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An End-to-End Computational Platform to Automate Seismic Design, Nonlinear Analysis, and Loss Assessment of Woodframe Buildings

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ABSTRACT

Due to their popularity, especially in residential construction, the seismic performance of woodframe buildings is an integral component of community resilience. To enable a comprehensive assessment that is rooted in the performance-based earthquake engineering framework, an end-to-end framework that automates the seismic design, nonlinear analysis and performance assessment is developed. The framework is formulated as a workflow and materialized into a computational platform using an object-oriented programming paradigm in the Python programming language. The workflow is presented as a ready-to-implement computational platform named "Auto-WoodSDA." The computational platform is developed to perform three major tasks: 1) generate code-conforming seismic designs of new buildings, 2) create a numerical model and perform nonlinear static and dynamic analyses, and 3) assess economic losses. The automated tool imports user inputs such as basic building information and seismic design parameters on one end and produces risk-informed seismic performance information such as expected annual loss on the other end, thus, effectively creating an "end-to-end" workflow. An example building is used to verify and validate the platform. The results obtained from the example implementation demonstrate the capability of the platform to reliably generate new designs, perform nonlinear analysis, and assess the economic loss of the woodframe buildings.

Introduction

The US housing inventory is dominated by woodframe buildings making up about 90 percent of all the residential construction. Despite being the most prevalent construction type, woodframe buildings have performed comparatively well in the historical earthquake events ensuring collapse safety as intended. However, the substantial nonstructural damage sustained during the 1989 Loma Prieta and 1994 Northridge earthquakes that resulted in significant economic losses highlighted some "beyond life safety" seismic vulnerabilities [1,2]. The vulnerabilities primarily stem from the design and construction practices. In general, the layout of a residential building is regular and symmetric with ample redundant elements. Oftentimes, the degree of redundancy is not well defined in any given building. When coupled with a prescriptive design methodology, which is overwhelmingly common in practice, the actual performance capacity of a residential woodframe building is not known. The inherent uncertainty in seismic performance has proved to be a boon in some historical earthquakes and a bane in others (e.g., the 1989 Loma Prieta and 1994 Northridge earthquakes). The substantial economic losses sustained by the residential dwellings in the last two major earthquakes

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are a clear indication that the performance-based assessment is essential to facilitating risk-informed decisions. More importantly, woodframe buildings are an integral part of community resilience because they support the functionality of a number of sectors (e.g., residential, commercial).

Fig. 1 shows the four fundamental steps involved in the second-generation performance-based earthquake engineering (PBEE) framework [3]: 1) ground motion (GM) hazard characterization, 2) structural response analysis, 3) damage analysis, and 4) loss assessment. Each step requires significant manual effort and computational resources. To overcome this challenge, a Python-based computational tool to AUTOmate WOODframe buildings' Seismic Design, analysis, and loss Assessment (Auto-WoodSDA) is proposed. The red box in Fig. 1 shows how the end-to-end platform implements the PBEE methodology. The primary objective of the Auto-WoodSDA platform (hereafter, WoodSDA) is to automate and streamline the methodology workflow for efficient implementation. The computational tool utilizes specified inputs on one end and produces risk-informed decision variables such as expected annual loss (EAL) on the other end, thus creating an "end-to-end" framework. WoodSDA disaggregates the workflow into four primary modules as illustrated in red in Fig. 1: 1) GM selection module, 2) design module, 3) modeling and analysis module, and 4) loss assessment module. This paper discusses the technical details of the latter three modules. The GM selection module was developed by the Natural Hazard Risk and Resiliency Institute [4]. The GM module requires minimal manual work to preprocess the selected records. Hence, it is initialized separately before executing the three suites of modules.

