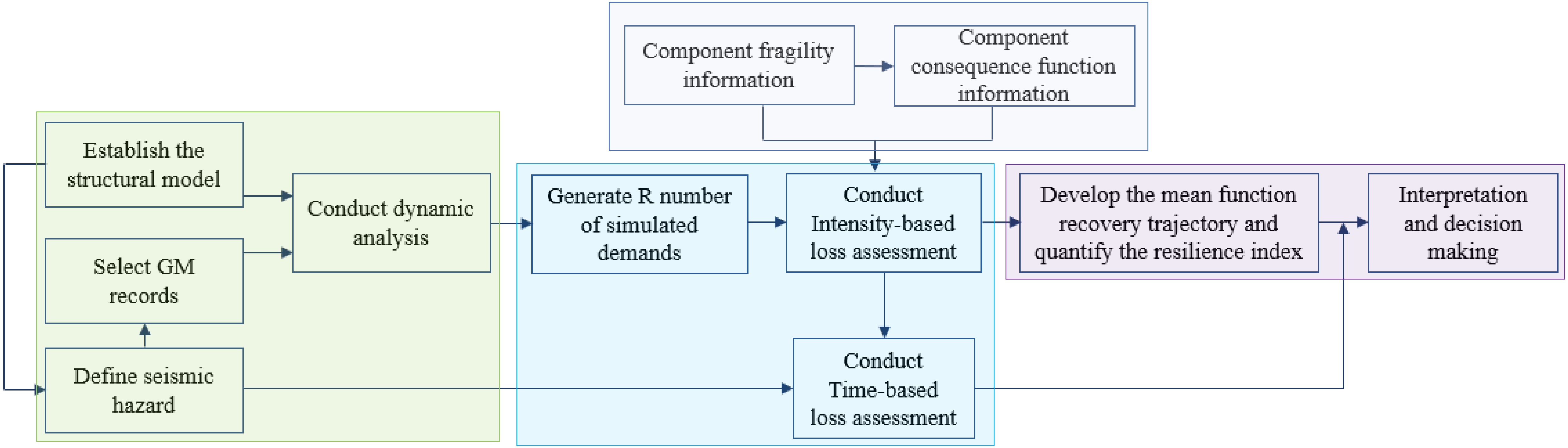
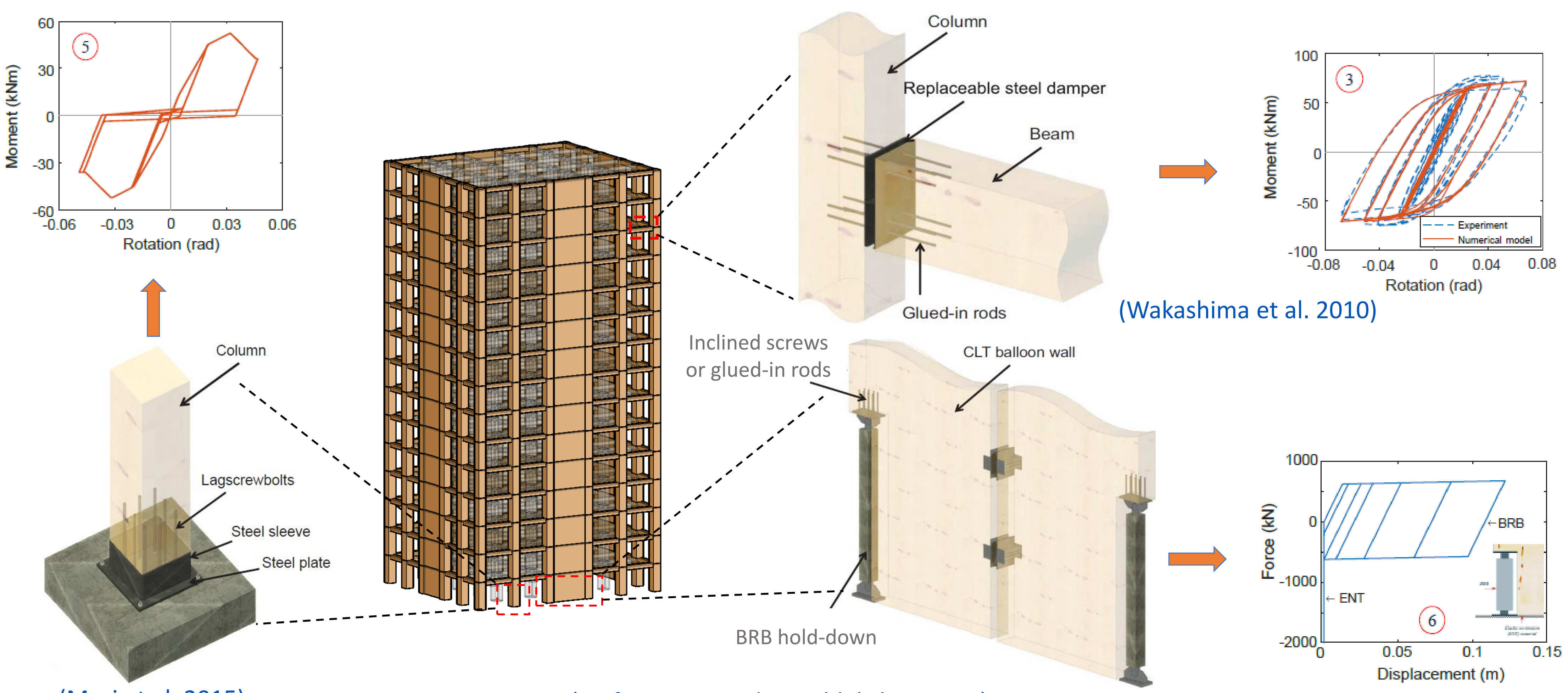


Fig. Procedure for seismic loss and resilience assessment of a structural system

* **GM**: Ground motion, **R**: Realizations.

Development and Assessment of the CLTW-GMRF System

System Description



(Mori et al. 2015)

(Wakashima et al. 2010)

(Tesfamariam and Teweldebrhan 2023)

(Tesfamariam et al. 2021)

Fig: CLTW-GMRF system components

Development and Assessment of the CLTW-GMRF System

System Mechanics and Design Method

- Under the action of a lateral load, different mode of deformations.
- Prescriptive-based seismic design based on targeted moment proportion (MP).
- MP (wall-to-frame) = to fully exploit the advantage of different structural systems.

