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Seismic assessment of pre-Northridge welded steel moment frame buildings and implications on community resilience

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ABSTRACT

Many tall office buildings in high seismic areas along the west coast of the United States rely on older, seismically deficient, welded steel moment frames (WSMFs) of the kind that experienced sudden brittle fractures during the 1994 Northridge earthquake. Despite the known vulnerability of these buildings, policymakers lack robust and reliable metrics to quantify risk and support decision-making regarding mitigation actions. This paper summarizes a project that tackles impediments to robust quantification of risk and post-earthquake consequences in tall WSMFs. This project contributes by developing (1) a high-fidelity model for fracture-critical connections, (2) a detailed database of tall WSMFs with their unique structural attributes, (3) an efficient damage indicator for post-earthquake re-occupancy decisions, and finally (4) an approach to quantify earthquake recovery time and economic loss for tall buildings and their neighboring structures.

Introduction

The 6.7M_w Northridge (1994, California, US) and 6.9 M_w Kobe (1995, Japan) earthquakes demonstrated that welded steel moment frame (WSMF) buildings are more vulnerable to earthquakes than comparable modern buildings due to premature brittle fractures of beam-to-column joint welds [1]. This experience led to an aggressive re-evaluation of the design and construction practice of new steel structures that transformed the industry. However, more than twenty-five years later, questions remain to address the risk posed by existing WSMFs in high seismic regions of the United States. The SAC project [2] reported that the majority of the buildings damaged by the Northridge earthquake were repaired to their pre-earthquake condition, which did not address the higher risk posed by either repaired or previously undamaged WSMF buildings.

Retrofit or upgrading of seismically deficient WSMF has not received much attention due to the lack of robust and credible evidence to justify the significant cost of seismic upgrading, thus explaining why most tall WSMFs remain un-retrofitted across the west coast of the United States. Nevertheless, this issue has gained the attention of the general public [3,4], which has prompted discussion of mitigation policies that consider the impact to both the at-risk buildings and their potential impact on the surrounding community. These calls for policy create the need to reliably quantify the

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earthquake risk of existing tall WSMF buildings [5], which is the focus of this study.

The scope of this project is summarized in Fig. 1. The first stage involves development of a high-fidelity model for welded beam-to-column connections that is capable of accurately predicting fracture initiation and the subsequent post-fracture behavior—aspects that are not captured well by state-of-practice models. The second stage entails the creation of a detailed database of the structural characteristics of tall WSMF buildings for the community of interest. This database includes enough information to develop representative structural archetypes that respect the unique features of these buildings. These two stages provide the inputs for the third stage that focuses on quantifying the earthquake performance of pre-Northridge WSMFs to identify the structural features that are detrimental to their safety and expected losses. The fourth stage harnesses the detailed connection modeling to develop an effective damage indicator for post-earthquake assessment of WSMFs. The final stage goes beyond individual building assessment to quantify regional impacts (i.e., effects on surrounding areas), including the potential effects of safety cordons using the framework developed by Hulsey et al. [6]. The proposed procedures are applied in a case study of tall WSMF buildings and the surrounding buildings in downtown San Francisco.