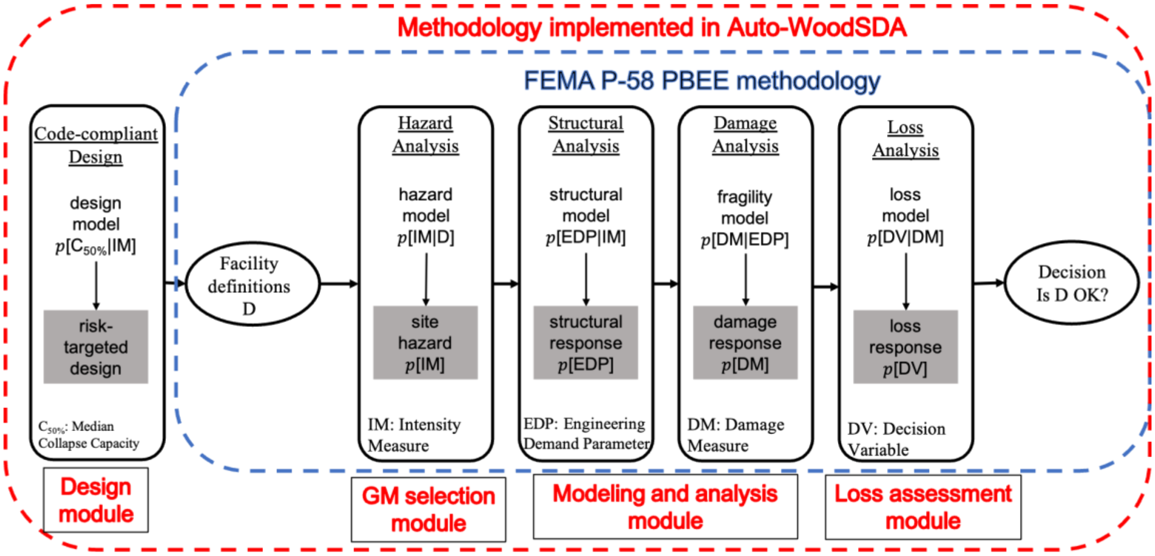

Figure 1. Overview of FEMA P-58 methodology and the modules implemented in the WoodSDA platform.

Design Module

The design module is the first tool initialized and executed in WoodSDA. Fig 2. shows a generalized workflow and the main steps followed in the iterative design process to generate code-compliant design. The design module is instantiated by importing user inputs such as the building information, shear wall database, and tie-down database. The databases consist of nominal strength capacity of the shear wall assembly and tie-down anchor rod, respectively. Given the required user inputs, the governing lateral seismic story force is computed. The story force is distributed to every shear wall in both transverse and longitudinal direction based on the diaphragm flexibility assumption. The module is equipped to handle a flexible or rigid diaphragm assumption, or the envelope analysis method. The floor level shear wall demand is then used to implement a search algorithm that finds the optimal shear wall assembly. The algorithm ensures that the selected assembly satisfies any user-specified detailing requirements such as nail size, nail spacing, panel thickness, panel material type, and D/C ratio. The apparent shear stiffness (Ga) of the optimal shear wall assembly is used to compute the elastic drift demand using the three-term shear wall deflection equation [5]. If the drift check is satisfied, the final design summary is outputted along with the Pinching4 material identifier [6]. Otherwise, the design is revisited to obtain the shear wall assembly with higher shear stiffness. However, if none of the shear wall assemblies in the database meet the strength or drift demand, an error message is printed out suggesting the user to revise the overall design.