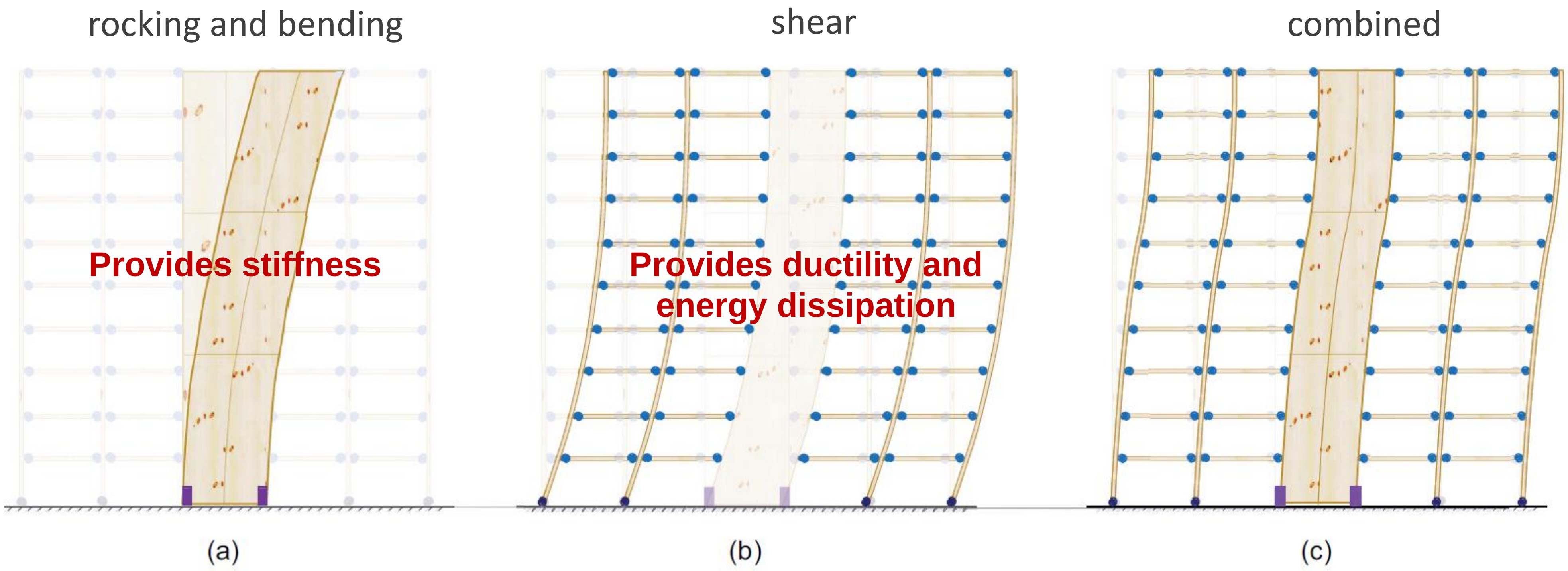


Fig: Mode of deformation: (a) CLT shear-wall, (b) Glulam MRF, and (c) Dual system (Teweldebrhan and Tesfamariam 2023a)

Development and Assessment of the CLTW-GMRF System

Numerical Model and Ground Motion Selection

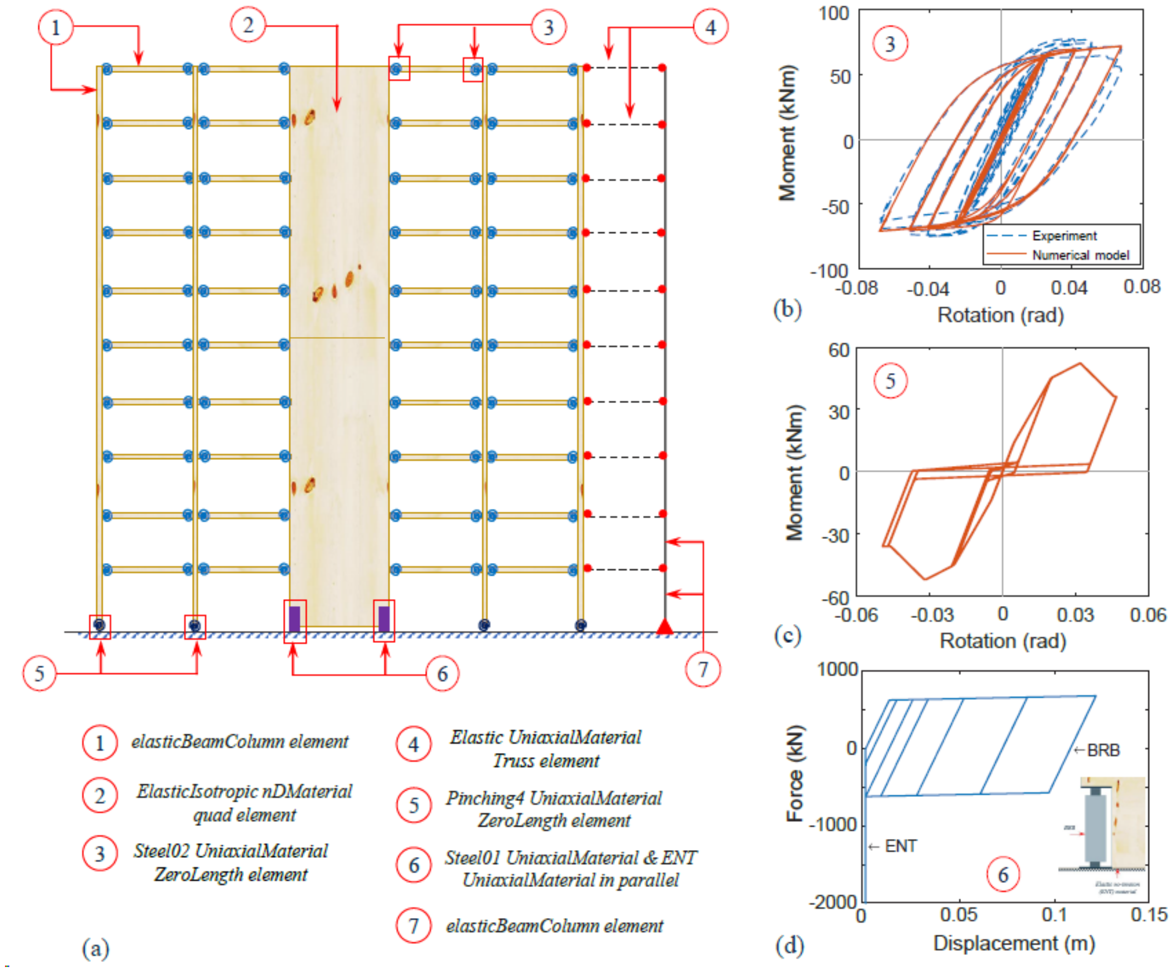


Fig: Numerical model: (a) system, (b) BCJ, (c) CBJ, and (d) hold-down (Teweldebrhan and Tesfamariam 2023b)

