Chapter 1

Introduction

Engineered structures can fail. Structures have design flaws and construction flaws. They deteriorate. Myriad sets of circumstances can conspire to destroy a structure. These circumstances could be natural or man-made, intentional or accidental, common or unusual, predictable or unforeseen. No matter the particular circumstances, every structure has its limits. A hurricane breaches levees; an inadequate design leads to a bridge collapse; unanticipated wind gusts topple a construction crane.

By anticipating some of these circumstances, engineers try to avoid catastrophic failure of structures. Academic structural engineering programs teach future engineers the principles of sound design. Practicing engineers specify designs intended to avoid flaws and, if unavoidable, expose unknown flaws before they cause failure. Professional engineering societies develop standards for design, construction, and maintenance based on scientific research and lessons learned through experience. Engineers believe that their designs and constructions are robust against catastrophic failure. If they believe anything different, they develop better structures.

The beliefs that an original structure is unsound, and that the original can be sufficiently improved, predicate pursuing a revised structure. An engineer must anticipate a problem before seeking a solution, and that solution must exist. But how do engineers come to believe a structure is sound or unsound? Engineers can know there is cause for concern, but knowledge of the future behavior of structures is no more than educated speculation; no one can predict the future with certainty. Yet an engineer must anticipate reasonable sets of circumstances that may happen and believe—not know—that the proposed or existing structure is robust in those circumstances. Separating knowledge from belief is a vital part of anticipating the behavior of structures.

The amount of control over catastrophic events, as well as knowledge and belief about the future, inform the proposed solutions to problematic structures. An engineer must first identify a problem, and then she must believe that the problem should be addressed. A solution to the problem assumes there is control over the circumstances that cause the problem. This hypothetical engineer cannot prevent hurricanes or earthquakes or floods, but she can control the structures located near the seashore or in seismically active areas or in flood plains. Belief about the severity and frequency of the circumstances that lead to failure affect how engineers perceive their amount of control over those circumstances. A second hypothetical engineer may believe that a great earthquake is so unlikely that he may neglect considering its effects. He knows that great earthquakes happen, but he believes that they are so infrequent that their consequences can be safely neglected. This belief implies a lack of control as well: a great earthquake may be inevitable, but it is so devastating that nothing can be done. Yet leveraging the control over the design and construction of structures may mitigate the worst consequences of an otherwise completely devastating event.

Thus it behooves the engineering community to identify, study, and resolve the circumstances that cause catastrophic failure. By making potential failures widely known, engineers may be able to develop robust solutions and integrate them into routine practice.

1.1 Motivation

Steel moment-resisting frame buildings are engineered structures, and like all structures, there are circumstances that can cause their failure. Steel moment frames exist in seismically active areas, and engineers employ this lateral force-resisting system in new designs. Depending on the seismicity of a particular region, this class of buildings may be subject to earthquakes that release small to moderate to enormous amounts of energy. The behavior of a steel moment frame depends on this original release of energy, on site characteristics, and on the design, construction, and modification of the building itself. In order to judge the adequacy of steel moment frame systems, an engineer must know how these systems behave in all plausible ground motions. Specifically, the most significant response of any structure is failure, and thus the types of ground motions that cause collapse or a total structural loss of steel moment frames should be identified. The purpose of this thesis is to characterize the responses of steel moment frame buildings to a variety of ground motions that cause elastic, inelastic, and collapse behaviors.

Unfortunately the most compelling evidence of structural response is experience. Engineers tend to be a conservative group, seeking solid evidence to inform their decisions. Since their judgment is critical, engineers should avoid speculation and incomplete evidence. Certainly the results of careful research and experimentation have transferred to engineering practice, but only disasters provide stark evidence and sufficient motivation to make important and swift changes to engineering practice. Waiting for real-life evidence of steel moment frame behavior in moderate (magnitudes between 6.5 and 7.0), large (magnitudes between 7.0 and 7.5), and great (magnitudes greater than 7.5) earthquakes is impractical given the uncertain recurrence of such events. Instead, this thesis relies on the results of simulations to provide evidence of steel moment frame responses in earthquakes over a range of magnitudes.

