

Accounting for damage accumulation in seismic fragility functions for ductile RC frame buildings via hysteretic energy

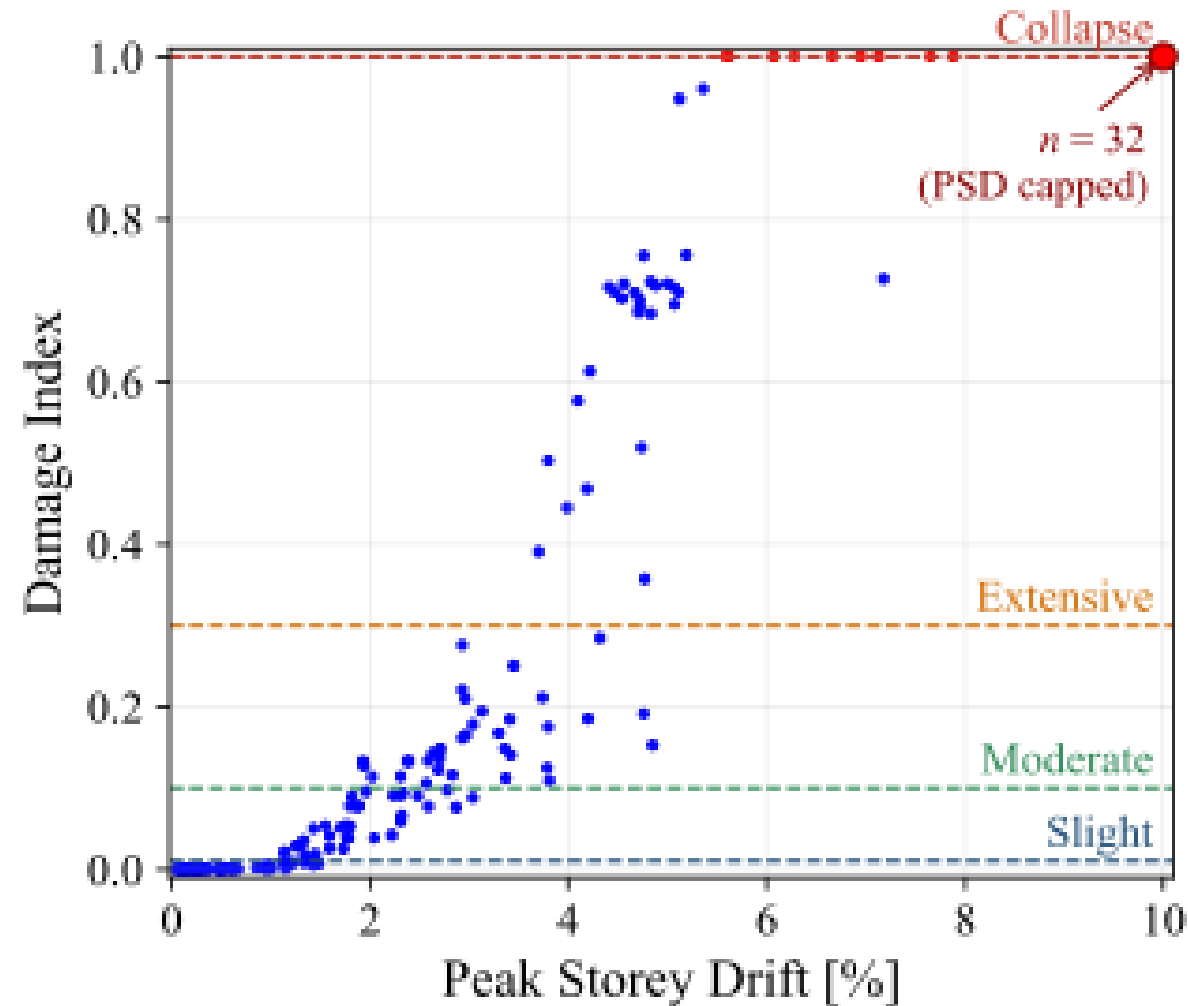
Serkan Hasanoğlu
IUSS Pavia, Italy



Motivation

- Seismic fragility studies typically quantify damage through displacement-based engineering demand parameters (EDPs) such as peak storey drift and peak roof displacement.
- These measures cannot capture the cumulative damage caused by repeated inelastic cycles and may bias the fragility estimates.
- Cumulative energy-based measures offer an alternative for characterising structural damage under cyclic loading; however, none has explicitly considered the hysteretic energy capacity ($E_{h, cap}$).
- This study proposes a **hysteretic energy capacity-based** damage assessment procedure for ductile RC frame buildings that explicitly accounts for cumulative damage, based on a concentrated plasticity modelling framework.