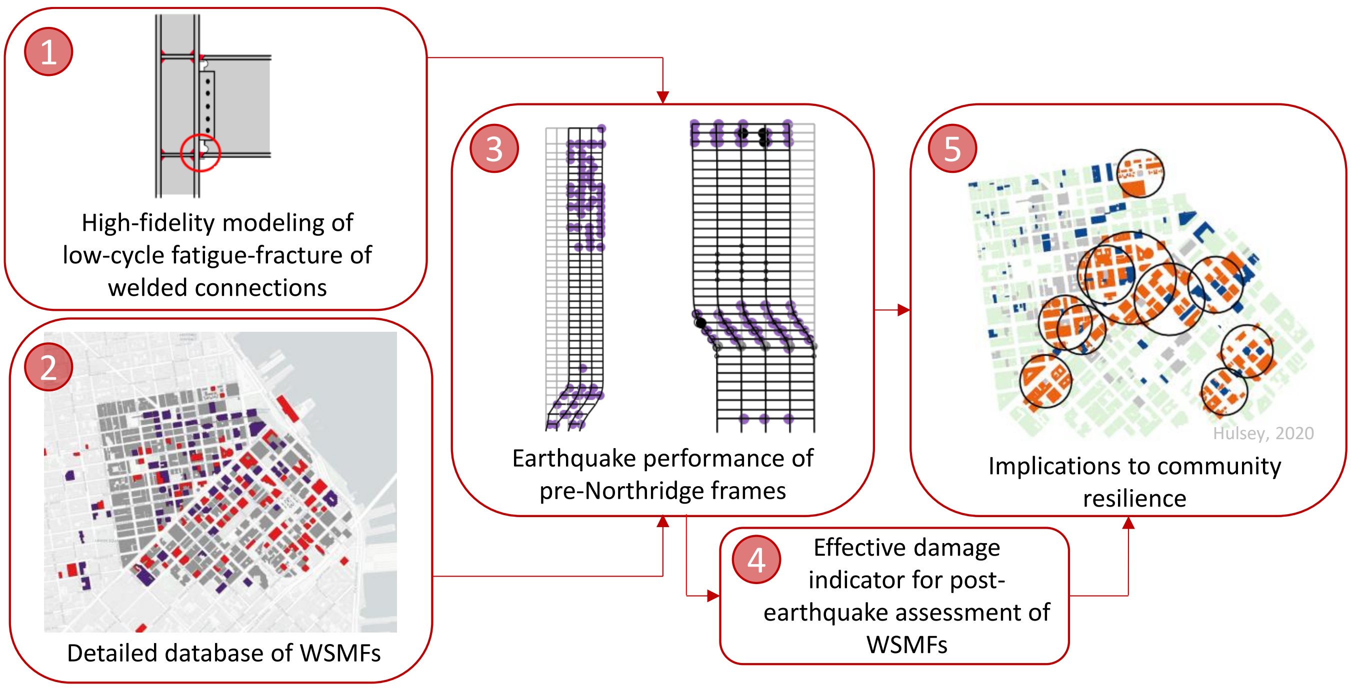

Figure 1. Tall WSMF project scope

The insights from this study can inform policy for assessment and retrofit of WSMF buildings that complements existing ordinances pioneered by two moderately sized cities [7,8]. San Francisco's Earthquake Safety Implementation Program [9] and the Los Angeles mandatory retrofit programs [10] plan to transition from required structural assessments and retrofit during substantial building renovation to a proactive ordinance, including all existing tall steel buildings, that follows similar policies for soft-story and non-ductile concrete buildings. Just as with current programs for concrete buildings, developing and implementing an effective program for tall steel buildings requires guidelines for screening and assessing WSMFs, along with practical and cost-effective retrofit solutions that can be informed with the tools developed in this project.

High-fidelity modeling of welded beam-to-column connections

The development and calibration of a high-fidelity model for simulating the behavior of welded beam-to-column connections entailed collecting and digitizing a database of 100 large-scale connection tests that failed due to flange fracture [11]. The database is combined with computational models of each connection that will be published in the NHERI DesignSafe Data Depot [12]. This data collection effort provides the foundation for developing and calibrating *SteelFractureDI*, a new steel material model, which has been implemented in OpenSees, that enables explicit simulation of fracture and post-fracture behavior of welded flanges in beam-to-column connections [13].

Shown in Fig. 2a is the proposed beam-to-column connection model that includes a fiber-section element that explicitly simulates the welded flanges and the shear tab with multiple fibers. The flange fibers are assigned *SteelFractureDI* to improve fracture prediction, allowing independent fracture of each flange and closely replicating the post-fracture connection behavior. *SteelFractureDI* differs from other material models because it includes a real-time damage rule that captures the reduction in fracture toughness, enabling a more accurate prediction of fracture as depicted in a cyclic test (shown in Fig. 2b), and it is capable of simulating the crack opening and closure behavior of fractured flanges using an adaptive constitutive law that allows loading in compression (below horizontal axis) as depicted in Fig. 2c.

