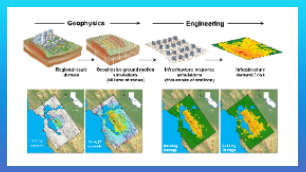


PEER International Pacific Rim Forum
June 16-17, 2021

Computational Workflows for Propagating Uncertainties in Simulations of Earthquake Performance of Buildings and Infrastructure

Gregory G. Deierlein
Blume Center for Earthquake Engineering
Stanford University

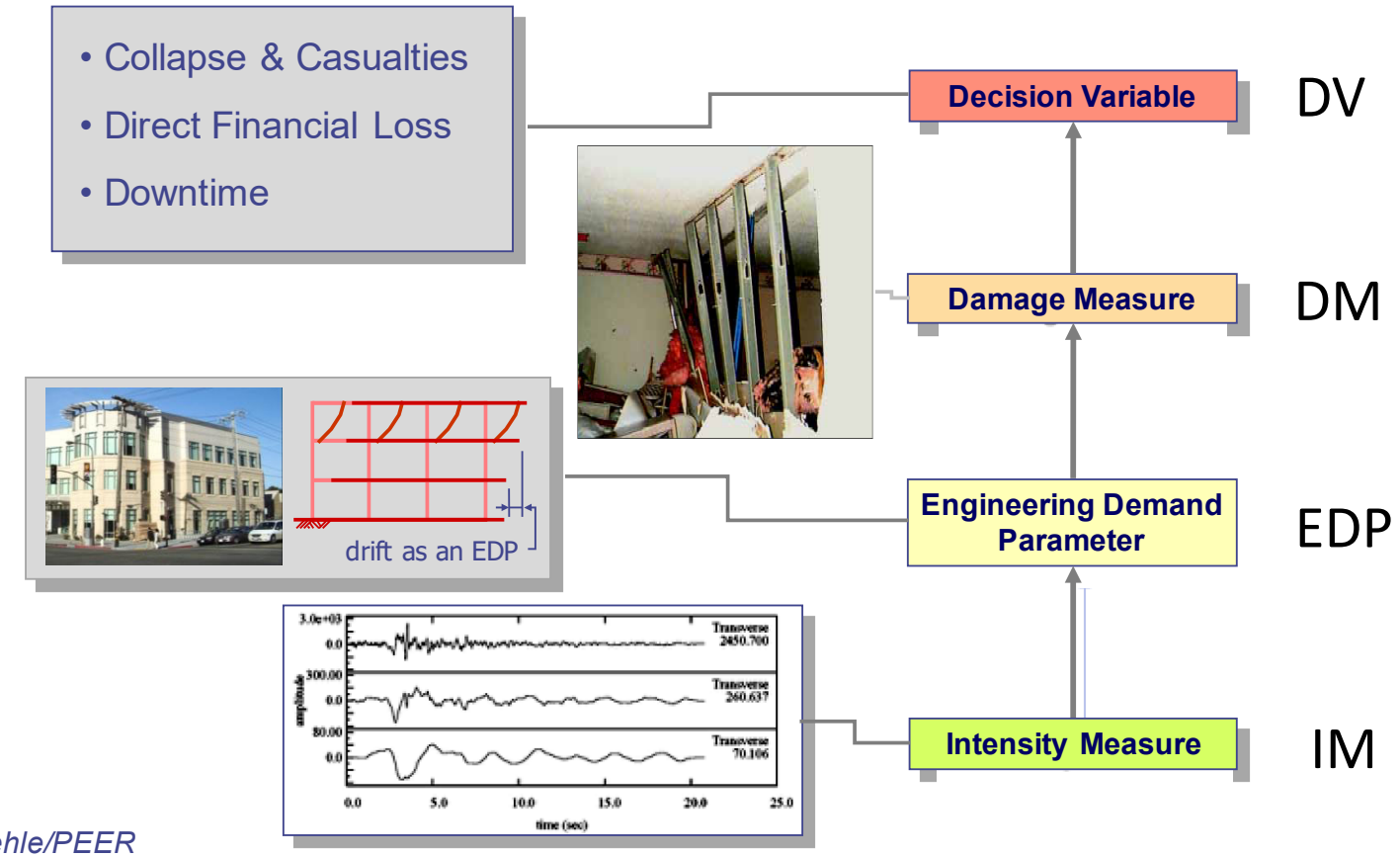
with contributions by many others …

June 17, 2021

SimCenter NHERI
Center for Computational Modeling and Simulation

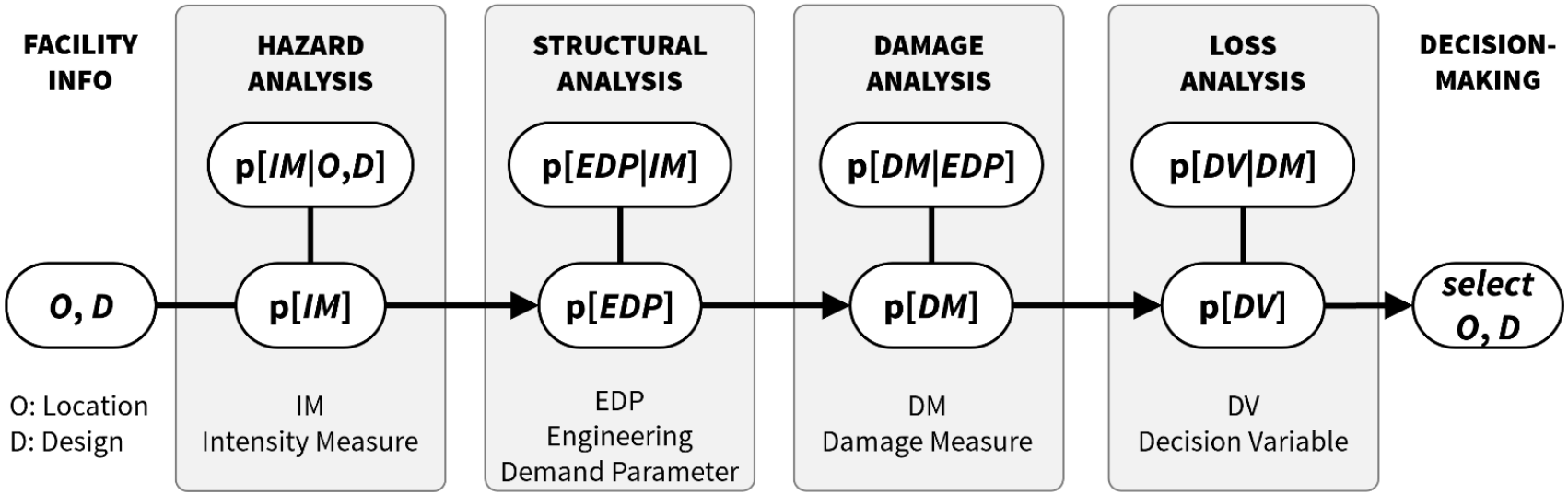
PEER

Performance-Based Framework



Moehle/PEER

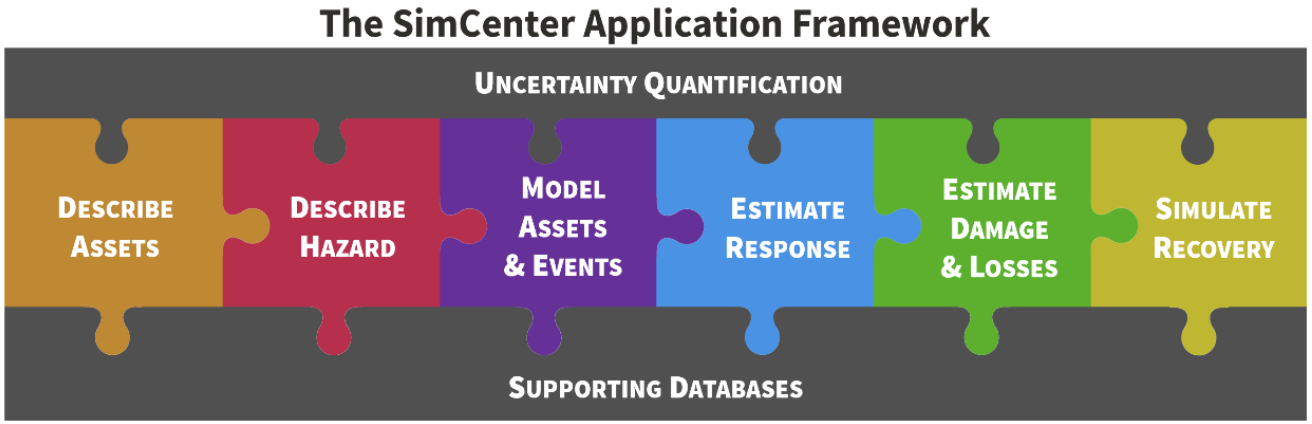
Performance-Based Framework

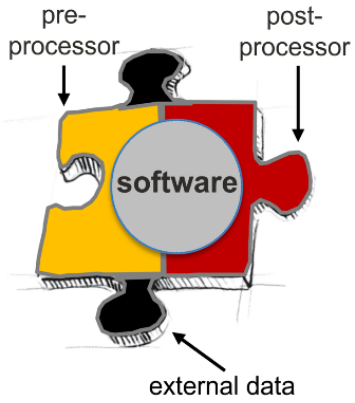


$$v(DV) = \iiint G\langle DV \mid DM \rangle \mid dG\langle DM \mid EDP \rangle \mid dG\langle EDP \mid IM \rangle \mid d\lambda(IM)$$

