NHERI SimCenter Application Framework for Simulating the Regional-Scale Impacts of Natural Hazards on the Built Environment

Disclosure: The following is a condensed version of "A Cloud-enabled Application Framework for Simulating Regional-scale Impacts of Natural Hazards on the Built Environment," *Frontiers in Built Environment*, 25 November 2020 (https://doi.org/10.3389/fbuil.2020.558706), written by Gregory G. Deierlein[1], Frank McKenna[2], Adam Zsarnóczay[1], Tracy Kijewski-Correa[3], Ahsan Kareem[3], Wael Elhaddad[2], Laura Lowes[4], Matthew J. Schoettler[2], Sanjay Govindjee[2]

Executive Summary

With the goal of facilitating evaluation and mitigation of natural hazard risk, the NHERI SimCenter is developing computational workflows for regional hazard simulations. These simulations enable researchers to combine detailed assessments of individual facilities with comprehensive regional-scale simulations of natural hazard effects. By integrating multi-fidelity and multi-resolution data and models to assess natural hazard impacts on buildings, infrastructure systems and other constructed facilities, the approach enables the engineering analysis of public policies and socio-economic impacts. Effective development of platforms for high-resolution regional simulations requires modular workflows that can integrate state-of-the-art models with information technologies and high-performance computing resources. Developed and disseminated as open-source software on the NHERI Design Safe Cyberinfrastructure, the computational models and workflows are enabling multi-disciplinary collaboration on research to mitigate the effects of natural hazard disasters.

1 Introduction and Overview of Computational Framework for Regional Simulation

Advances in computing resources and computing technology as well as advances in computational modeling of natural hazard events and their damaging effects on the built environment make it possible for **researchers** and **superusers** to develop regional models simulating the effect of natural hazard events and interrogate these models to better understand the risk and risk reduction that can be achieved by various mitigation strategies.

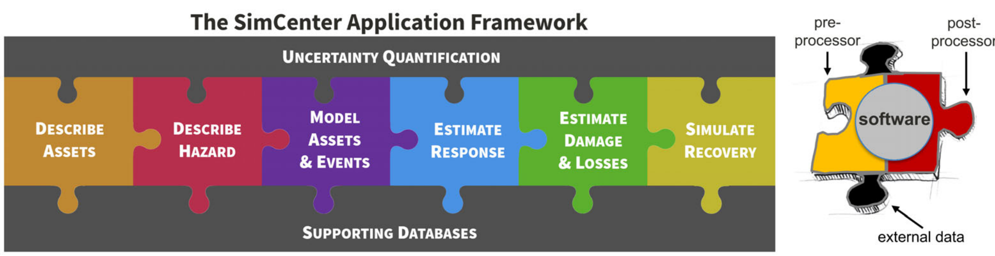

Figure 1 – Modules of the Software Application Framework developed by the SimCenter

Figure 1 illustrates the basic framework for simulation to assess natural hazard risk that is captured by SimCenter regional simulation platform. Moving from left to right, the process is (1) characterization of the assets that compose the built environment and description of the hazard (e.g., earthquake ground shaking), (2) modeling assets and hazard events, (3) simulation to estimate response of assets, (4) damage analyses to quantify asset damage, and (5) consequence analyses to evaluate the resulting risks to life safety, economic losses, and downtime. Input and output variables from each stage of the assessment are clearly defined as part of an underlying probabilistic formulation to propagate statistical data through the analyses. The resulting performance data inform decisions about the design and/or risk management of the facility.

2 SimCenter Framework Data, Components, and Applications

Figure 2 is a more detailed abstraction of the framework, where the items listed across the bottom of the figure represent key components and the applications shown higher in the figure are workflow applications that the SimCenter has developed (McKenna 2020). components include the following:

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BE – Built Environment Inventory: The *BE* comprises meta-data and data files that define the inventory of physical assets (e.g. buildings) for a regional simulation. To facilitate development of inventories, the SimCenter developed artificial intelligence (AI) tools for building inventory data collections (BRAILS, Wang et al. 2019) and for data enhancement (SURF, Wang 2019), along with web data query/collection techniques.