* **BCJ**: Beam – column joint, **CBJ** : Column – base joint

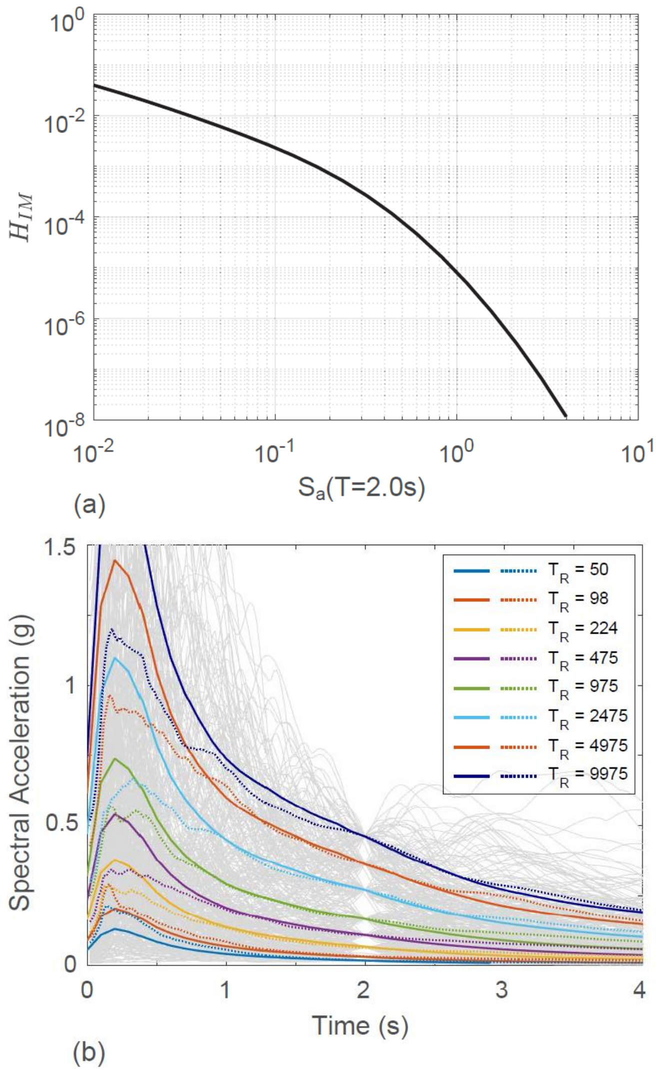


Fig. GM - characteristics: (a) seismic hazard curve; and (b) response spectra of selected GM records at different intensity levels. (Tesfamariam et al. 2023)

Development and Assessment of the CLTW-GMRF System

System Analysis

- Pushover analysis.
- Nonlinear time-history analyses: MaxISDR, ResISDR, PFA, BCJ, CBJ, and hold-down responses.

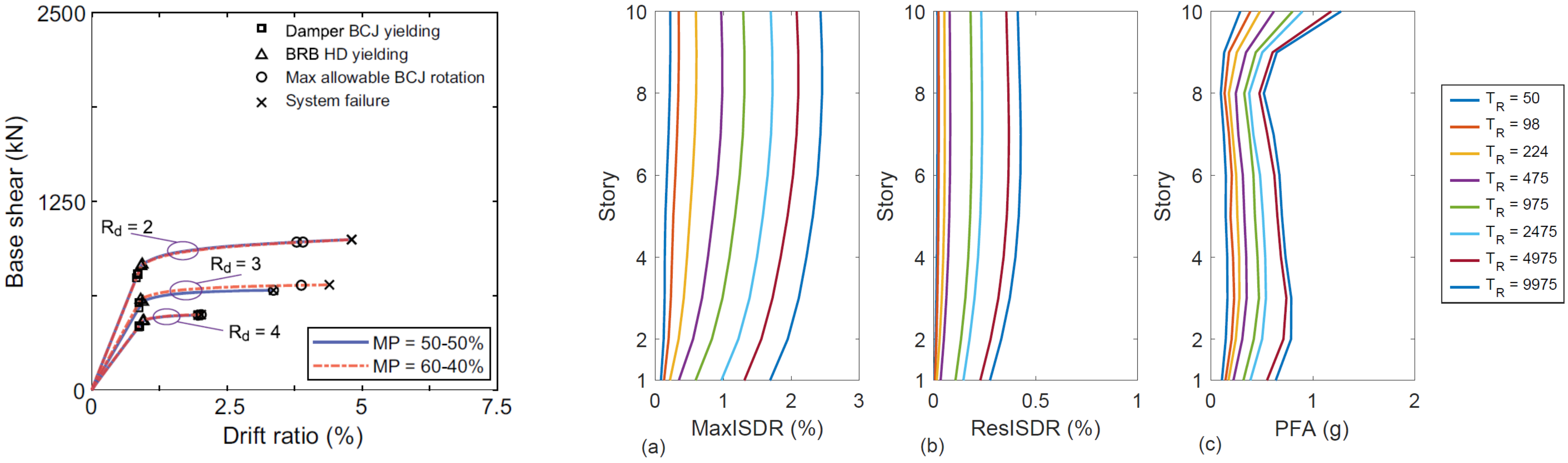


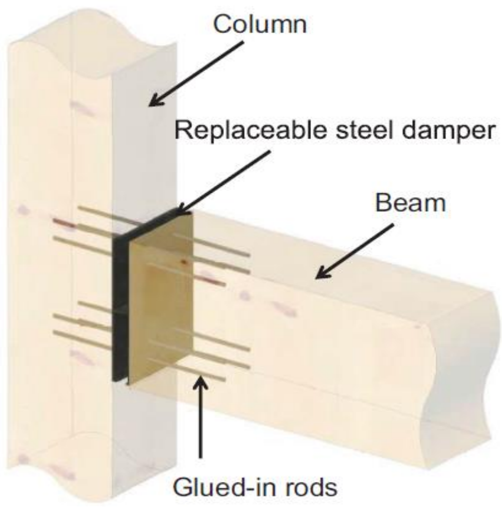
Fig. Baseline system performance: pushover and NLTHA analyses.