Impact | **Performance (Loss) Models and Simulation** | **Hazard**

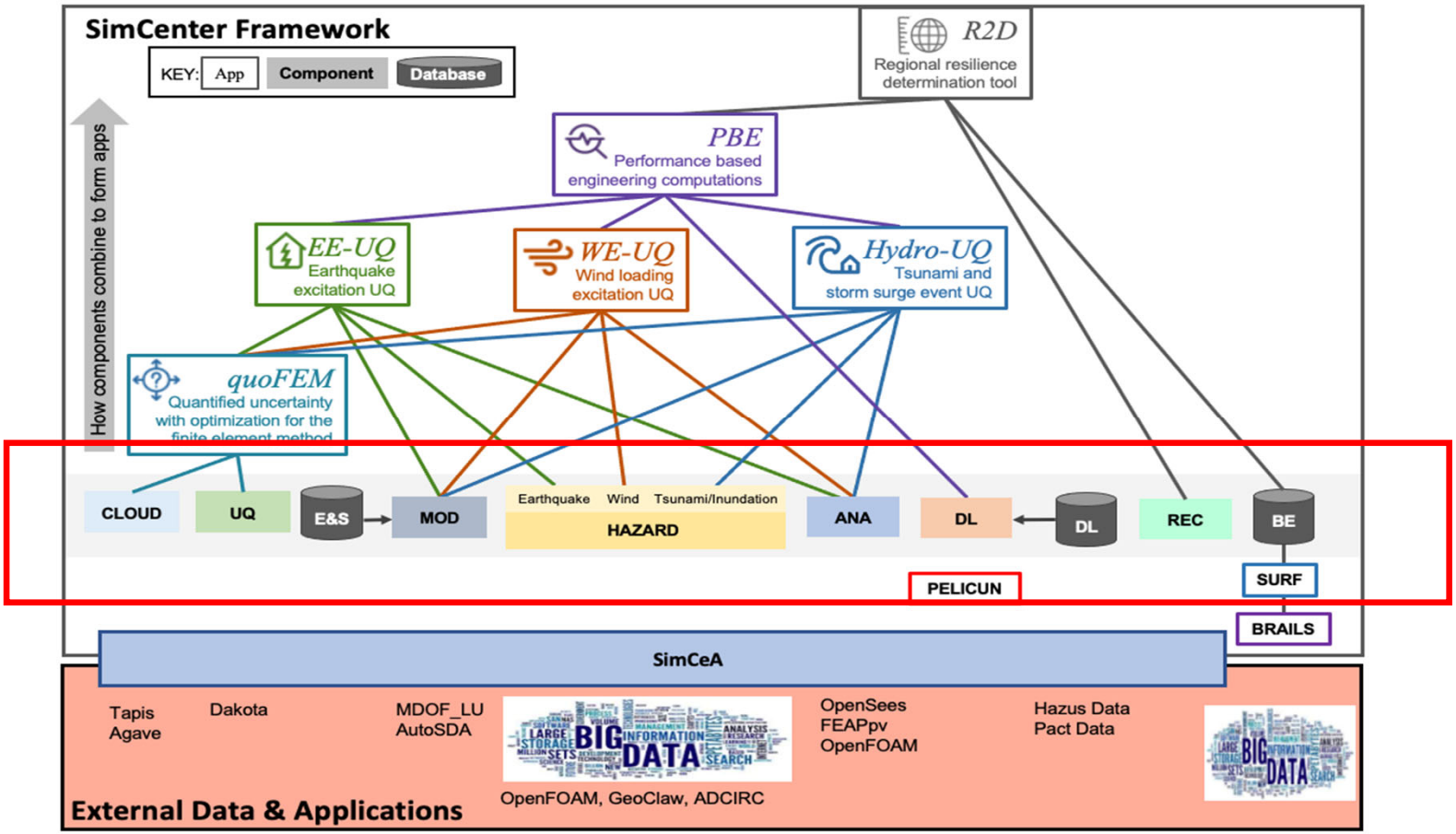
Computational Workflow Components



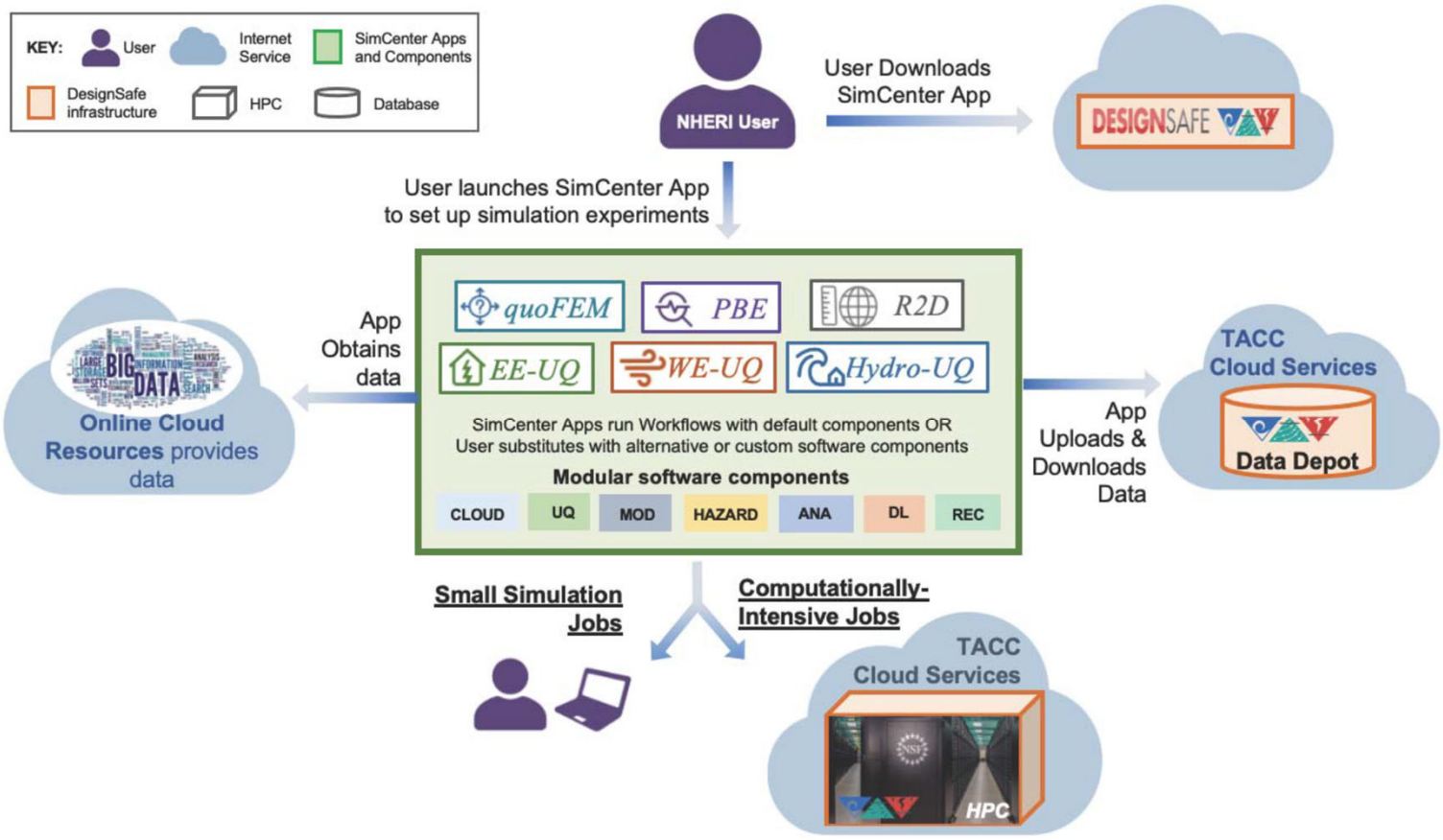


OpenSource :: Multi-Fidelity :: Multi-Hazard

Computational Workflow Components



Computational Workflow Components



Workflow Applications

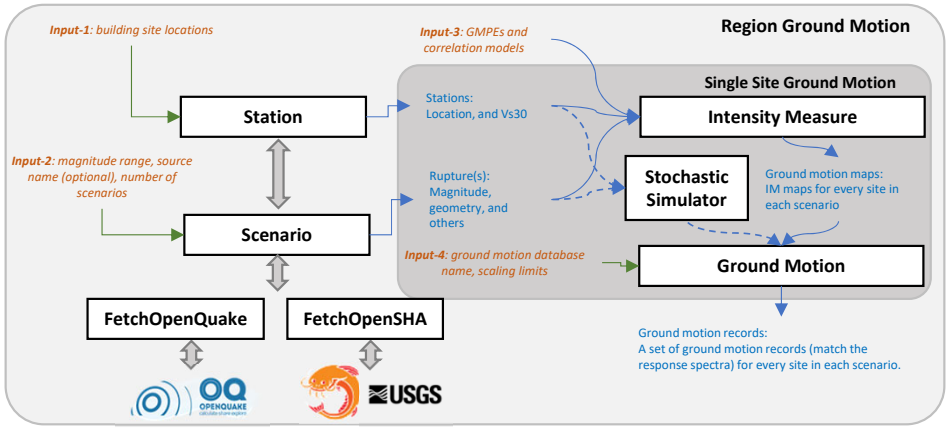
Coupling: Quantification of Uncertainties & Optimization with FEM

Response of structure to natural hazard effects: ground shaking, wind effects, and surge/tsunami flows

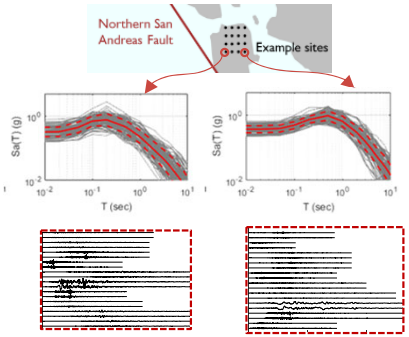
Performance-based computations of individual facilities to natural hazards

Regional assessment of facilities and systems to natural hazards to support resilience decision making

Workflow: Hazard



Target Spectra & Ground Motions

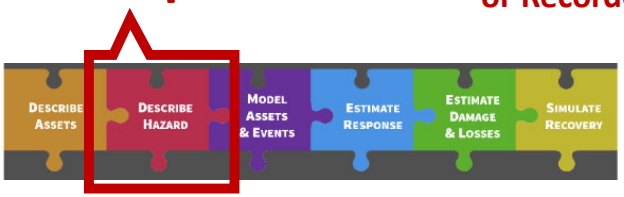


Ground Motion Database

- NGA-West2 (PEER)
- User-Defined

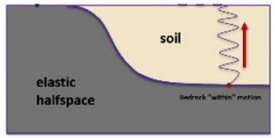
Scenario Spectra & Ground Motions

Earthquake



Direct Simulation or Recorded EQ

Site Responses



RV:

- ***Vs30***
- ***Depth to rock***

SW4

Lawrence Livermore National Laboratory

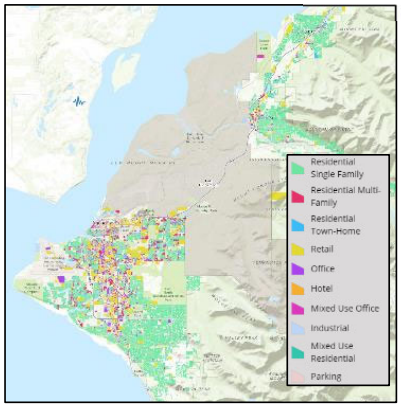
SCEC AN NSF+USGS CENTER

USGS

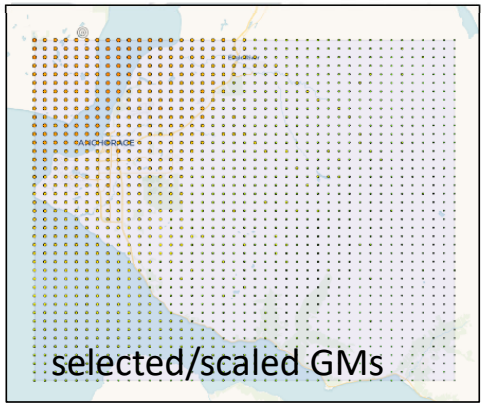
Workflow Tesbed – Anchorage M7.1 (2018)

RDT

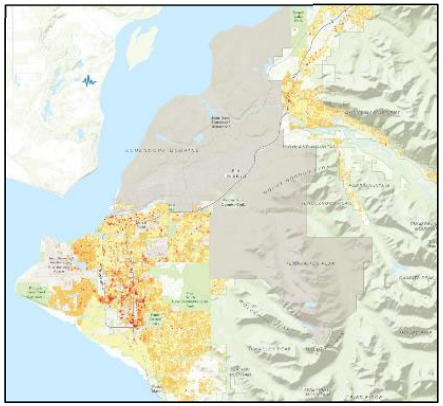
Illustrate Post-Event Simulation w/recorded motions



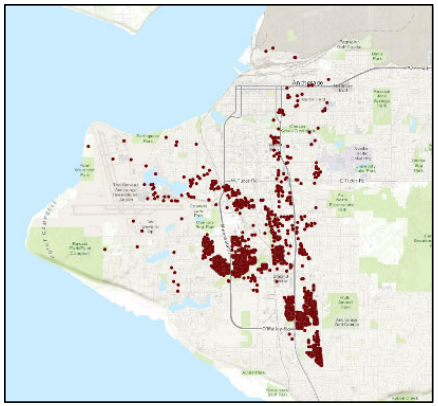
Building Inventory



Ground Motions



Loss Ratios



Red Tags

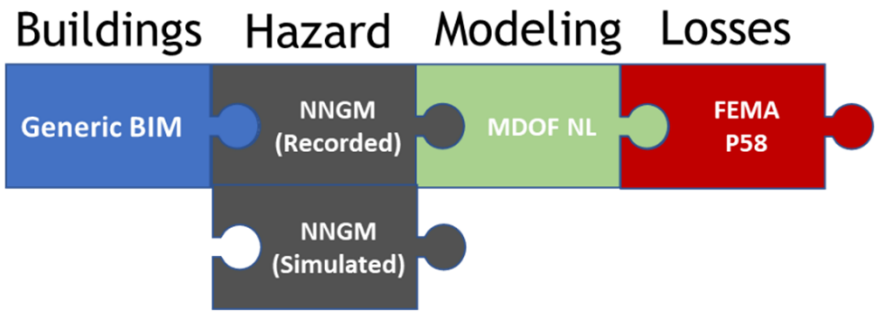
- Reference: StEER: Alaska Earthquake P-VAT joint Report, 2018 Source: Time Magazine, Image Credit: Marc Lester - Anchorage Daily News/AP

Workflow Tesbed – Anchorage M7.1 (2018)

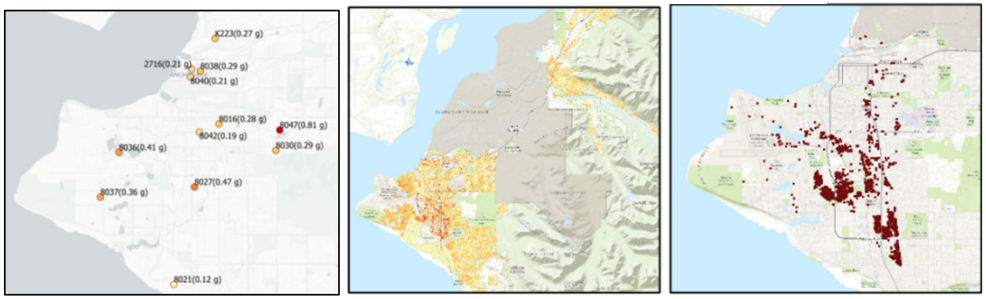
Anchorage M7.1 (2018) – sensitivity to GM estimates

Estimated Losses

	Recorded GM	Simulated GM
Repair Cost [$Billion]	7.5	7.3
Red Tags	3800	626
Loss Ratio [%]	14.5	12.5



As Recorded Motions for M7.1 Event

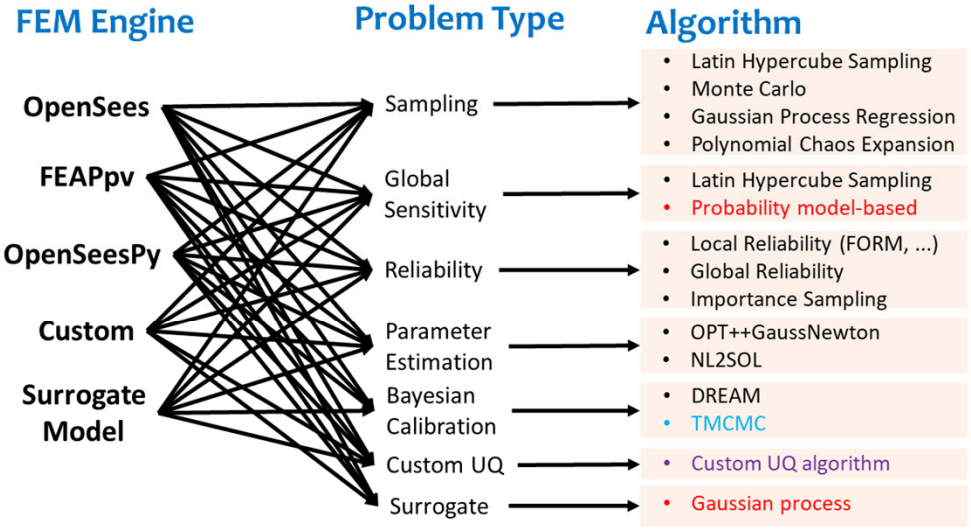


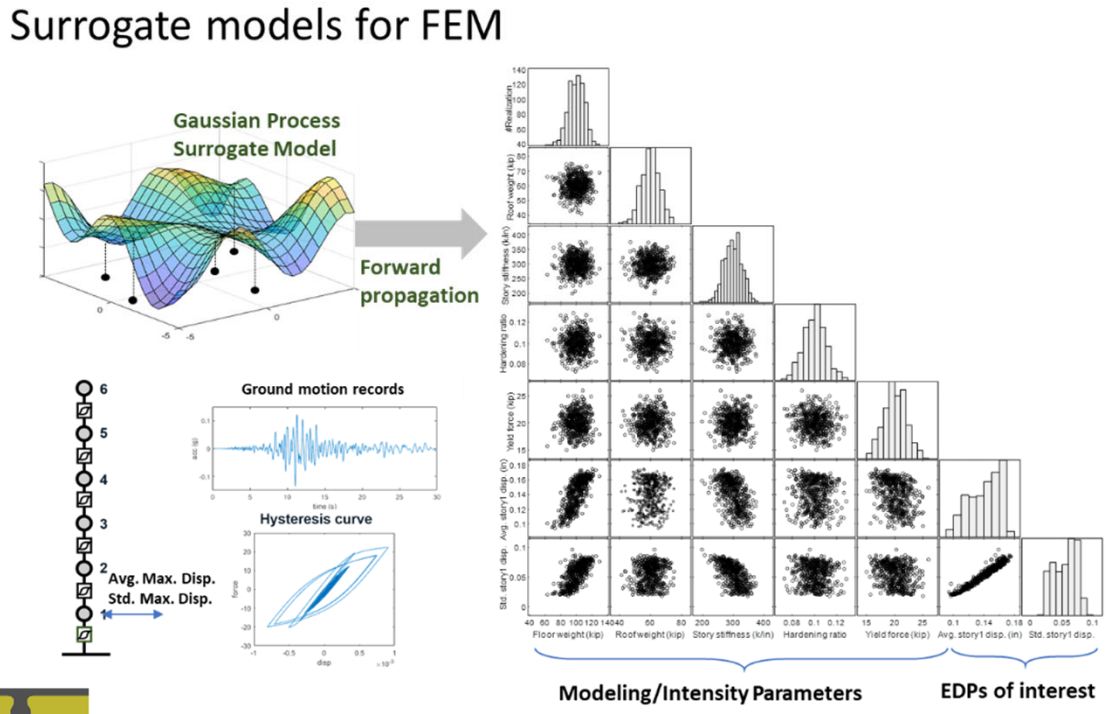
Scenario (Selected/Scaled) Ground Motions

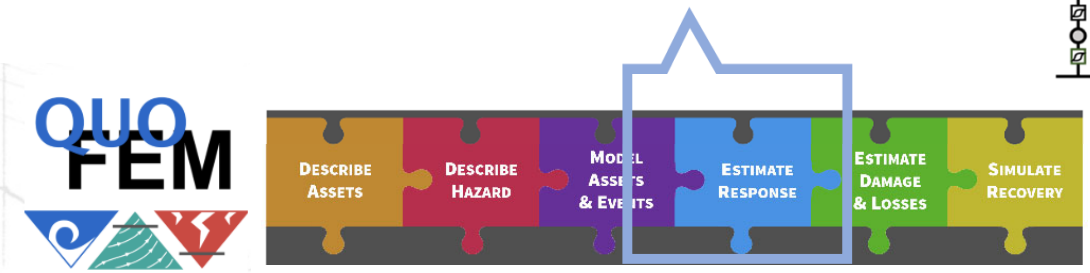
GM Stations | Parcels Loss Ratios | Buildings Red Tags

post-EQ inspections report > 750 homes/buildings suffered substantial damage; another 900 buildings sustained minor damage. The state has received > 6,000 reports from people reporting damage to homes.