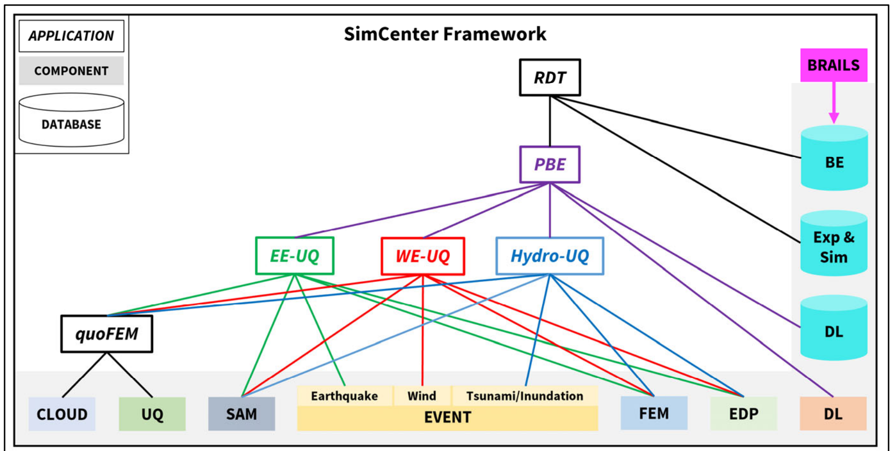

Figure 2 – SimCenter Framework Components and

EVENT – Hazard Event: The *EVENT* consists of meta-data and data files that define the hazard data (e.g., earthquake ground motions, wind fields, storm surge inundation, tsunami inundation). For earthquake hazard studies, the SimCenter workflow tools include software applications for (i) generating earthquake target spectra from the USGS OpenSHA web service, (ii) selecting and scaling recorded ground motions from the PEER NGA database, (iii) generating simulated stochastic ground motions, and (iv) ingesting simulated ground motions from databases of simulated and recorded ground motions. For wind and storm surge studies, the workflow can support (i) generating wind field time histories stochastically or using OpenFOAM (2020), (ii) incorporating experimental wind tunnel datasets utilizing online resources such as Vortex Winds (Kareem and Kwon, 2017) and the TPU Aerodynamic Database (TPU 2020) , or a user's own local dataset, and (iii) interfaces for querying and ingesting wind speeds and storm surge inundation heights from external applications.

SAM – Structural Analysis Model: The *SAM* is the workflow component that includes rule-based, AI and other applications to translate descriptive information from the built environment inventory into information used to create models for simulating asset response to hazard loading.

FEM – Finite Element Modeling: The *FEM* module consists primarily of wrappers for input/output to existing finite element software to simulate the response of structures and geotechnical materials to earthquake ground shaking, wind, storm surge wave loading, and tsunami wave loading.

EDP – Engineering Demand Parameters: The *EDP* represents the workflow component that defines and manages the output of hazard-induced deformation or other demands from a finite element or other type of analysis model for input into the damage and loss assessment.

DL – Damage and Losses: DL is the workflow component where damage and losses are calculated for the assets in the built environment inventory. Since these calculations are essential to all performance assessments and not readily available in existing software, the SimCenter developed an application framework called PELICUN, Probabilistic Estimation of Losses, Injuries and Community Resilience Under Natural Disasters, (Zsarnóczay and Deierlein, 2020, Zsarnóczay, 2019) to generalize the FEMA P-58 methodology to evaluate damage and losses in buildings and other facilities under earthquakes, hurricanes and other hazards.

UQ – Uncertainty Quantification: The *UQ* component provides an interface to software and routines for methods of uncertainty quantification that can be interfaced with other components. DAKOTA (Adams et al., 2014) offers a range of methods for uncertainty quantification and is supported by *UQ*.

DL Data: Databases of fragility curves for damage and loss calculations for various types of facilities (buildings, bridges, etc.) subjected to demands from various hazards (earthquake, wind, surge).

Exp/Sim Data: Databases of experimental and/or computational research data that is utilized for machine learning *SAM* applications and code validation.

3 Illustrative Testbed Applications of Regional Simulations

To demonstrate the features and capabilities of the cloud-based computational workflows for regional simulation, two testbed studies have been developed. These are an earthquake scenario for the San Francisco Bay area and a hurricane scenario for the Atlantic City region of the New Jersey coast. These testbeds are presented in detail in Deierlein et al. (2020) and the computational framework is presented on the SimCenter website (https://simcenter.designsafe-ci.org/research-tools/r2dtool/).

The San Francisco Bay Area Scenario is presented here. This scenario employs the regional risk assessment framework to assess the performance of 1.84 M buildings in San Francisco, Oakland, San Jose and surrounding areas due to a Mw 7.0 earthquake rupture on the Hayward fault. Components of the scenario are discussed below. Mean loss rations for individual buildings are presented in Figure 3.

Building Inventory: A parcel-level inventory of buildings in the Bay Area was developed by UrbanSim (Waddell 2002) using public resources. The database includes locations (latitude, longitude), total floor area, number of stories, year of construction, and occupancy type for each building. The building location and geometry were refined by merging the UrbanSim database with the publicly available Microsoft Building Footprint data (Microsoft 2020). These data were used to populate two additional attributes, replacement cost and structure type, using a ruleset based on local design practice and real estate pricing (Elhaddad et al. 2019).