Why not just use drift?

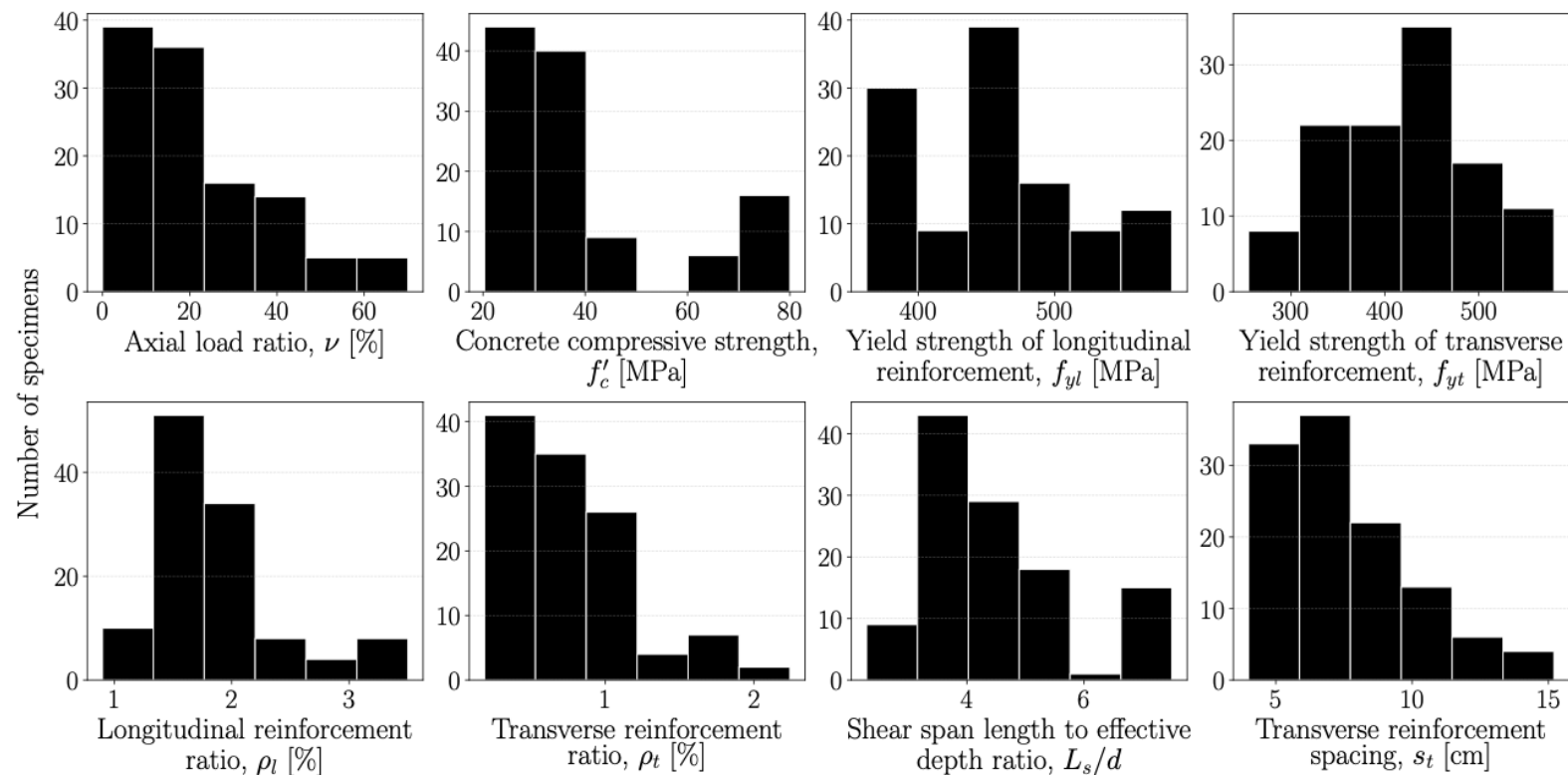


Methodology

1. The parameters for the cyclic response envelope of ductile rectangular RC beam-column elements.
2. The hysteretic energy capacity, $E_{h, \text{cap}}$, of RC elements, which is used as a reference to quantify the level of flexural damage.
3. Damage index (DI) based on $E_{h, \text{cap}}$.

Experimental database

Filtering criteria	
Axial load ratio, ν	≤ 0.7
Concrete strength, f'_c	< 80 MPa
Long. bar yield, f_{yl}	< 600 MPa