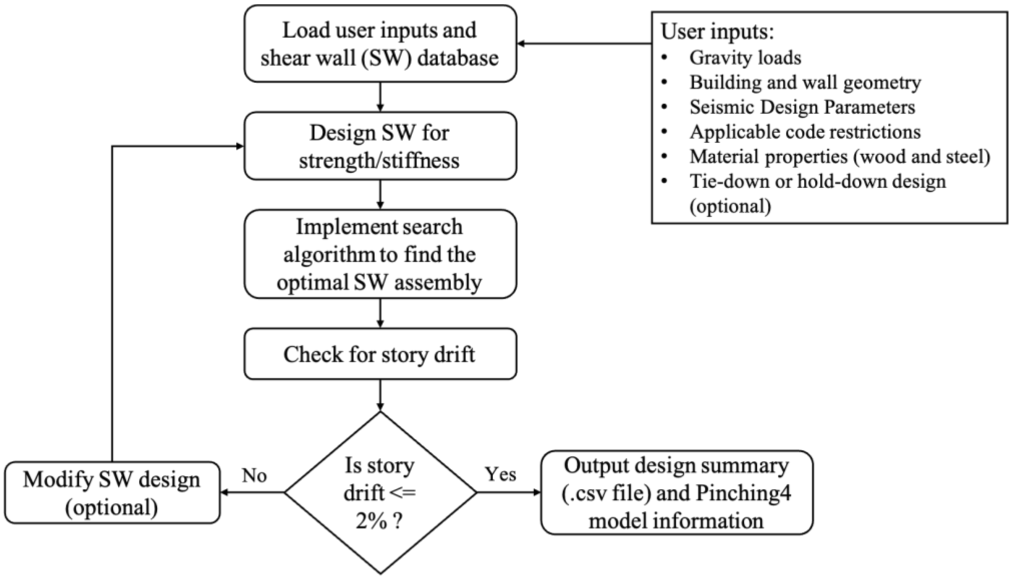

Figure 2. Flowchart of an iterative design process adopted in the design module.

Modeling and Analysis Module

The modeling and analysis module pipelines inputs (e.g., building information, Pinching4 material identifier, etc.) directly from the design module to generate nonlinear numerical models, simulates structural response, and conducts damage analysis. The modeling and analysis module used in the WoodSDA platform was originally developed by Yi [7] as a part of his PhD work to study the effectiveness of different retrofit schemes of soft weak, and open front (SWOF) and cripple wall buildings. The blue box in Fig. 3 highlights four major tasks executed in this module.

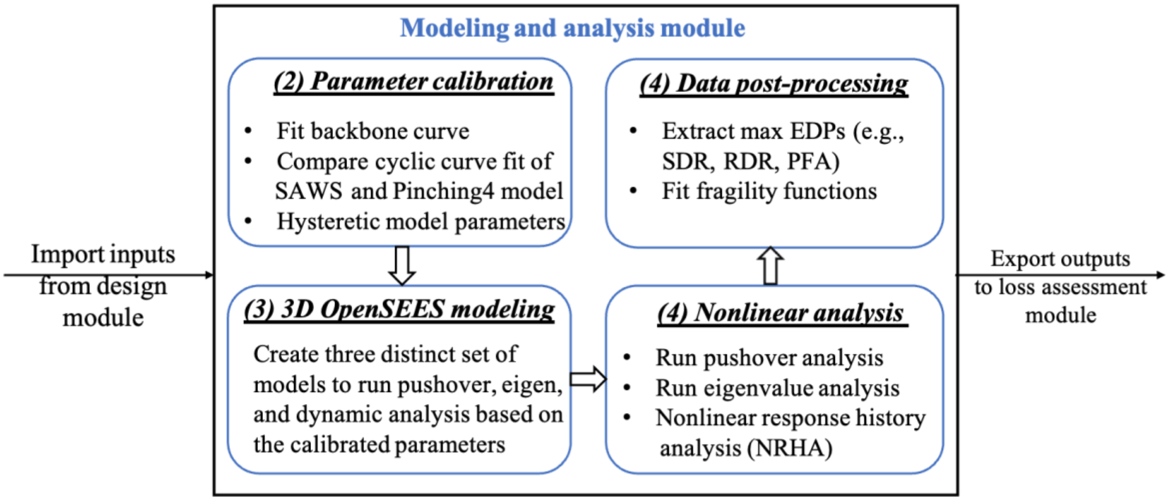

Figure 3. Overview of the major steps in the modeling and analysis module.

