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Leveraging automation, optimization, and distributed computing to perform high-fidelity regional seismic risk and resilience assessment

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ABSTRACT

The ability to quantify regional-scale risk of building inventories is one of the essential components of evaluating community resilience. At its core, resilience-based assessments seek to a quantify the functionality of the buildings, supporting infrastructure, and their interdependencies after an earthquake event. Historically, the mandated design codes for buildings have been governed by life-safety standards with no emphasis on economic loss or functional recovery. Recent advancements in the earthquake engineering domain have put in motion a national-level initiative to make functional recovery the baseline seismic performance standard. While the importance of resilience-based design standards has been broadly acknowledged by engineers, scientists, and policymakers, there is a need to develop efficient regional-scale computational frameworks. Such frameworks would be instrumental in 1) quantifying the risk and resilience of buildings across a region and 2) addressing the computational challenges of performing a large-scale assessment. The quantified regional risk and resilience metrics, in turn, would determine the shape and form in which the community resilience objectives are incorporated into design codes.

The primary objective of this study is to develop a suite of computational engines that leverage automation, optimization, and high-performing computing resources to facilitate high-fidelity (HiFi) seismic risk and resilience assessments. In the context of regional-level assessment, HiFi risk simulations are based on the modern performance-based earthquake engineering (PBEE) methodology, which is designed to conduct individualized and explicit loss (e.g., financial loss and functional recovery time) analysis. The methodology is inherently cumbersome and compute-intensive as it relies on building-, site-, and hazard-specific information that requires substantial data preprocessing. At its core, the methodology systematically transforms seismic hazard into quantifiable risk metrics through three major computational modules: 1) probabilistic seismic hazard analysis (PSHA), 2) probabilistic seismic demand analysis (PSDA), and 3) loss analysis using Monte Carlo simulation. The PSHA is a mathematical representation of the seismic hazard that encompasses uncertainties in the size, location, rate of occurrence, and resulting ground motions that a particular site is likely to observe. Subsequently, the PSDA computes the structural response, ideally via nonlinear response history analyses using the ground motion records selected as part of the PSHA. The distribution of the structural response is ultimately used to perform Monte Carlo simulation-based loss assessment. In this study, the economic loss is assessed following the FEMA P-58 guidelines while the time to regain functionality of a building is calculated based on the ATC-138 procedure. The three modules are executed sequentially as each module hinges on the inputs from the preceding one.

To scale the implementation of a building- and site-specific risk assessment to a region, we developed a Python-based automation engine named "Auto-WoodSDA". Rooted in the PBEE methodology, the Auto-WoodSDA is an end-to-end computational tool that automates code-confirming seismic design, nonlinear dynamic analyses, and loss assessment of an individual building. For the scope of this study, the Auto-WoodSDA is equipped to generate three-dimensional numerical (3D) numerical models of single- and multi-family residential woodframe buildings. Although computationally demanding, the explicit 3D nonlinear time history analysis is adopted as a trade-off to maintain high confidence in the estimated loss metrics. To circumvent the computational inefficiencies at large-scale assessments, we exploit high-performance computing (HPC) resources. The Auto-WoodSDA is a sequential task as seismic design, nonlinear analysis, and loss assessment need to be performed in successive order. However, once the hazard is determined at an individual site, the loss assessment is an independent task that enables the use of distributed computing.

Regional hazard simulation is a complex problem that involves computationally extensive high-dimensional large-scale mathematical simulations. Ultimately, the hazard simulation produces a distribution of shaking intensity maps and representative ground motion records for all the sites across a region. A consistent hazard simulation must consider spatial correlation of shaking intensities both within and between the possible rupture scenarios. The rupture scenarios are selected from the catalog of OpenSHA's Mean UCERF3 model. Moreover, the spatial correlations are incorporated in the intensity maps through eigenvalue decomposition which has a time complexity of O(n3) for n-sites across a region. Once the distribution of shaking intensity is determined, a unique set of ground motion records are selected to enable site-specific nonlinear dynamic analysis. To alleviate the computational burden imposed by hazard simulation and ground motion selection, we leverage the Open MPI library to parallelize the workflow. Specifically, the MPI module is adopted to parallelize the computation on distributed compute nodes in the HPC. The ground motion selection is also parallelized through the MPI module to optimize the Input/Output flow.

In addition to leveraging automation and HPC to address the computation bottleneck, we also optimize the number of unique HiFi simulations such that the computational resources are not exhausted on sites that are likely to experience an identical distribution of losses. Although the optimization routine is trivial, it is based on the proposed strategies that allow the users to control the level of fidelity by defining the granularity of building and hazard representation at a regional scale. The optimization routine is projected to reduce the number of HiFi simulations by 20% in a region with at least 10,000 sites.

Finally, the suite of computational engines is implemented to assess the risk and resilience of residential buildings in the City of Los Angeles. The inventory consists of 17,241 woodframe buildings that were permitted since 2013. First, we performed regional hazard simulation to generate shaking intensity maps and concurrently select 40 ground motion pairs at each site. Utilizing parallel computing across 256 CPUs, the hazard simulation is projected to take 70 CPU hours. Subsequently, an optimization routine is implemented to determine that 14,000 HiFi risk simulations were sufficient to represent the risk at all 17,241 sites. Lastly, Auto-WoodSDA is initialized on 256 distributed CPUs to perform HiFi loss assessment. On average, the end-to-end risk assessment takes 100 minutes per site per node. Assuming 250 nodes are available uninterrupted, the HiFi regional risk simulation is estimated to take less than 250 CPU hours.

Bridging the gap between the HiFi regional risk assessment and computational expense has far-reaching implications. The computational engines developed in this study will pave the path forward to optimize the key building design parameters (e.g., response modification factor (R), importance factor (I_e), and displacement amplification factor (C_d)) to achieve a regional-level functional recovery-based performance objective. Such a study will be crucial in providing a scientific basis for including the resilience-based performance objectives into the design codes.