Transv. bar yield, f_{yt}	< 600 MPa
Long. reinf. ratio, ρ_l	≤ 0.04
Shear span ratio, L_s/d	≥ 2



Revised ACI 369 Rectangular Column Database (Avgin et al. 2025)

Methodology: cyclic backbone parameters

$$\frac{EI_y}{EI_g} = 0.08 \times 1.25^{10\nu} \times 1.2^{L_s/d} \text{ where } 0.2 \leq \frac{EI_y}{EI_g} \leq 0.8$$

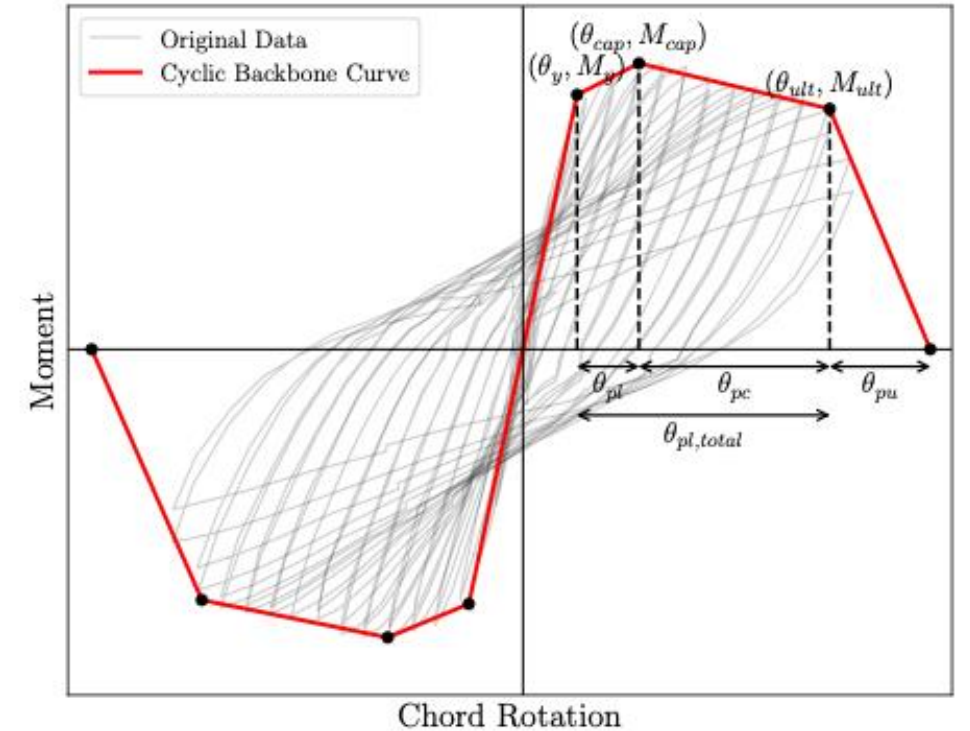
$$\theta_{pl} = 0.009 \times 0.25^{0.01f'_c} \times 0.23^\nu \times 2.17^{100\rho_l}$$

$$\theta_{pc} = 0.01 \times 0.07^\nu \times 1.78^{100\rho_t} \times 1.18^{0.01f_{yl}}$$