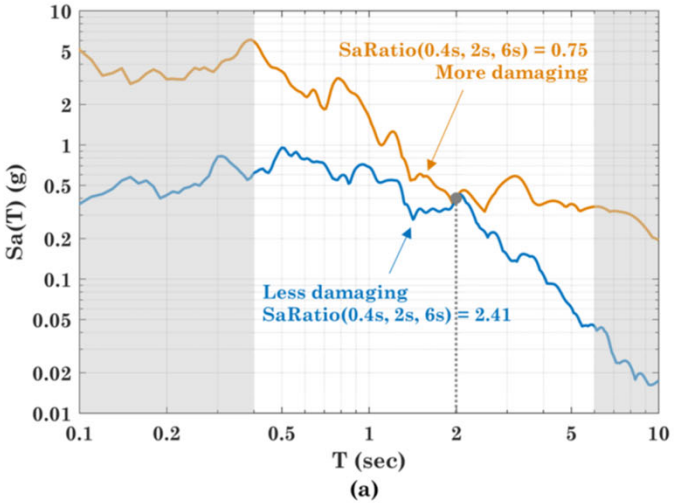
Workflow: Estimating Response



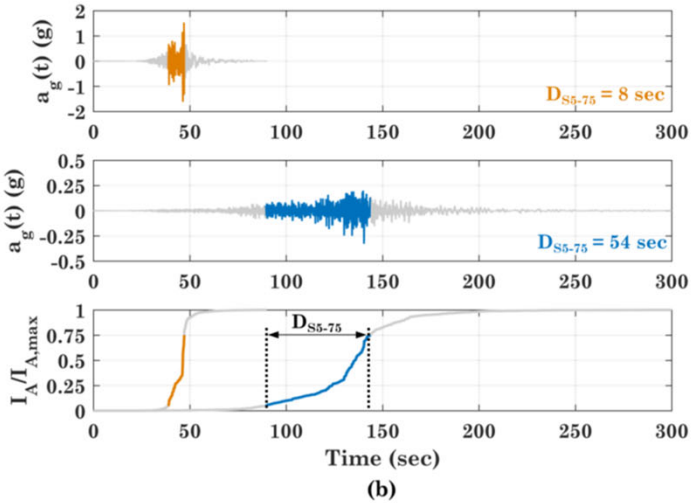




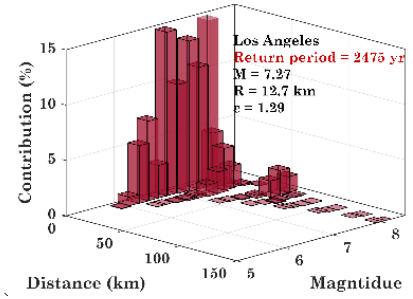
Workflow Module – Surrogate Models

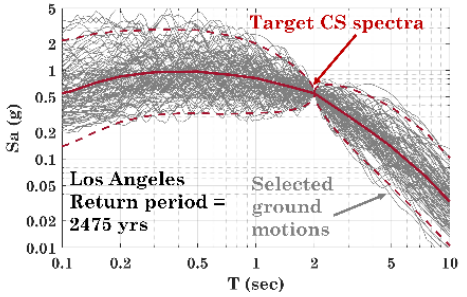


Spectral Shape



Significant Duration



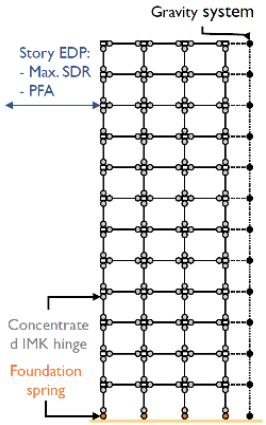


Ground Motion Characteristics: Sa(T) intensity, Spectral Shape, Duration …

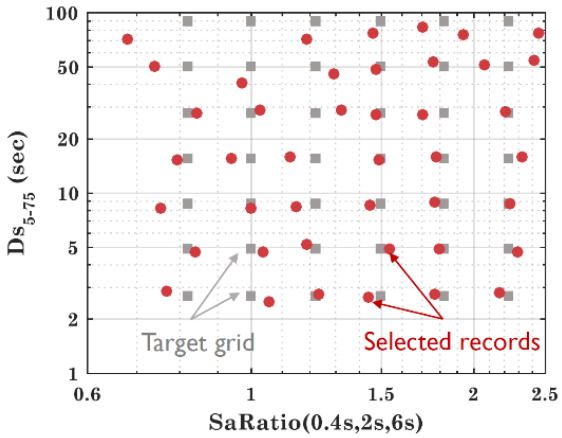
Structural Analysis Strategies:

1. Multi-Stripe Analyses (GMs selected/scaled/matched to characteristic targets)
2. Site-Specific Adjustments to Incremental Dynamic Analyses (SAF-IDA)

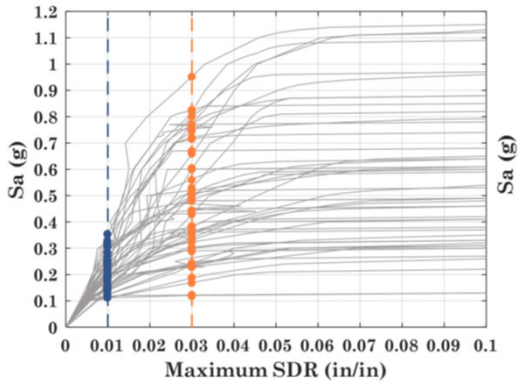
Workflow Module – Surrogate Models



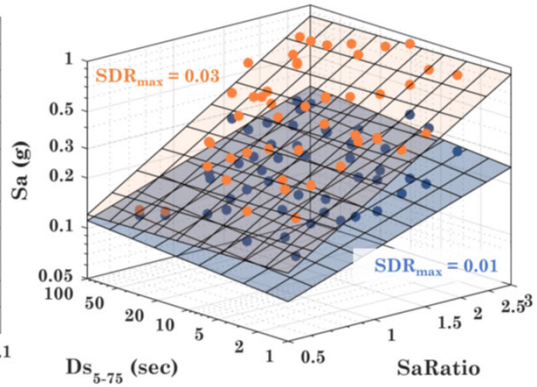
12-story SMF



Grided Ground Motions



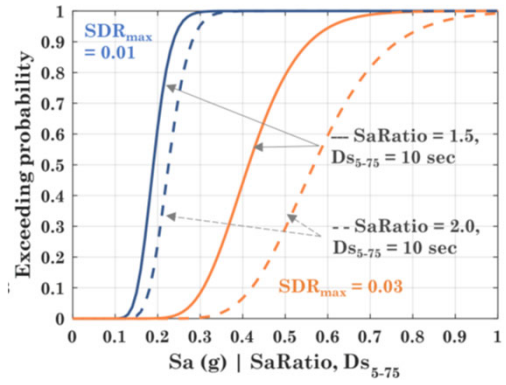
Conventional IDA



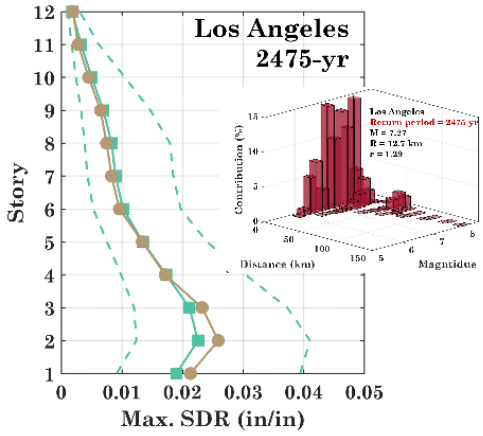
EDP>edp: Sa(SaRatio, Ds)

Site-Specific Adjustment Framework for IDA (SAF-IDA)

- Compute IDA response using grided ground motion set
- Fit *ln*Sa-linear model for each EDP threshold of interest
- Establish SaRatio and Ds based on site and Sa intensity
- Compute adjusted EDP's (median, P(EDP>edp), etc.)