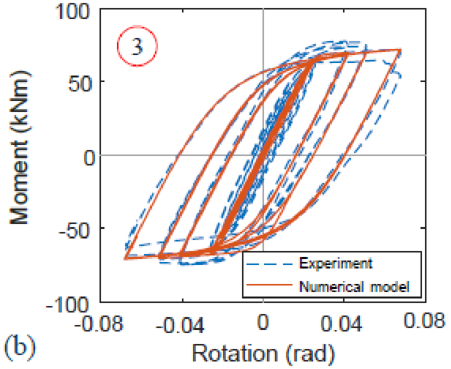
(Teweldebrhan and Tesfamariam 2023a)

* **MaxISDR**: Maximum Inter-storey Drift Ratio, **ResISDR**: Residual Inter-storey Drift Ratio, **PFA**: Peak Floor Acceleration, **NLTHA**: Nonlinear Time History Analysis.

Component Fragility and Consequence Functions

Beam-Column Joint





Damage States: Joint Rotation *(Wakashima et al. 2010, Gohlich et al. 2018)*

- Around 0.02 rad, the joint started to show out-of-plane local buckling of the web,
- Around 0.03 rad, the joint showed excessive out-of-plane local buckling of the web,
- Around 0.04 rad, local buckling of the flanges occurred along with gap openings between the columns and the column side plates,
- Around 0.05 rad, complete failure of the joint system.

Consequence and Repair Solutions

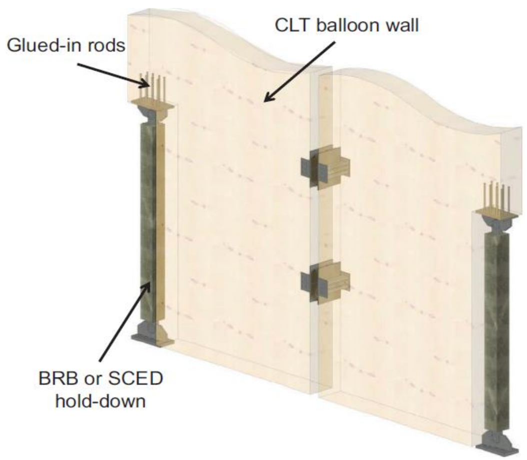
- Repair cost and time: taken from FEMA P-58, referencing reduced beam section (RBS) that exhibited similar damage behavior.

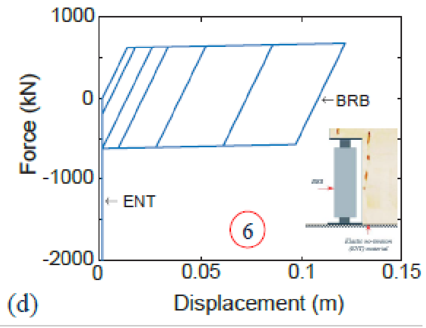
Component type	ID	EDP type	Damage state	Median (%)	Dispersion	Repair cost ($*)	Repair time (days)
Replaceable steel damper BCJs	B1035.071	Joint rotation angle	DS1	2.0%	0.30	7395-10875	4.35-6.40
			DS2	3.0%	0.30	14790-21750	8.70-12.79
			DS3	4.0%	0.30	24905-36625	14.65-21.54
BRB hold-downs	B1033.201	Axial strain	DS1	1.0%	0.40	33226-53992	22.0-36.0
CLT shear-wall	B1081.001	Story drift ratio	DS1	0.3%	0.44	1840-2990	1.8-2.9
			DS2	0.5%	0.30	2337-3330	2.3-3.2
			DS3	2.7%	0.16	3825-5400	3.7-5.2
Conventional CBJs	B1031.201	Joint rotation angle	DS1	0.45%	0.40	509-827	0.5-0.8
			DS2	2.0%	0.40	10176-16536	9.88-16.05
			DS3	3.2%	0.40	15264-10812	10.49-14.82

*: Repair costs are given per 100 sq. ft for CLT shear-wall and per unit quantity for the rest of the structural components.

Component Fragility and Consequence Functions

BRB Hold-down





Damage States: Axial Strain (FEMA P-58; Tian et al 2023)

- The median ISDR of BRB corresponding to DS1 is 2% in FEMA P-58 (FEMA, 2018).
- The corresponding BRB strain is 1%.

Consequence and Repair Solutions

- Repair cost and time: taken from FEMA P-58, referencing BRB.

Component type	ID	EDP type	Damage state	Median (%)	Dispersion	Repair cost ($*)	Repair time (days)
Replaceable steel damper BCJs	B1035.071	Joint rotation angle	DS1	2.0%	0.30	7395-10875	4.35-6.40
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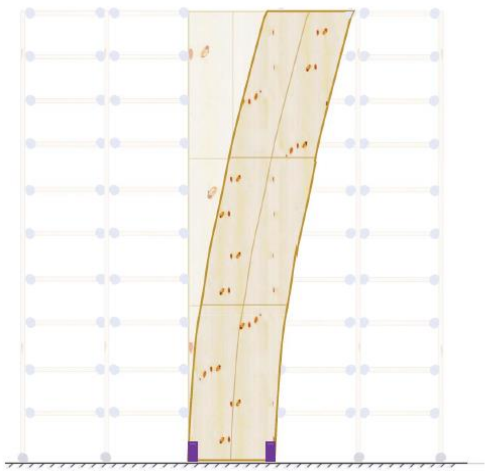
Component Fragility and Consequence Functions

CLT Balloon Wall



Damage States: Connection Failure *(Shahnewaz et al 2021; Tian et al 2023)*

- DS1 indicates that bolts come loose.
- DS2 indicates plastic deformation of steel joints;
- DS3 indicates fracture of bolts or steel plates;

Consequence and Repair Solutions

- Repair cost and time: taken from FEMA P-58, referencing light-framed wood walls.