$$\theta_{pu} = 0.0023 \times 1.96^{0.1f'_c} \times 2.74^{100\rho_l} \text{ where } \theta_{pu} \leq 4\theta_{pc},$$

$$\frac{M_{cap}}{M_y} = 1.08^\nu \times 1.38^{10\rho_l} \times 1.14^{0.1L_s/d}$$

$$\frac{M_{ult}}{M_{cap}} = 0.91^{0.01f'_c} \times 0.80^{0.1L_s/d}$$



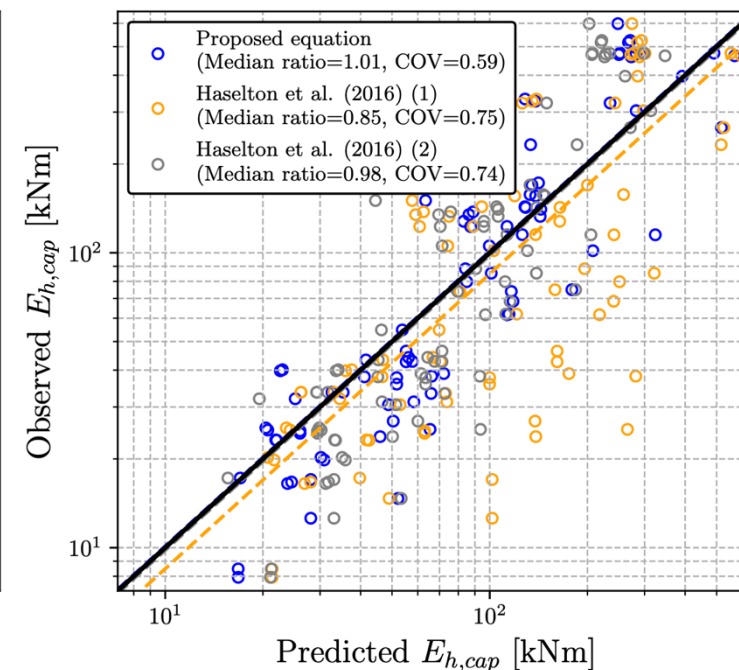
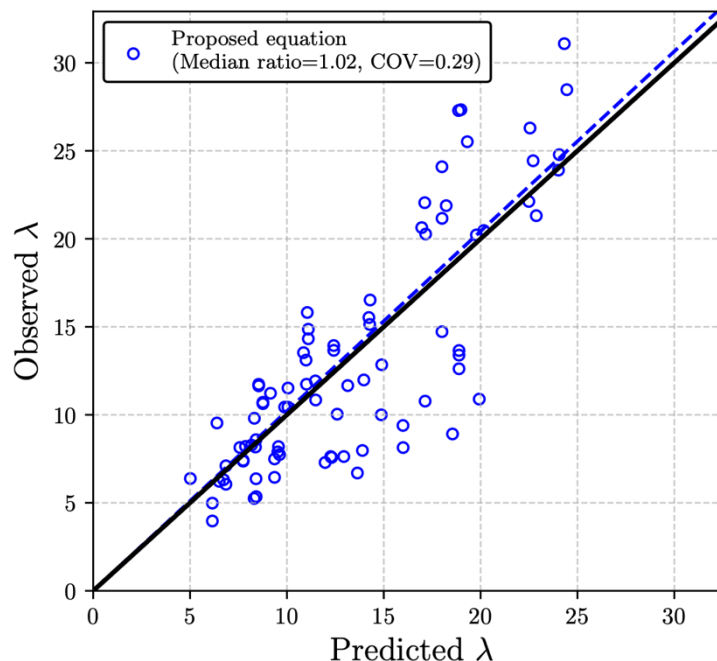
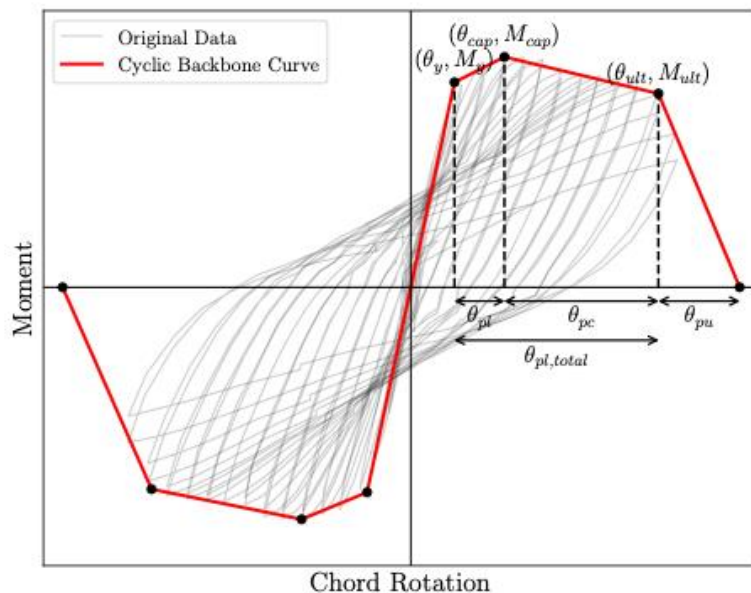
Methodology: hysteretic energy capacity