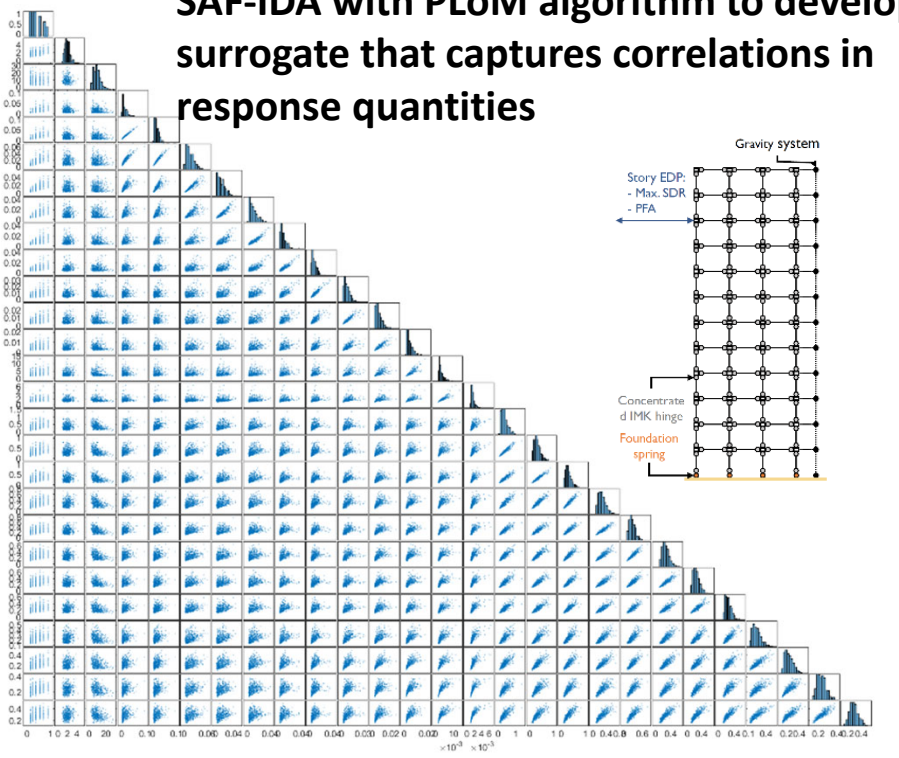
P(EDP>edp|Sa,SaRatio, Ds)



MSA vs SAF-IDA

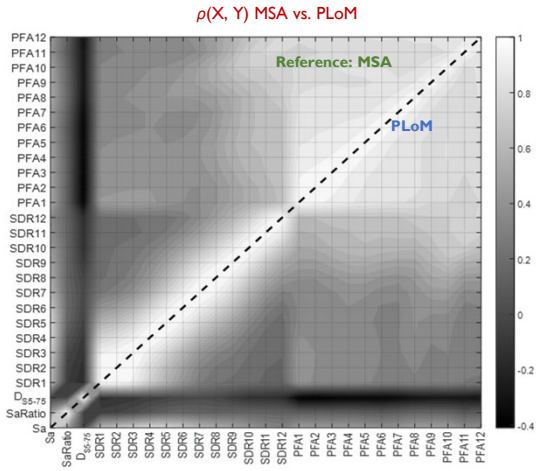
Workflow Module – Surrogate Models

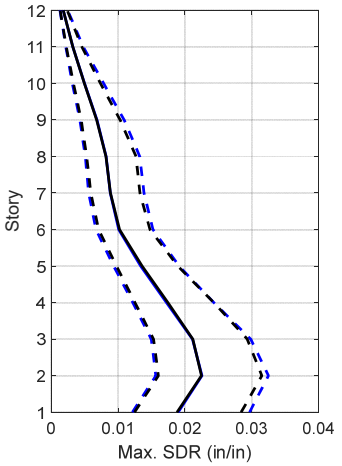
SAF-IDA with PLoM algorithm to develop surrogate that captures correlations in response quantities

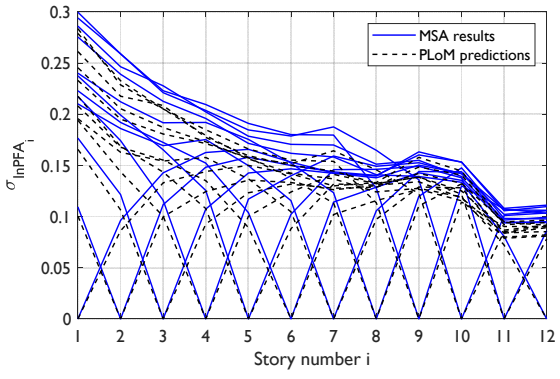


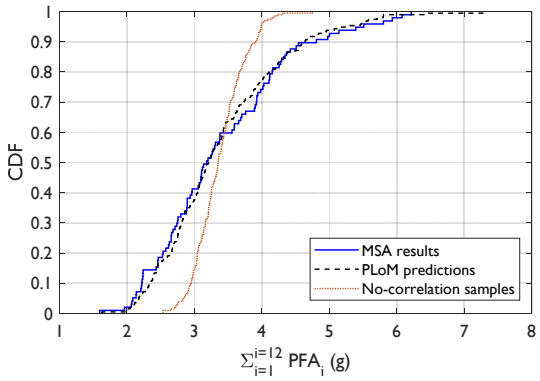
Correlations in GM Input and Response Parameters

Algorithm: Probabilistic Learning on Manifolds (PLoM)
Soize and Ghanem (2020)



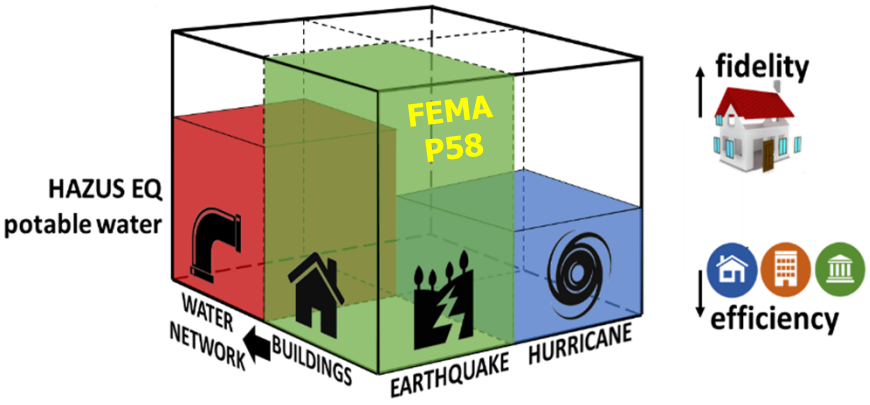


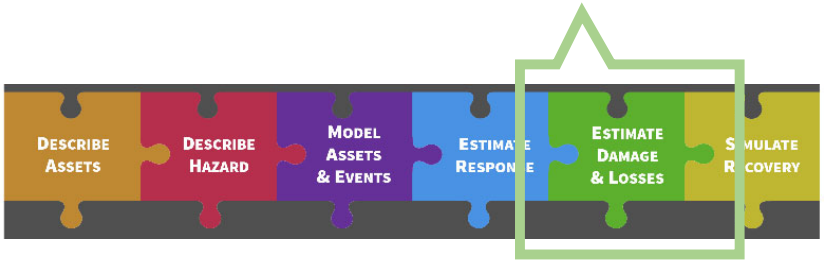




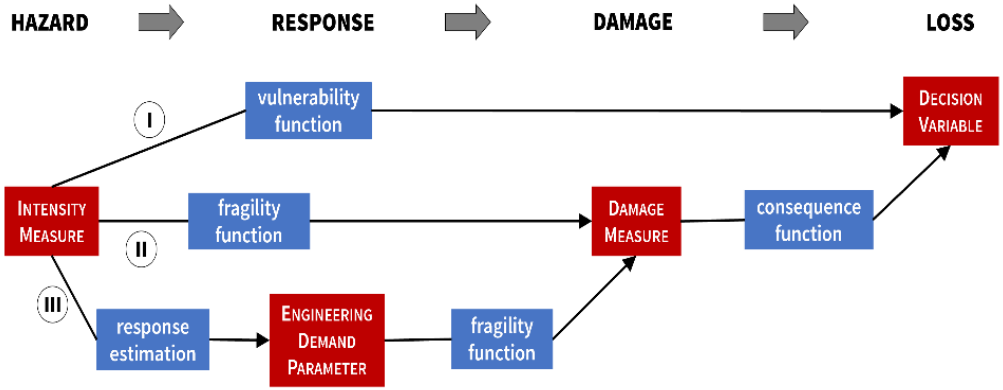
Comparison of MSA vs PLoM Surrogate Model

Workflow: Damage and Losses





Multi-Fidelity Framework



SimCenter - PELICUN Library

(PROBABILISTIC ESTIMATION OF LOSSES, INJURIES, & COMMUNITY RESILIENCE UNDER NATURAL DISASTERS)

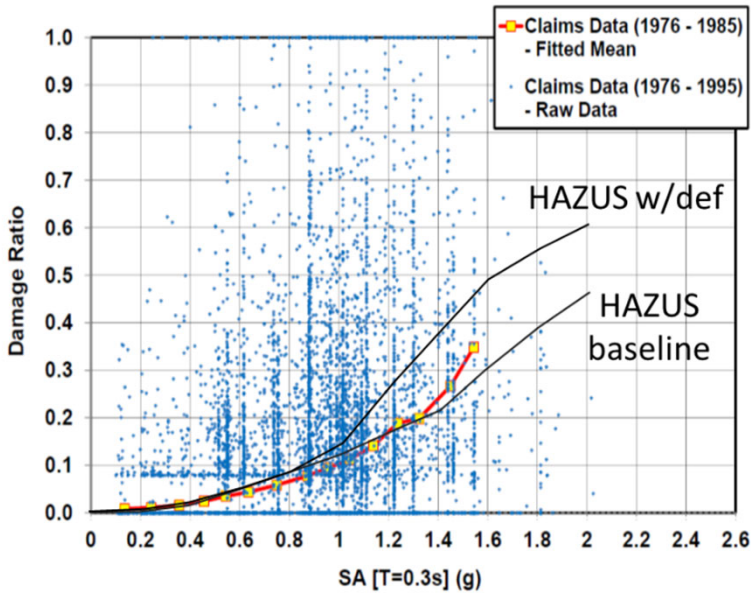
Workflow Application: PBE Risk Mitigation