Earthquake Event: The ground motions for the Mw 7.0 Hayward earthquake were simulated by Rodgers et al. (2019) at the Lawrence Livermore National Lab using the SW4 finite difference code (Petersson and Sjogreen, 2017). Simulation data comprised three-component seismograms for grid points spaced at 2 km throughout the study region. A set of 25 seismograms are assigned to each building using weighted random sampling of the time histories at the nearest grid points.

Response Simulation: The nonlinear response of buildings to ground shaking is simulated using OpenSees (OpenSees 2020) and an application, MDOF-LU, that generates an idealized structural analysis model based on structure type, height, plan area, year of construction and the type of occupancy. The MDOF-LU application is based on a method developed by Lu et al. (2014) that uses the building configurations in the HAZUS earthquake technical manual and corresponding capacity curve descriptions to define a multi-story nonlinear shear-column model with lumped masses.

Performance Assessment: Building performance assessment was performed using PELICUN (Zsarnóczay and Deierlein, 2020), where damage and losses are calculated with story-level fragility functions based on the peak story drift and floor acceleration demands. The story-based damage and loss fragility functions are derived from corresponding building-level damage and loss functions from the HAZUS earthquake model (FEMA, 2018) based on the characteristic data for each building (e.g., year of construction, structure type, occupancy type).

Illustrative Results: An example of the losses calculated for the Mw 7.0 Hayward scenario are shown in Figure 3. The color shading represents the loss ratios for each building, calculated as the mean repair costs normalized by the building replacement value.

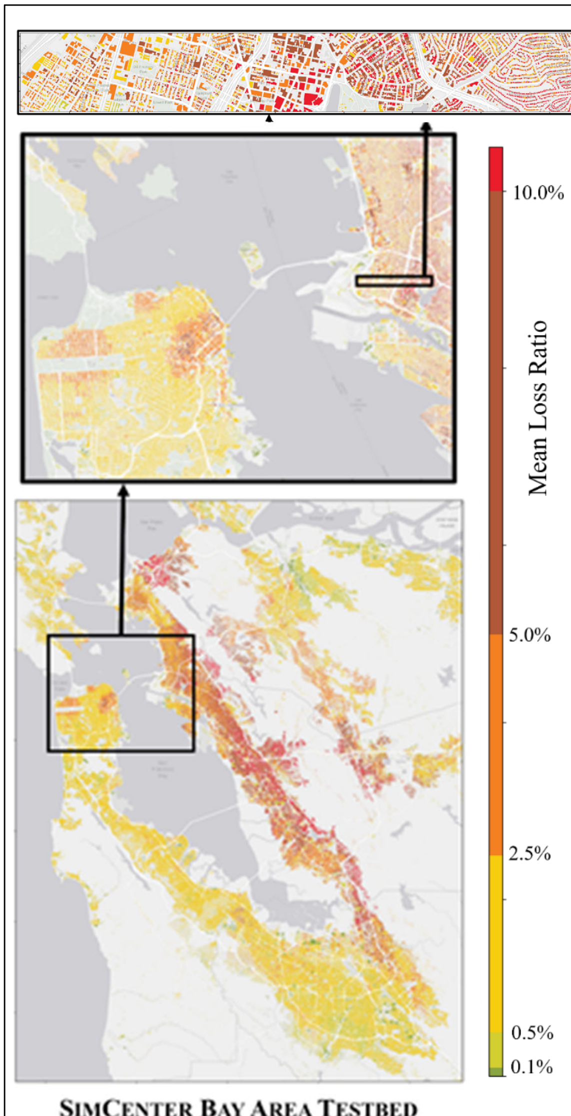

Figure 3 – Simulated Building Loss Ratios

4 Concluding Remarks

The computational open source workflow tools and applications that have been released and continue to be developed by the SimCenter are organized around a framework to facilitate the integration and sharing of models and data for comprehensive analyses of natural hazards and their effects on the built environment. The development and testbed applications of these workflows have identified how open data and high-fidelity simulation capabilities can shift the paradigm from empirical fragilities projecting losses over census blocks to direct simulation of site-specific building performance for natural hazard scenarios. These applications have also identified gaps and limitations of available data and models and how the contributions of the research community can be leveraged to advance regional simulation of damage, consequences, and recovery of buildings and lifeline systems. The SimCenter looks forward to continued collaboration with the natural hazard community to develop and expand computational workflows for integrating data and simulation models across multidisciplinary fields.

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