In the WoodSDA, to accurately capture nonlinear cyclic strength and stiffness degradation, the 22-parameter Pinching4 hysteresis model [6] is utilized. As shown in Fig 3. the first task is to calibrate the Pinching4 parameters for various shear wall archetypes. Due to the lack of the Pinching4 parameters available in the literature for wood shear walls, an iterative process is implemented to calibrate the Pinching4 parameters based on the commonly used SAWS parameters [8]. Following the hysteresis parameter calibration, three separate three-dimensional (3D) OpenSees [9] models are created to perform nonlinear static, eigenvalue, and dynamic analysis. Finally, damage analysis is performed to generate fundamental periods, modes, pushover curves, EDP data, and fragility functions which is then pipelined into the loss assessment module.

Loss Assessment Module

The loss assessment module integrates hazard characterization, structural analysis, and damage assessment to evaluate the decision variable in terms of economic loss. The intensity-based economic loss is computed for all hazard levels across all damage states. It follows a simulation-based procedure highlighted in Figure 7-1 and implements Eq. 7-1 of FEMA P-58 [3]. When integrated with the hazard curve, module produces the total expected annual loss (EAL) as the final output.

An Example Implementation

This paper utilizes a four-story multi-family dwelling archetype (archetype ID: *MFD-3B*) studied as a part of the ATC-116 Project which has been published in FEMA P-2139-2 [10]. For detailed information about the archetype, the reader is referred to the FEMA P-2139-2 document. The primary purpose of this example implementation is to verify and validate that the WoodSDA platform can produce reliable results as compared to the state-of-the-art study, FEMA P-2139-2. Based on a modal analysis, the fundamental period obtained using the WoodSDA (0.52 seconds) is found to be almost identical to the 0.51 seconds reported in the FEMA P2139-2. The pushover analysis produced peak normalized base shear of 34 percent of the total seismic weight as compared to the 35 percent presented in the FEMA P-2139-2. Similarly, the ultimate drift demand (drift at 80 percent peak strength) for the WoodSDA and FEMA 2139-2 were found to be 1.2 and 1.0 percent, respectively. Fig. 4 illustrates the comparison of the fragility function where the collapse fragility curve obtained from WoodSDA (black line) is in good agreement with the one obtained in the ATC-116 project (orange line) [10]. The comparable results demonstrate that the WoodSDA platform can reliably produce seismic designs and dynamic analysis results.

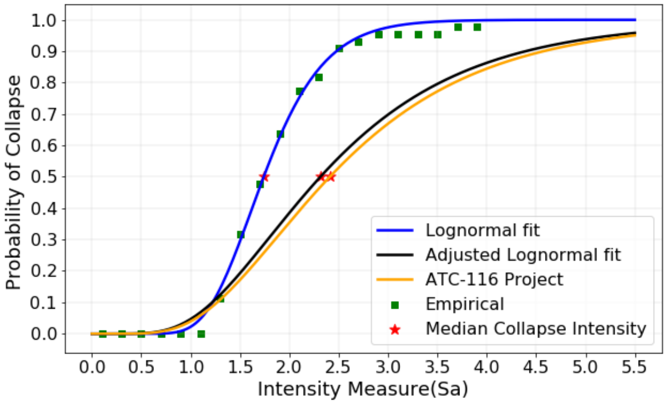

Figure 4. Comparison of the collapse fragility curve obtained from the WoodSDA with FEMA 2139-2.

Conclusion

This paper presents a streamlined comprehensive workflow capable of automating the seismic design, nonlinear static and dynamic analysis, and performance-based loss assessment of residential woodframe buildings. The workflow is materialized into a single user-executable program using an object-oriented programming paradigm in Python. The results obtained from an example implementation study demonstrates that the platform can produce reliable results. Auto-WoodSDA is an efficient ready-to-implement computational platform that has the potential to facilitate performance-based seismic design and analysis of woodframe buildings. By utilizing an automated computational engine, regional seismic performance assessments can be efficiently performed. Quantifying regional performance would provide an opportunity to optimize seismic performance factors such as response modification factors (R), deflection amplification factors (C_d), and overstrength factor (Ω) while explicitly considering the spatial distribution of seismic hazard and building inventory.

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