PBE

Application - Economic Benefits of Cripple Wall Retrofit

Photo Credit: CEA

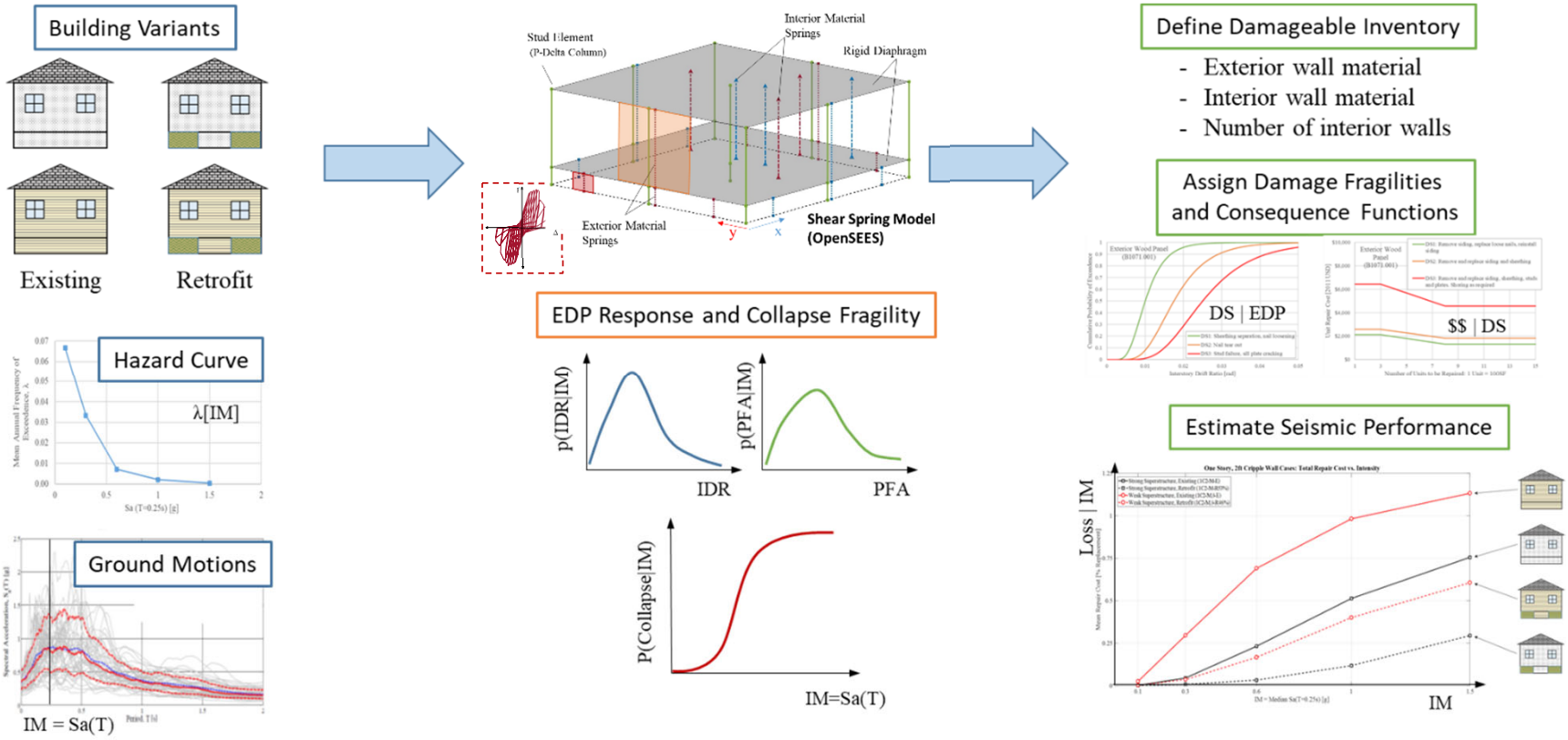
Observations of cripple wall retrofit in 2014 South Napa EQ



Limits to "The Law of Averages"

PEER CEA CALIFORNIA EARTHQUAKE AUTHORITY

Workflow Application: PBE Risk Mitigation

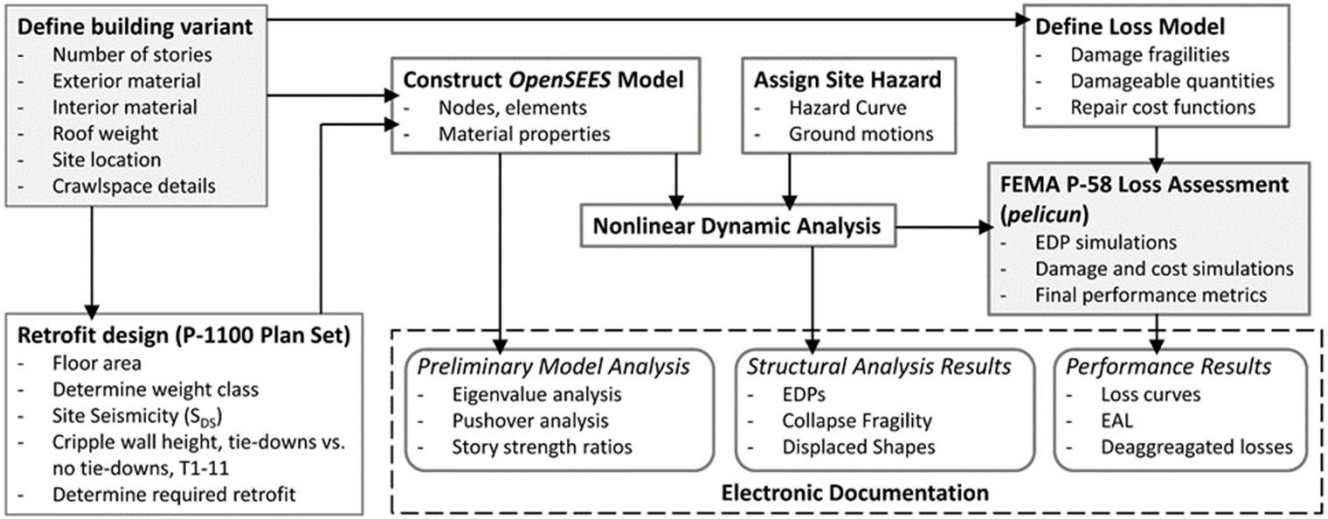


FEMA P-58 Loss Assessment (OpenSees-Pelicun Workflow)

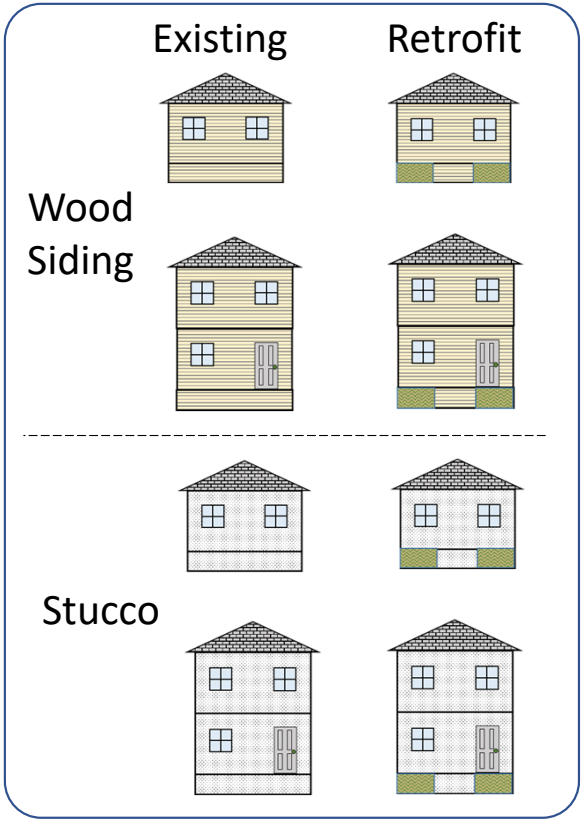
Workflow Application: PBE Risk Mitigation

Challenge:

- Develop about 250 (125 pairs) of damage (loss) curves
- Entails ~110,000 nonlinear dynamic analyses and millions of FEMA P-58 statistical damage/loss simulations



Computational Workflow – BIM to OpenSees to Pelicun to Database



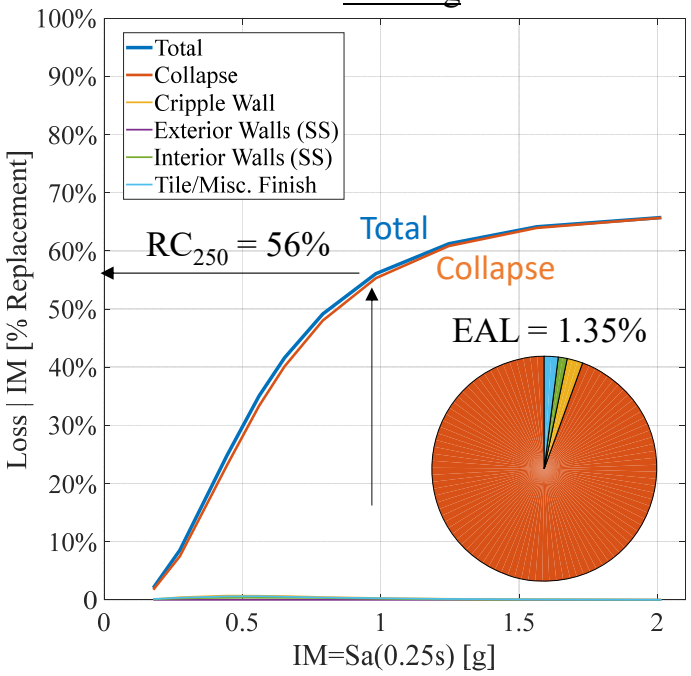
Workflow Application: PBE Risk Mitigation