Component type	ID	EDP type	Damage state	Median (%)	Dispersion	Repair cost ($*)	Repair time (days)
Replaceable steel damper BCJs	B1035.071	Joint rotation angle	DS1	2.0%	0.30	7395-10875	4.35-6.40
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Component Fragility and Consequence Functions

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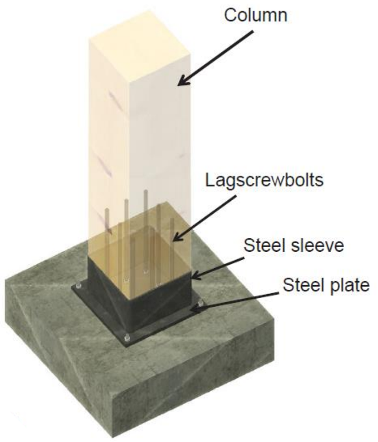
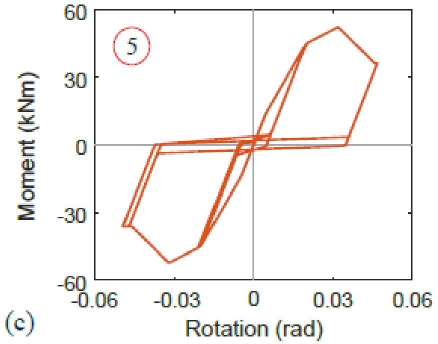
Column-Base Joint





(c)

Damage States: Joint rotation *(Mori et al 2015)*

- DS1 (around 0.0045 rad), the joint might exhibit partial tearing of the steel sleeve or potential crack initiation at the intersection of the steel sleeve and steel plate.
- DS2 (around 0.02 rad), the lagscrewbolts undergo a non-linear (post-yielding) deformation.
- DS3 (around 0.032 rad), characterized by a near-complete pullout of the lagscrews from the timber column, signaling an imminent loss of vertical load resistance.

Consequence and Repair Solutions

- Repair cost and time: taken from FEMA P-58, referencing column base.

Component type	ID	EDP type	Damage state	Median (%)	Dispersion	Repair cost ($*)	Repair time (days)
Replaceable steel damper BCJs	B1035.071	Joint rotation angle	DS1	2.0%	0.30	7395-10875	4.35-6.40
			DS2	3.0%	0.30	14790-21750	8.70-12.79
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Component Fragility and Consequence Functions

Non-Structural Components

Table 2: Quantity of non-structural components

Pact fragility ID.	Name	Performance group quantity	PACT Unit	Dispersion	Floors
B2022.001	Curtain walls	21.53	30 SF	0.6	All
B3011.011	Concrete tile roof	13.78	100 SF	0.9	Roof
C1011.001a	Wall partition	5.17	100 LF	0.3	All
C2011.001a	Stairs	0.52	1 EA	0.4	All
C3011.001a	Wall finishes	1.64	100 LF	0	All
D1014.011	Traction elevator	1.46	1 EA	0.8	1st
D2021.011a	Potable water pining	0.46	1000 LF	0.4	All
D3041.011a	HVAC ducting	0.26	1000 LF	0.6	All
D3041.031a	HVAC drops/diffusers	3.44	10 EA	0.4	All
D3041.041a	Variable air volume box	1.72	10 EA	0	All
D4011.021a	Fire sprinkler water piping	0.95	1000 LF	0.1	All
D4011.031a	Fire sprinkler drop	0.52	100 EA	0.1	All
D5011.011a	Transformer	11.7	1 EA	0.5	1st
D5012.021a	Low voltage switchgear	0.02	225 AP	0.3	All
D5012.031a	Distribution panel	3.05	1 EA	0.2	1st

EA: each; SF: square feet; LF: linear foot; HVAC: heating, ventilation, and air conditioning; AP: ampere.

Seismic Loss and Resilience Assessment

Loss Assessment Method

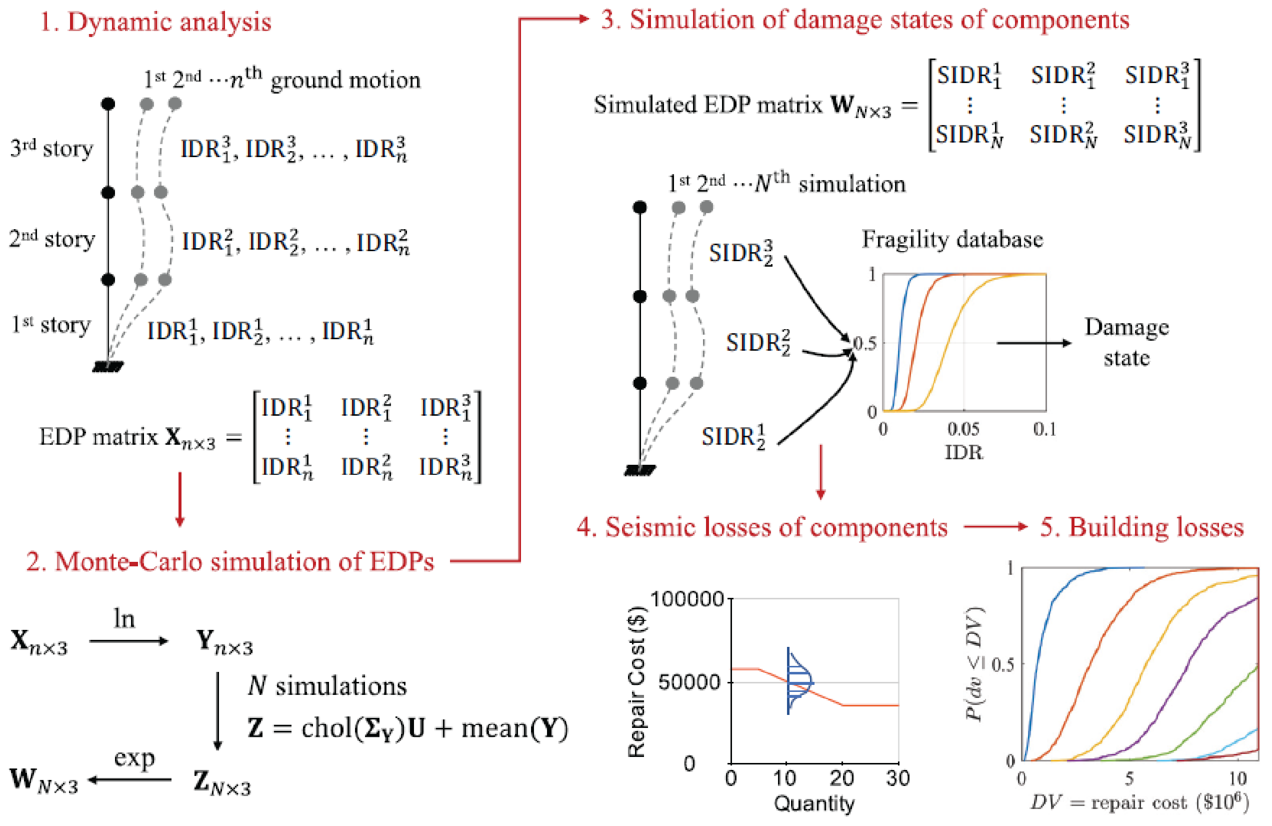


Fig. Seismic loss assessment of a structural system (You et al. 2023)