$$E_{h,cap} = M_y \times \theta_{pl,total} \times \lambda$$



$$\lambda = 52 \times 0.41^{0.01(f_c + 0.1f_{yl})} \times 0.34^v \times 0.21^{s_t/h}$$

$$\lambda = \frac{E_{h,cap}}{M_y \theta_{pl,total}}$$



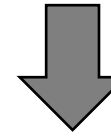
Hasanoğlu & O'Reilly (2026). Calibration of cyclic backbone parameters and hysteretic energy capacity of ductile RC members. (Under review).

Methodology: $E_{h,cap}$ -based damage index

Section-level DI:

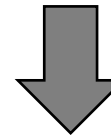
$$DI_{uni-direct,i} = \begin{cases} 1, & \text{if } |\theta_i| > \theta_{ult,i} \\ \min \left(1, \frac{\sum E_{h,i}}{E_{h,cap}} \right), & \text{otherwise} \end{cases}$$

$$DI_{bi-direct,i} = \min \left(1, \sqrt{DI_{i,x}^2 + DI_{i,y}^2} \right)$$



Storey-level DI:

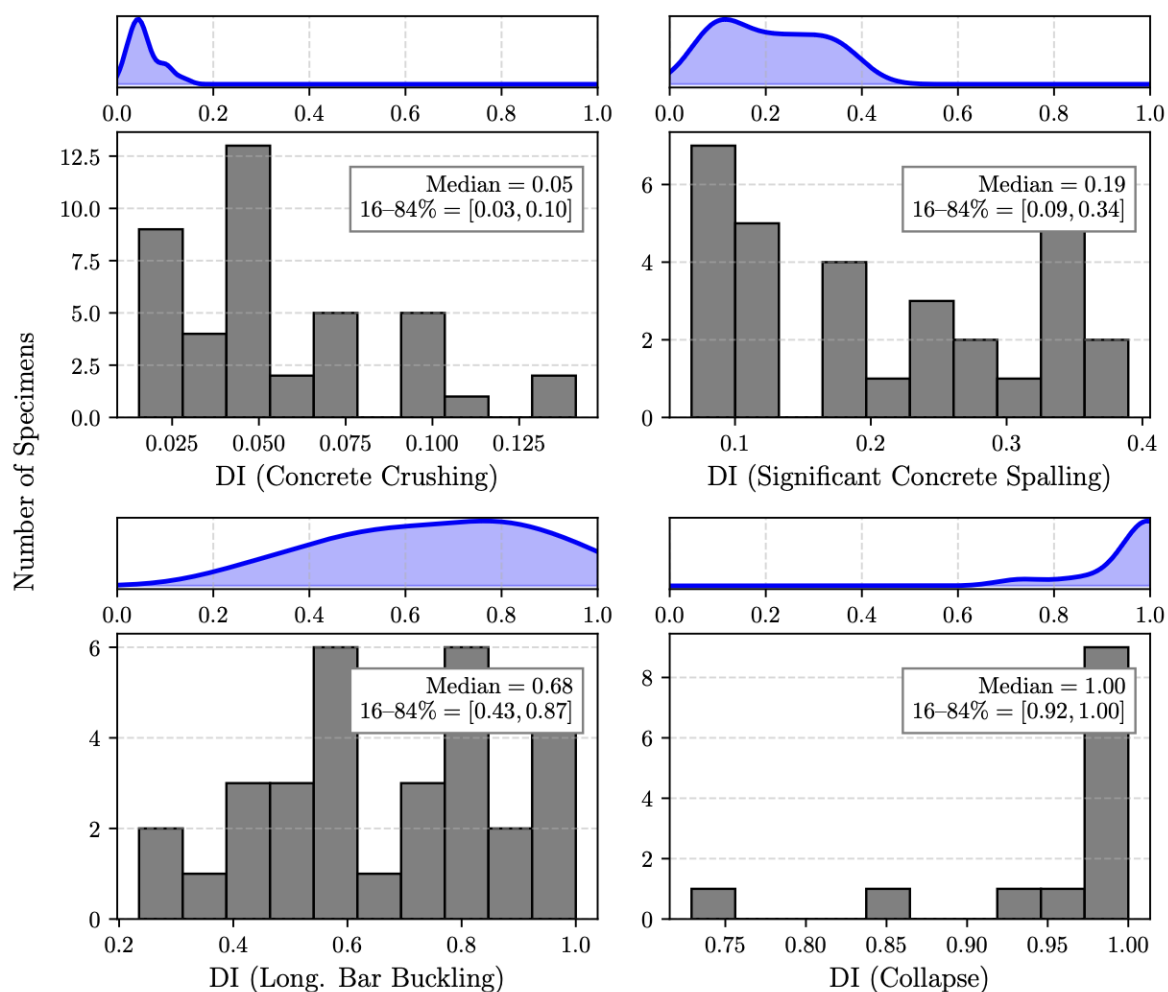
$$DI_j = \frac{\sum_{i=1}^m DI_{ji} E_{h,cap,ji}}{\sum_{i=1}^m E_{h,cap,ji}}$$



Structure-level DI:

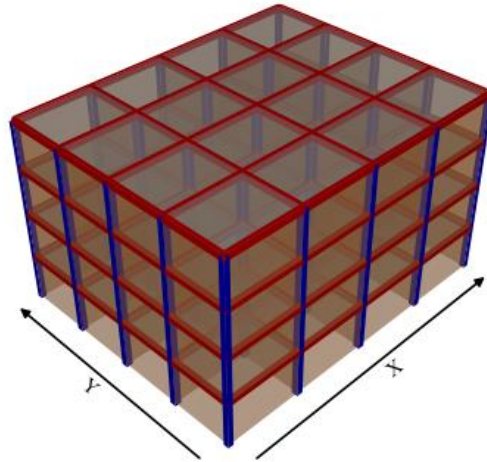
$$DI_{struct} = \max_j DI_j$$

Methodology: $E_{h, cap}$ -based damage index



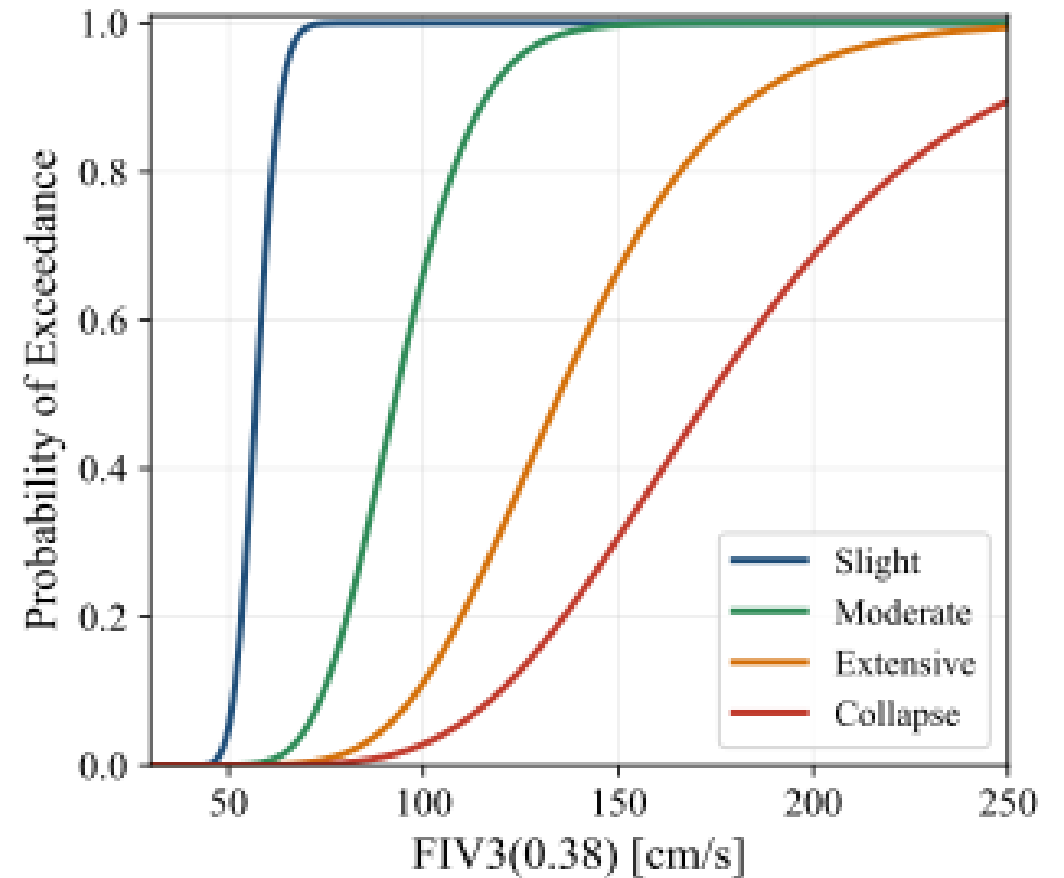
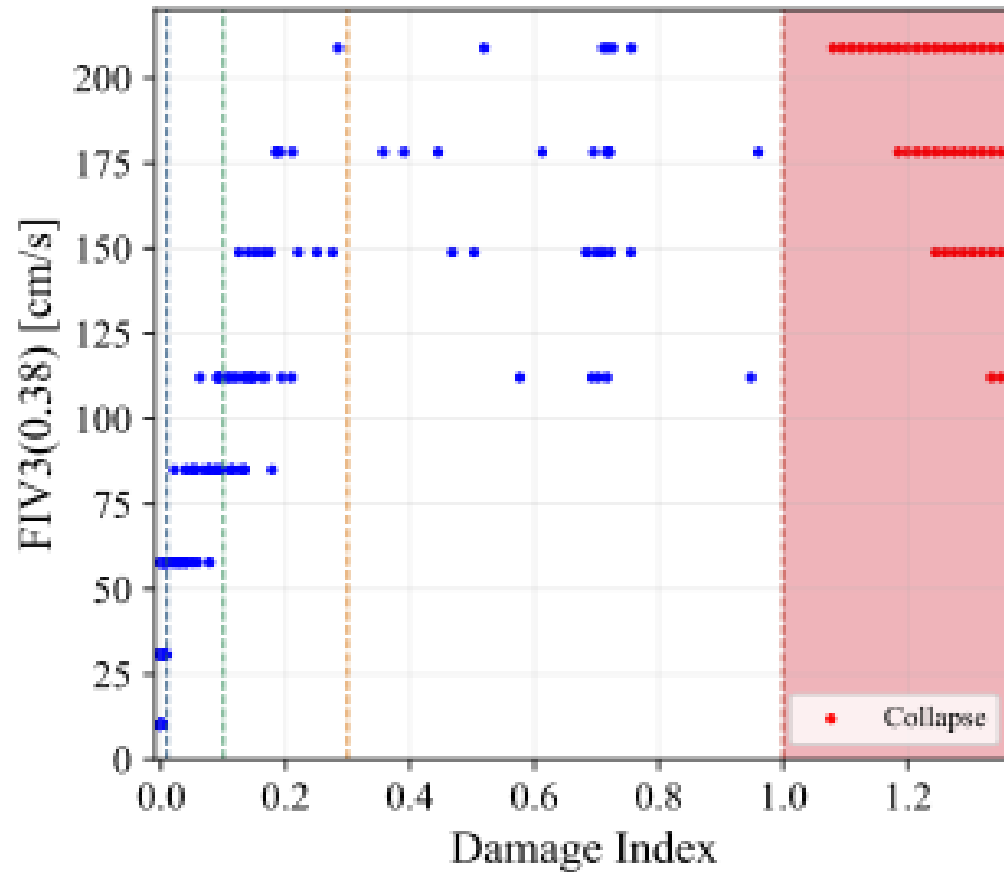
Damage state	Damage description	Median	16 th –84 th percentiles	Proposed thresholds
Slight (DS1)	Concrete crushing	0.05	0.03–0.1	0.01–0.1
Moderate (DS2)	Significant concrete spalling	0.19	0.09–0.34	0.1–0.3
Extensive (DS3)	Longitudinal bar buckling	0.68	0.43–0.87	0.3–1.0
Collapse (DS4)	Longitudinal bar fracture & Loss of axial load capacity	1.0	0.92–1.0	1.0