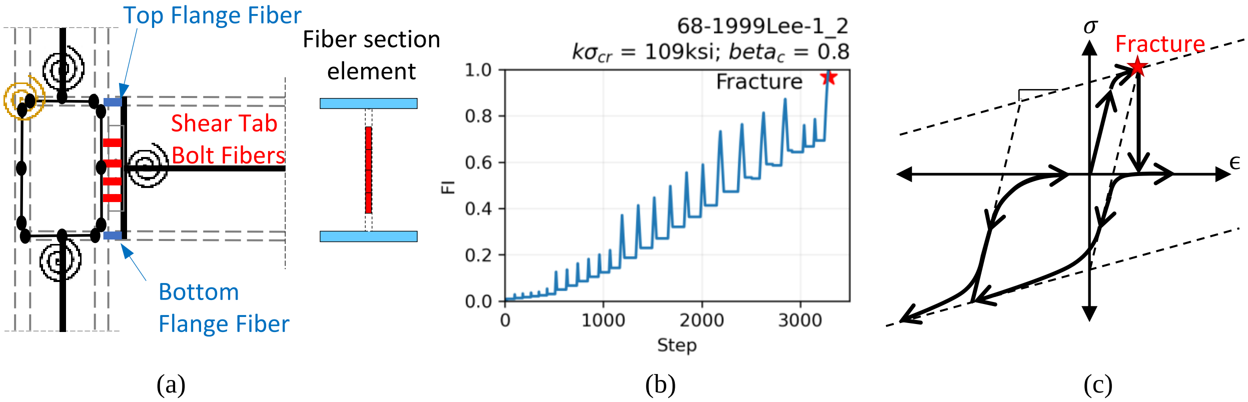

Figure 2. Proposed beam-to-column connection model (a) Schematic depiction of the fiber-section model for welded-flange and bolted web connections. (b) Sample evolution of the real-time Fracture Index (FI) on a cyclic beam-to-column connection test. (c) Post-fracture constitutive law for the flange fiber materials to simulate the opening and closing of the crack.

Detailed database of pre-Northridge WSMFs

The second stage of this research involved the collection of structural details for 89 tall WSMF buildings, located in San Francisco. This building database includes sufficient information to create representative structural and FEMA P58 performance models that respect the unique characteristics of each building. Fig. 3 shows the general distribution of the construction year, height, and height-to-width ratio for the buildings. Note that most of the pre-1980 tall WSMFs are space frames while most of the post-1980 buildings are perimeter frames.

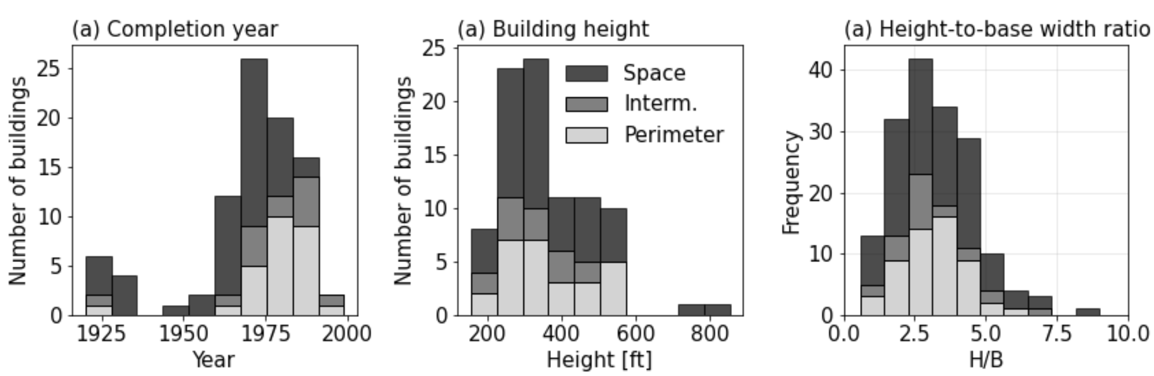

Figure 3. Sample results from the database: (a) Distribution of framing system by construction year; (b) Distribution of framing system by building height; and (c) Distribution of height-to-width (H/B) ratio for building frames in two orthogonal framing directions.

Earthquake performance of pre-Northridge WSMFs

The structural and FEMA P58 performance models constructed from the database are fundamental inputs for quantifying the structural collapse safety, repair costs (economic loss), and recovery time of these buildings using the performance-based earthquake engineering framework. This phase of the project includes a systematic risk-based assessment of representative WSMFs that includes all structural features that affect performance. These assessments allow the identification of the most critical structural characteristics to guide preventive policy.