Recovery Trajectory

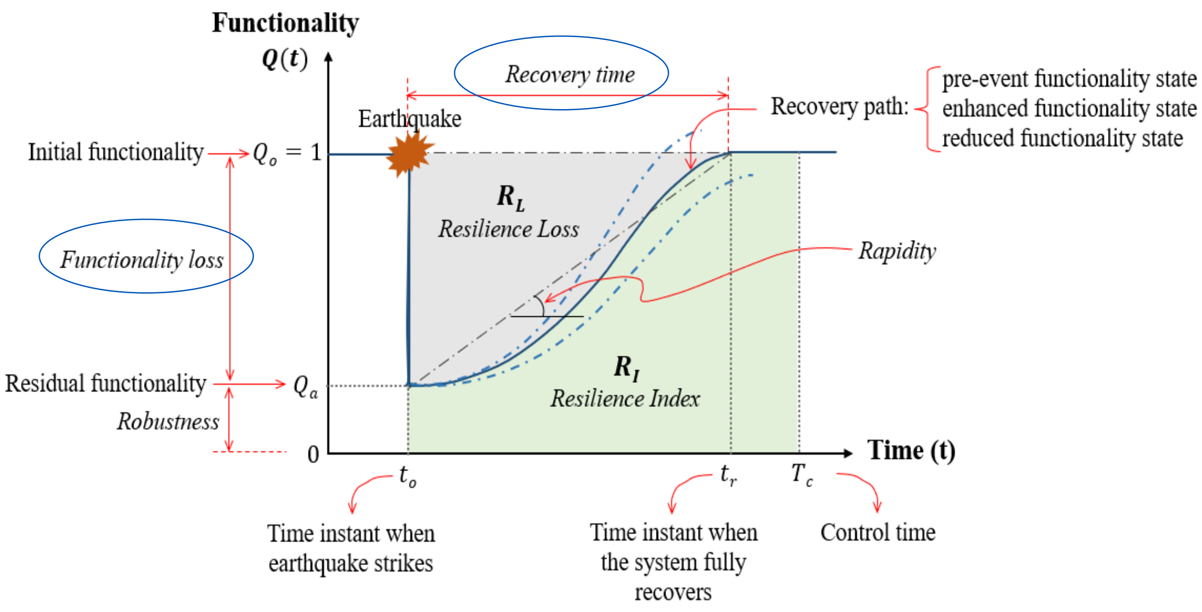
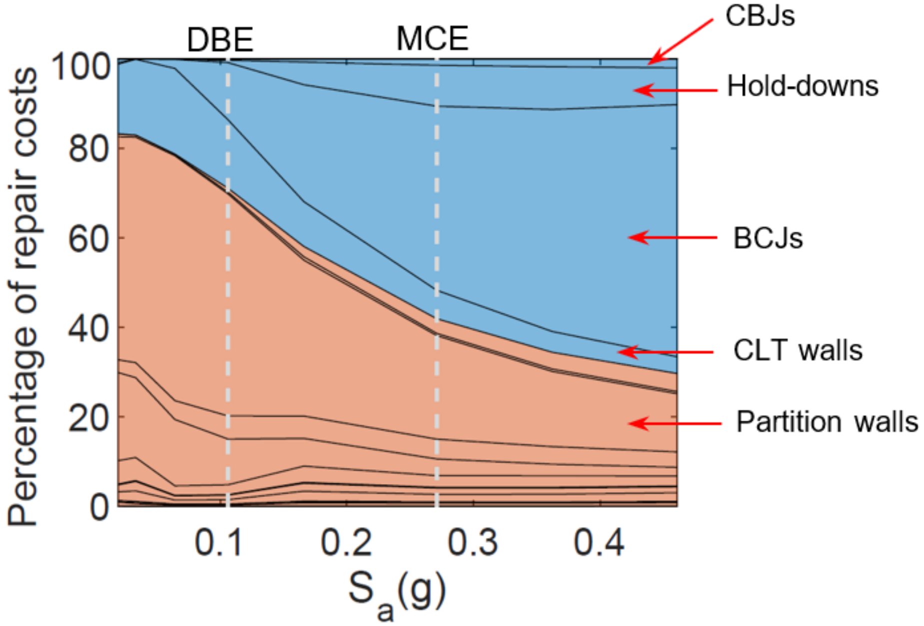


Fig. The concept of resilience triangle

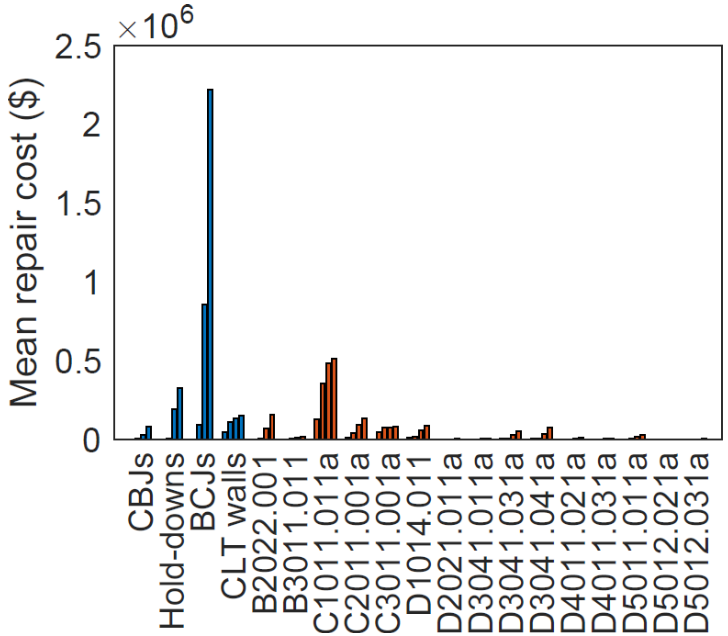
(Adapted from Bruneau et al. 2003)