Example Application



Property	Value	Property	Value
Number of storeys	4	Design class	tr_0018_dch
Storey height	3 m	β	0.1
Number of bays (X)	4	Concrete grade	C25
Number of bays (Y)	4	Steel grade	S420
Bay width (X)	5 m	Column section	square
Bay width (Y)	4 m	Beam section	emergent
Slab type	two-way solid slab	Slab thickness	15 cm

Example Application



Conclusions

- Drift-based EDPs cannot distinguish structures that reach the same peak demand through very different numbers of inelastic cycles, which can **bias fragility estimates** at higher damage levels.
- The proposed $E_{h, cap}$ -**based damage index** links dissipated hysteretic energy directly to an element's energy capacity, giving a physically consistent measure of cumulative flexural damage.
- Since it explicitly tracks accumulated damage, the method can be used directly to develop **state-dependent fragility models**.
- The proposed model for $E_{h, cap}$ provides a suitable basis for **energy-based design procedures**.

Thank you

Questions?



Hasanoğlu, Serkan; O'Reilly, Gerard J. (2026) "Accounting for damage accumulation in seismic fragility functions via hysteretic energy", 18th European Conference on Earthquake Engineering, Berlin Germany.

Accounting for damage accumulation in seismic fragility functions via hysteretic energy

Serkan Hasanoğlu¹, Gerard J. O'Reilly¹

1- Centre for Training and Research on Reduction of Seismic Risk (ROSE Centre), Scuola Universitaria Superiore IUSS di Pavia, Pavia 27100, Italy

serkan.hasanoglu@iusspavia.it

Abstract

Accurate quantification of cumulative damage remains a significant challenge for seismic risk studies, particularly for regions affected by long-duration ground motions or earthquake aftershock sequences. Typically, seismic fragility studies rely on peak response quantities, such as displacement or drift, which fail to capture the accumulation of structural damage under cyclic loading. To overcome this limitation, this study presents a hysteretic energy-based methodology for seismic fragility assessment of reinforced concrete (RC) frame buildings based on experimentally calibrated cyclic backbone and hysteretic energy capacity, $E_{h, cap}$, models. To this end, a database of reversed cyclic column tests was first compiled and filtered to obtain a representative subset of experiments for typical RC buildings, and was later used for model calibrations. Based on the proposed $E_{h, cap}$ formulation, an energy-based damage index was developed to consistently quantify the progression of flexural damage in RC building structures. The models for the calibrated cyclic backbone parameters, $E_{h, cap}$, and the proposed damage index were then implemented in a 3D numerical model, and time-history analyses were conducted to compare the effects of each structural assessment method. The results demonstrate that the proposed methodology improves the representation of cyclic behaviour, and the difference between the two approaches becomes critical, particularly at high levels of structural damage.