Damage indicator for post-earthquake assessments of WSMFs

Identifying the structural characteristics that make an intact WSMF unsafe guides preventive mitigation policies, but it provides little insight for disaster response where one of the main questions is whether damaged buildings are safe to reoccupy or need to be evacuated and/or cordoned off. Addressing these questions requires (1) the evaluation of the collapse safety of damaged building to future earthquake ground shaking or other loading effects, and (2) a clear criterion to judge the minimum acceptable collapse safety, recognizing that even an undamaged existing building is likely to have lower collapse safety than is generally deemed acceptable for new buildings. This project addresses these issues using risk-based performance assessments on representative WSMFs from the database for multiple damage cases as illustrated in Fig. 4a. Each representative frame is subjected to sequences of ground motions to, first, produce a damage case, and then, quantify the remaining level of safety as compared to the intact frame. These analyses show that specific damage case produce different reductions in safety (left shift of the collapse fragilities in Fig. 4b). This project identifies building level damage metrics that can be correlated to the reduction in collapse safety. These metrics could be used in a post-earthquake scenario to aid re-occupancy decisions of damaged buildings.

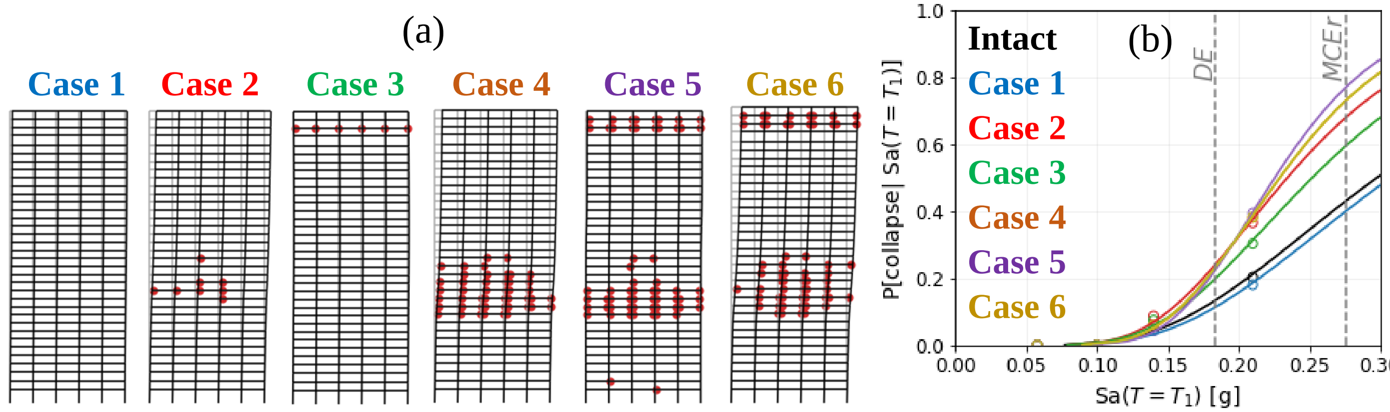

Figure 4. Seismic collapse safety of damaged buildings (a) Damaged instances for a 35-story WSMF archetype; (b) Collapse fragility function from multi-stripe analysis on the intact frame and six damaged instances (cases) using back-to-back or sequential ground motions.

Implications to community resilience

The last stage of the project involves merging of the high-fidelity models for tall WSMFs, the recommended post-earthquake damage indicators, and the remaining building inventory to quantify the potential impacts of building damage on the loss and recovery of downtown San Francisco. This stage harnesses recent developments in high-performance computing and regional risk assessment from the NHERI SimCenter [14].

Conclusions

Welded steel moment frame buildings (WSMF) constructed before 1995 pose a larger earthquake risk than originally expected due to their fracture-vulnerable connections. However, the performance of these buildings varies depending on their unique structural characteristics, which makes it challenging to perform regional earthquake risk assessments to reliably inform retrofit ordinances. Capturing structural uniqueness is especially important to consider when assessing existing tall WSMF buildings, which are prevalent in cities in California, Washington, and Oregon. This research is one of the most recent efforts explicitly addressing structural uniqueness in regional risk assessments using high-fidelity simulations of tall steel buildings and applying the full performance-based earthquake engineering framework by harnessing recent developments by the NEHRI SimCenter [14]. The results of this research will contribute by (1) quantifying the risk posed by large inventories of existing steel frame buildings and (2) developing appropriate policy interventions to mitigate those risks.

Acknowledgments

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