Results

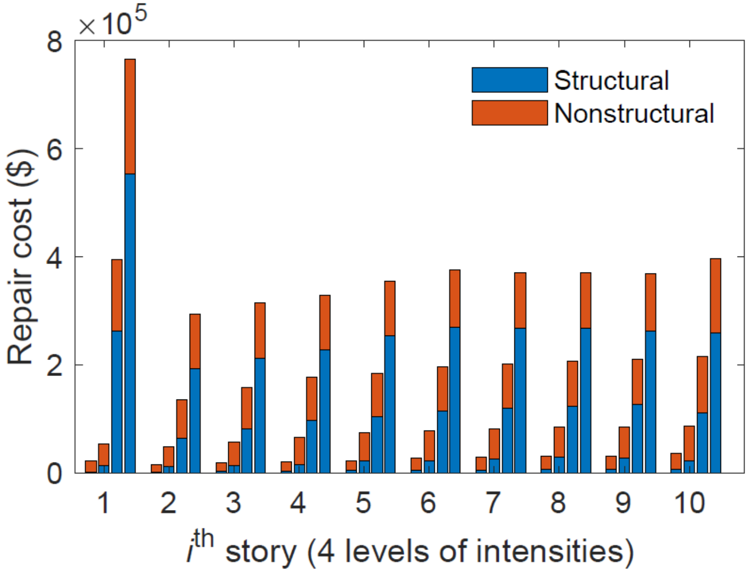
Component-level Seismic Loss



Repair cost percentage contribution from different components



Repair cost contribution from different components

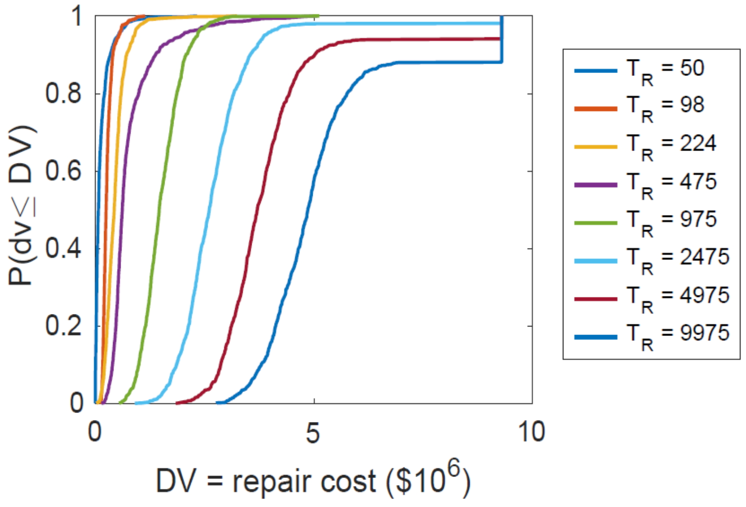


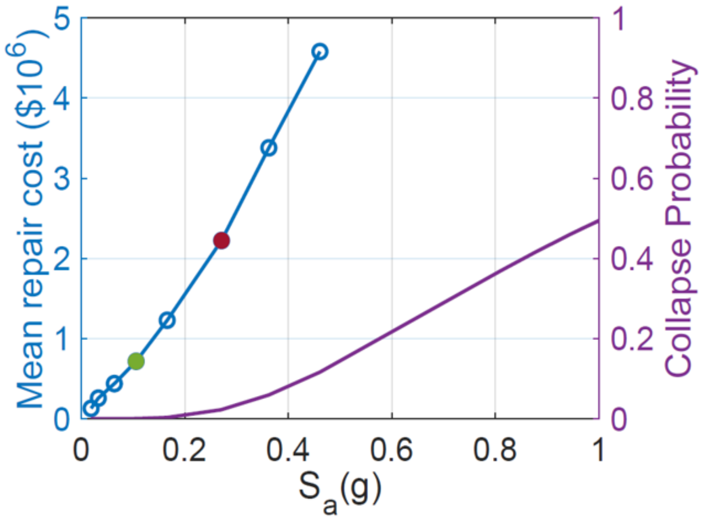
Repair cost per floor level

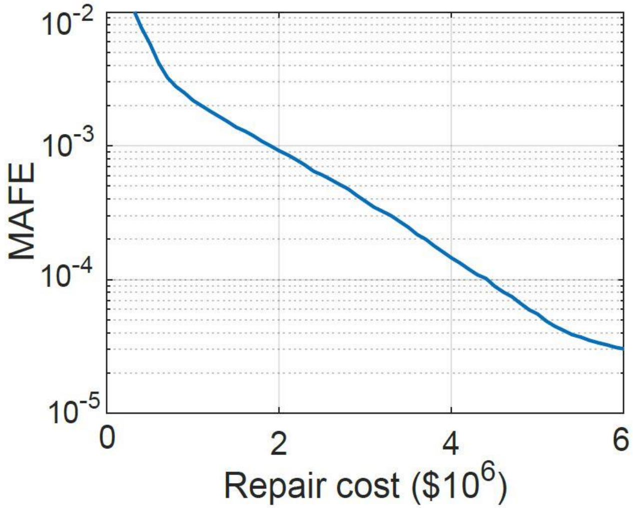
Four bars represent the result from four GM intensity levels with T_R of 98, 475, 2475, and 9975 years.