P[C | MCE] = 98%

RC_{250} = 56%

EAL = 1.35%

Existing

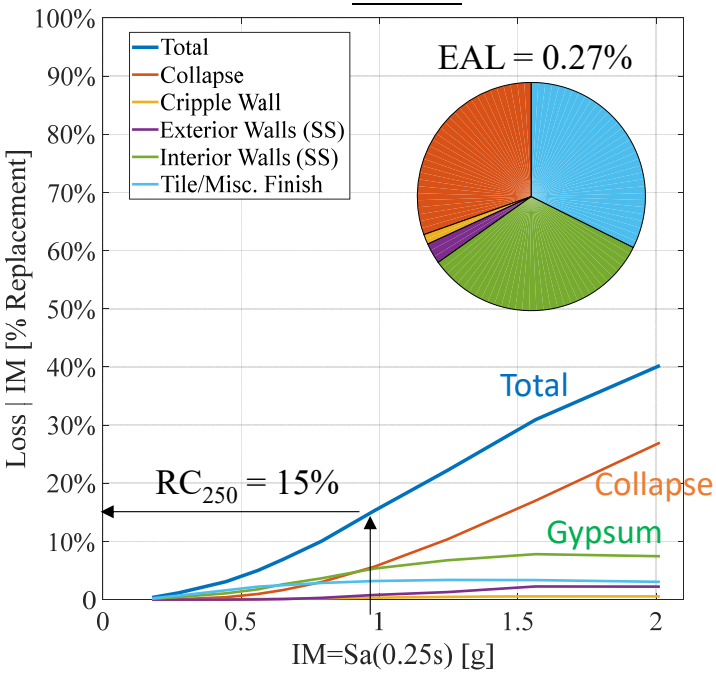


P[C | MCE] = 22%

RC_{250} = 15%

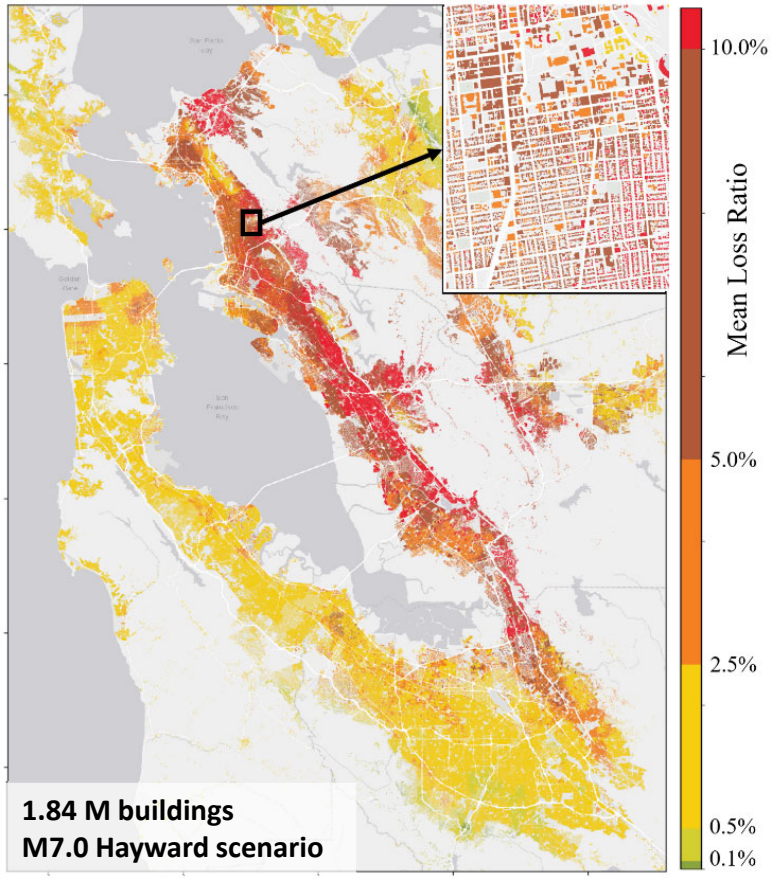
EAL = 0.27%

Retrofit



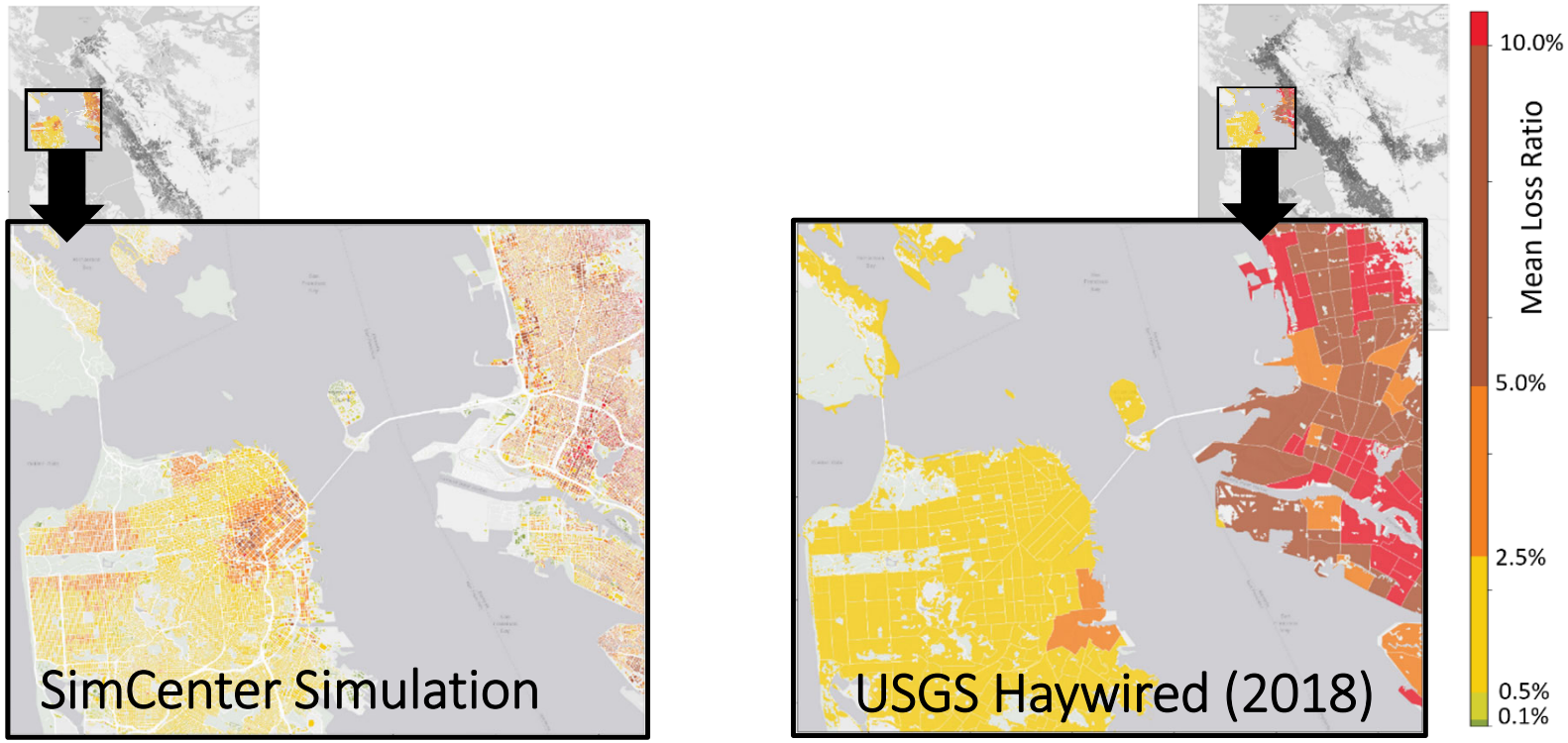
Workflow Testbed – M7.0 Hayward (SF Bay Area)

- **M7.0 Hayward simulation (LLNL-SW4)**
- **1.84 M individual buildings**
- **Parcel-level inventory enhanced by AI tools**
- **Building Evaluations**
  - *HAZUS building configurations*
  - *OpenSees MDOF (story shear) models*
  - *25 response realizations*
  - *HAZUS story-level damage functions*
  - *modeling uncertainty*
- **DesignSafe HPC (Stampede2)**
  - *16 hr runtime on 12,800 cores*



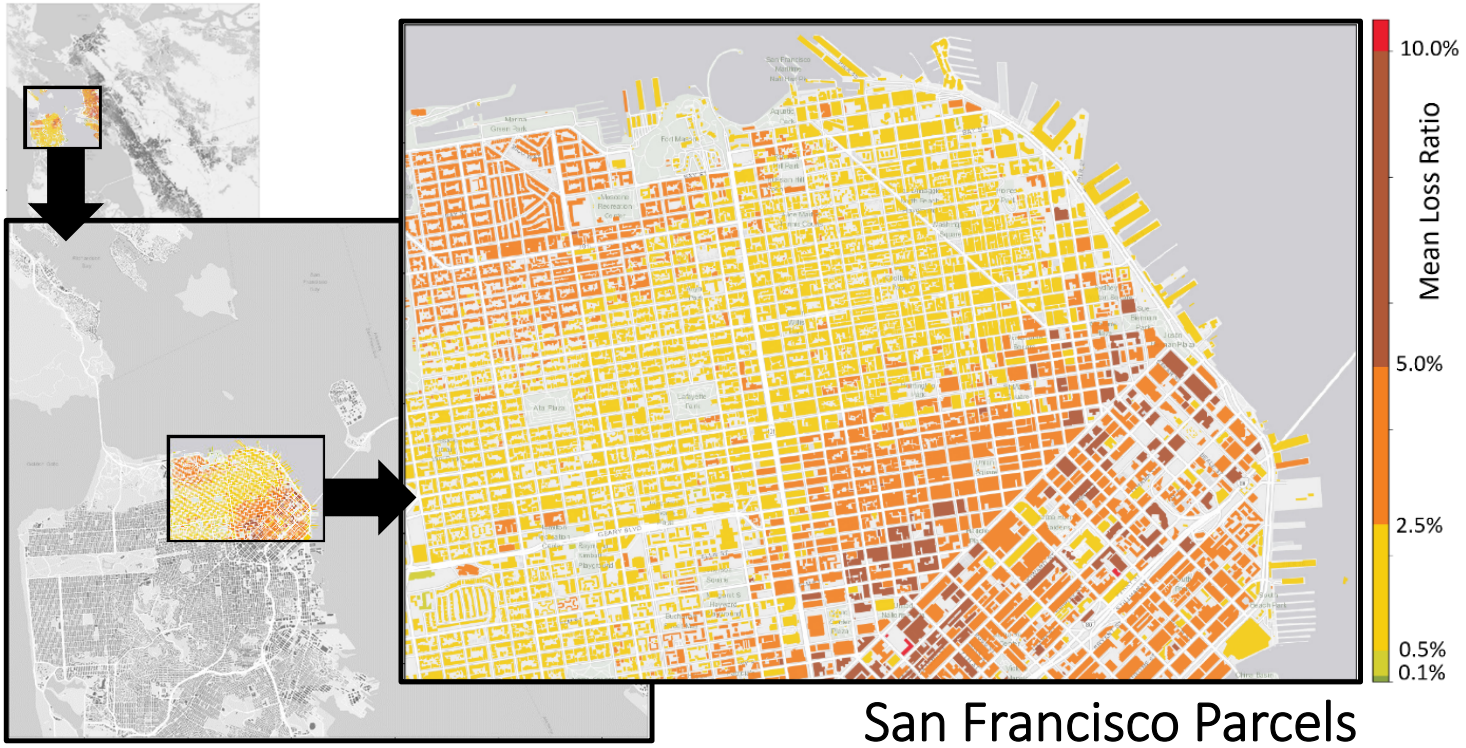
Workflow Testbed – M7.0 Hayward (SF Bay Area)