Results

System-level Seismic Loss



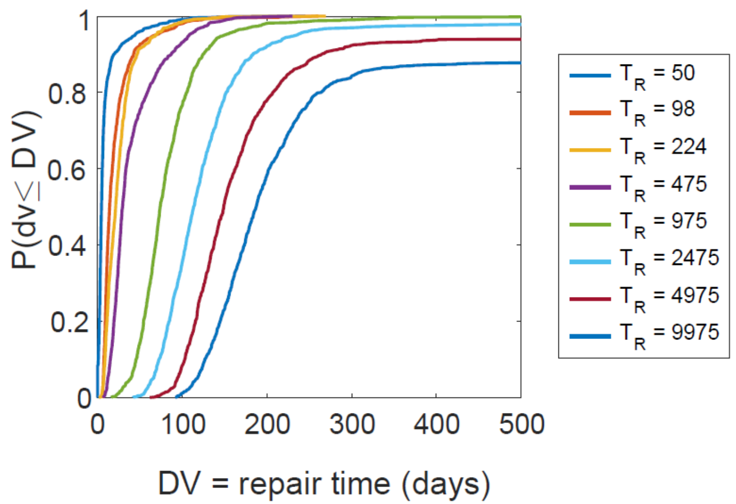


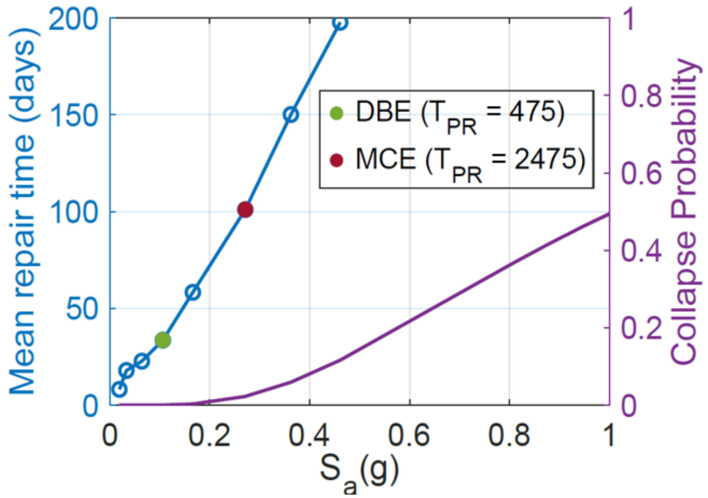


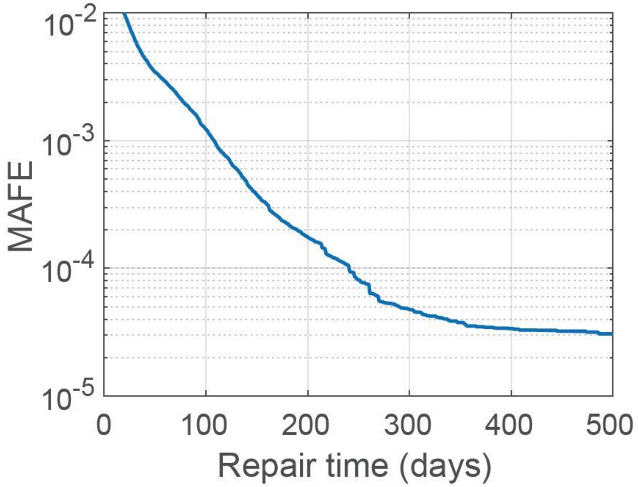
Probability of non-exceedance

Mean values

Mean Annual Frequency of Exceedance

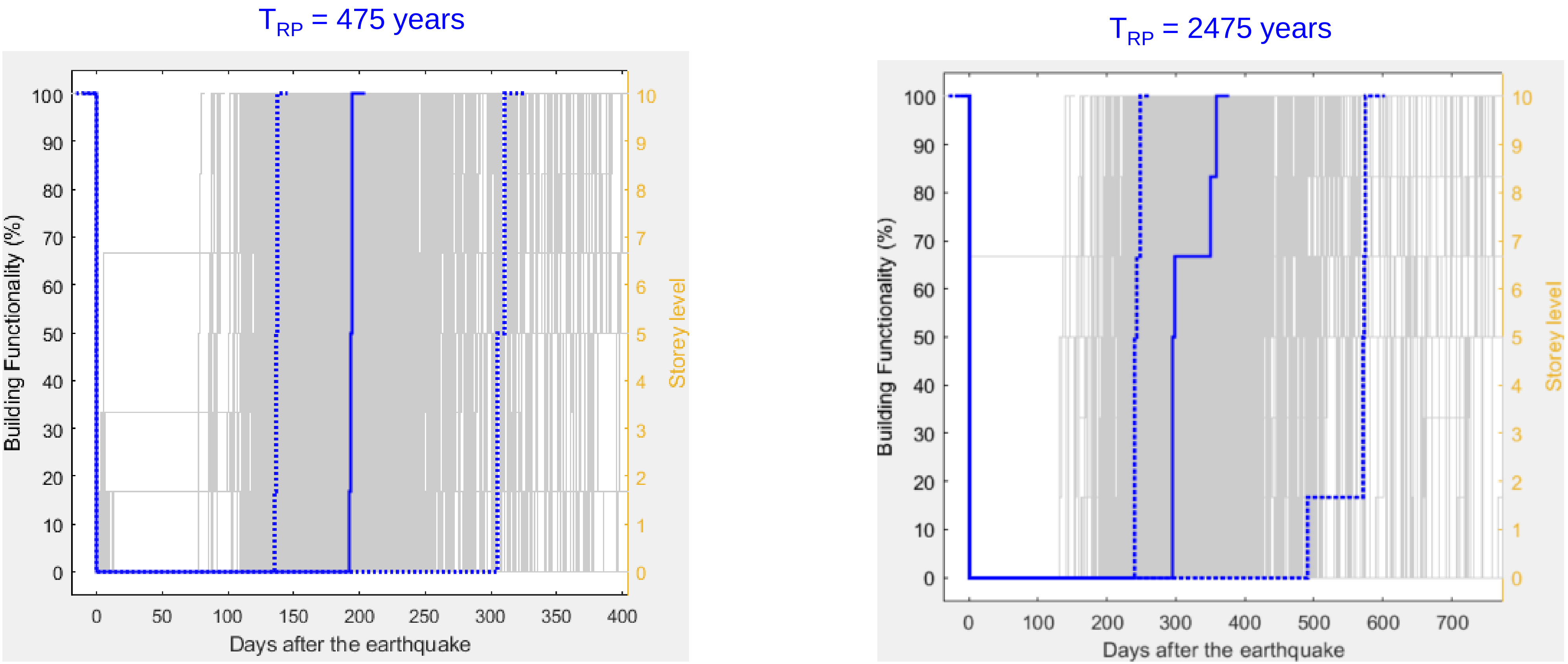






Results

Recovery trajectories



Functionality recovery trajectories

*Each realization, median, 10th and 90th percentiles.

Conclusion

- The CLTW-GMRF system showcased significant resilience under seismic events. Repairing the structure post an earthquake is often more viable than a complete reconstruction.
- Non-structural components significantly influence repair costs at lower seismic intensities, but as the intensity increases, structural components become the primary contributors to the costs.
- The BCJs contributed to most of the repair cost and time, specially at higher seismic intensities.
- The BCJs, due to their replaceable nature, present a strategic advantage in the design, offering an efficient recovery route after seismic events.
- The functional recovery trajectories of the system is developed. Most of the downtime is contributed from the impeding factors, that takes around 190 and 295 days for DBE and MCE, respectively.
- Once the impeding delays are completed, the system regains its functionality quickly after an earthquake, demonstrating the effectiveness of the system.

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Thank You!

Q&A