High Resolution Modeling:
Building parcel versus census block resolution of losses



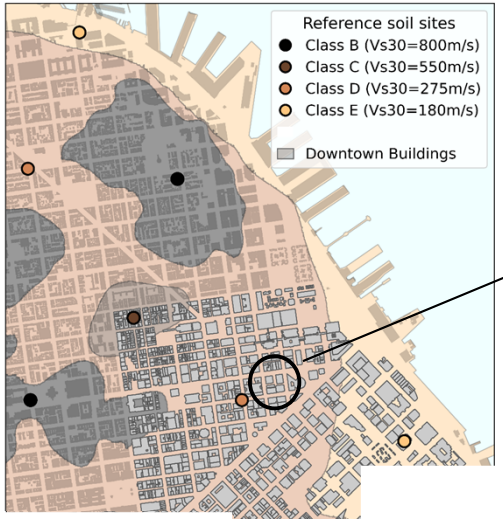
Workflow Testbed – M7.0 Hayward (SF Bay Area)

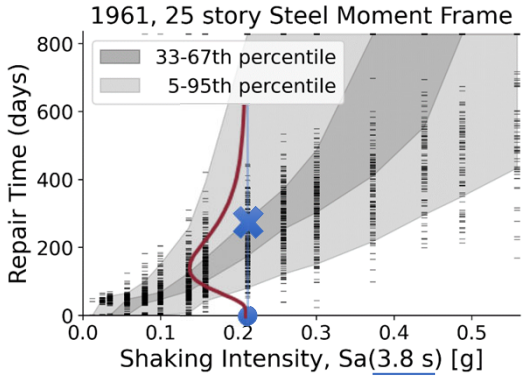
High Resolution Modeling: Parcel-level resolution enables unprecedented quantification of *engineered interventions for policy level decisions*

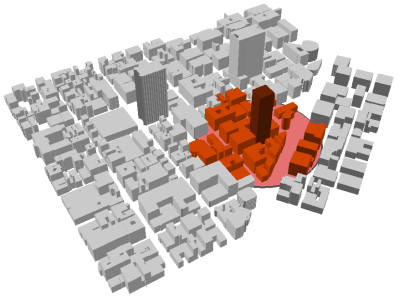


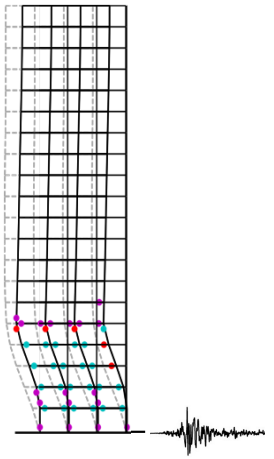
San Francisco Parcels

SF Downtown Recovery

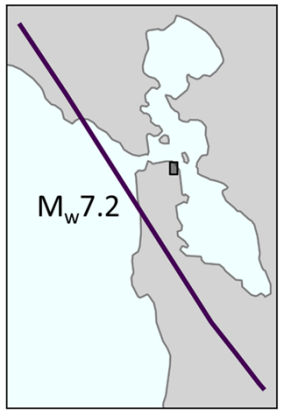


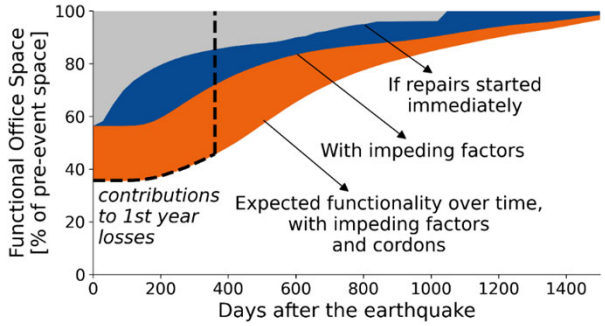




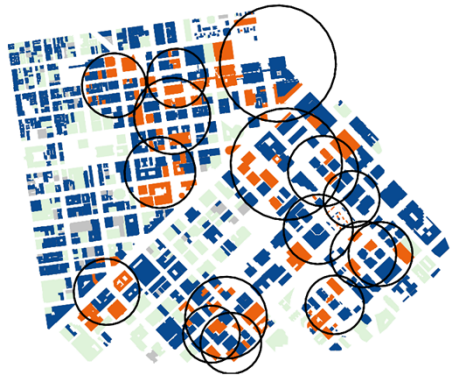


Influence of Tall Building Cordons on Recovery

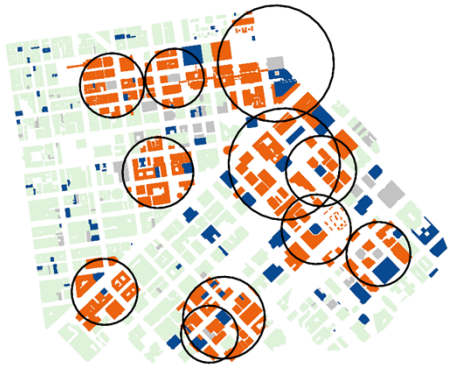




Recovery of Office Space

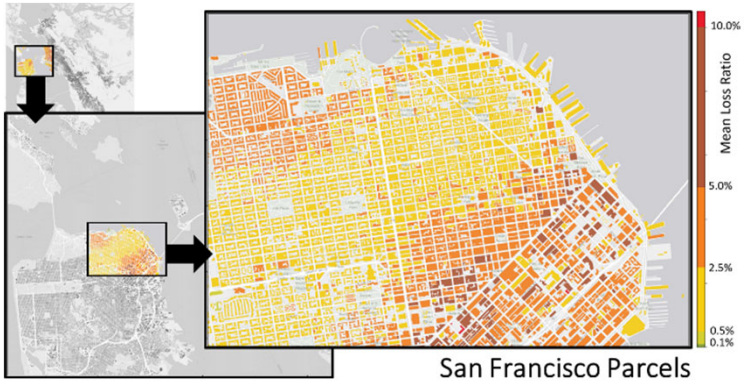


4 months



12 months

High Resolution Simulation of EQ Impact & Recovery



Modeling of Uncertainties and Correlations

Hazard (Ground Motion) Modeling

- EQ Rupture
- Geology/Wave Propagation
- Local Site (Geotechnical) Conditions

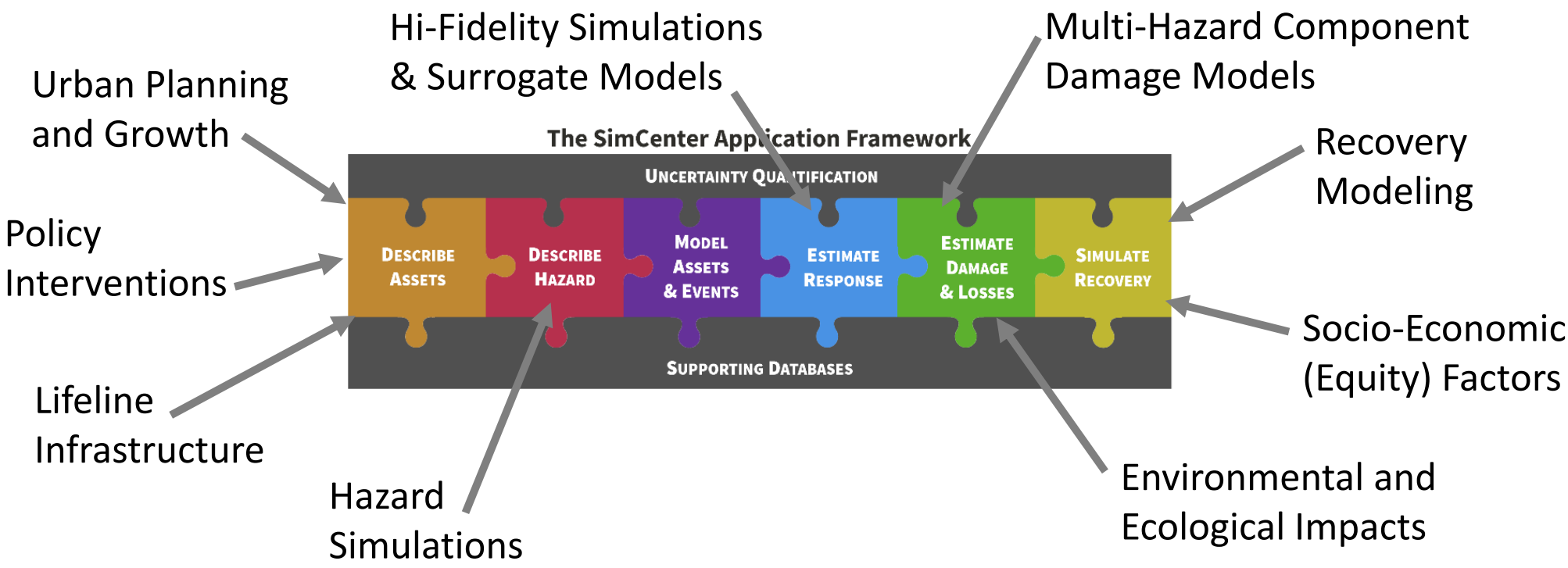
Damage, Direct Losses, Functional Impact

- Building Characteristics (configuration, age, type, etc.)
- Building Response (quality, materials, details, etc.)
- Building Functional Sector
- Transportation & Utility Components/Systems

Recovery and Impact

- Impeding Factors (permitting, cordons, services, …)
- Socio-Economic Factors (business interruption, demand surge, equity, ...)
- *Other Factors …*

Extensible Workflow Framework



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