This work characterizes the response of steel moment frames by applying simulated ground motions to nonlinear finite element models of the buildings. This study could have simulated the building responses with other methods, some of which are discussed in the next section on previous work. Nonlinear finite element models, however, rely on the fewest simplifications and assumptions. Although the finite element models lack some important known behaviors, using these nonlinear models is necessary to adequately characterize the response of steel moment frames. The results of this and similar studies may justify the use of simpler models in the future.

Recorded strong ground motions are limited to a relatively few, but growing, number of instrumented sites. In a sufficiently large earthquake, every point on the surface of the earth moves, but scientists cannot record all the movements. Seismologists first deployed modern instrumentation in the 1920s, and thus there are historic earthquakes for which there are no adequate ground motion records. Simulated ground motions can fill in these spatial and temporal gaps in recorded ground motions, albeit in a speculative and potentially contentious way. Seismologists are developing sophisticated models of the earth's crust to simulate the rupture mechanics of, and wave propagation in, an earthquake. The products of these simulations represent plausible descriptions of how the earth's surface could have moved in a historic earthquake or could potentially move in a future earthquake. Simulated ground motions provide a wealth of information about possible but as yet unrecorded ground movements. More to the point of this thesis, simulated ground motions can be applied to building models to predict how structures may behave in future earthquakes.

Information about the full range of steel moment frame responses can be used to characterize the seismic risk of this lateral force-resisting system. A complete seismic hazard analysis must consider all possible earthquakes and evaluate their likelihoods, and similarly a complete seismic risk analysis of structures must predict the response of the structure in all possible earthquakes. One way to discuss the seismic risk of steel moment frame buildings is to compare different designs. Given the same seismic hazard, does a shorter or taller design assume less risk? Does a stiffer, higher-strength design perform better than a more flexible, lower-strength design? What effect does a design flaw such as fracture-prone welds have on the seismic risk? This thesis simulates the responses of models with these characteristics, compares their performances, and comments on the adequacy of the structural system. The conclusions about the relative performances of the different designs can inform the choice of one proposed design over another.

A second way to understand the seismic risk of steel moment frames is to follow the methodology of Performance-Based Earthquake Engineering. This method attempts to quantify the probabilistic cost of structures in terms of monetary losses, lost operational time, and casualties. This thesis develops relationships between characteristics of ground motion (also known as intensity measures) and steel moment frame responses (termed engineering demand parameters). These relationships characterize the best prediction of the building response given a value of the ground motion characteristic, as well as an estimate of the uncertainty of the predicted building response. Used in conjunction with a probabilistic seismic hazard analysis, the steel moment frame response relationships developed in Chapter 6 can quantify the probabilistic response of a similar building in its lifetime. These responses can then be used to predict economic losses in a building's lifetime (for example, Mitrani-Reiser (2007)). However, the relationships between intensity measure and steel moment frame response developed in this thesis should be used with caution since they have not been validated with evidence from historic earthquakes.

1.2 Previous Work

1.2.1 Studies of Historic Earthquakes

The experiences of past earthquakes significantly influence the understanding of seismic building response. Certain classes of building may perform better or worse than others, and thus they are deemed superior or inferior designs. These impressions of relative performance are not always supported by a careful examination of the specific circumstances of building construction or local ground motions. Although experiences of building responses in earthquakes provide invaluable information, the interpretation of that information must be supported by often fragmentary evidence and should be as free of personal bias as possible. Reconnaissance reports of structural response in earthquakes can influence the general understanding of seismic building performance.

Engineering reports following the 1906 San Francisco earthquake generally praised the performance of steel frame buildings. In a survey of fire proofing systems, Himmelwright (1906) noted:

> The successful manner in which tall [steel] buildings withstood the effects

> of the earthquake was most gratifying to those who designed them. These buildings had never before been subjected to violent earthquake shocks, and many architects and engineers doubted their ability to withstand such surface movements without injury. Their very satisfactory behavior under the recent severe test furnishes also abundant and conclusive proof that the principles involved in their design are correct. (pp. 242–243)

Failures of engineered buildings were attributed to poor construction or soft soils:

> Any one who has carefully studied earthquake destruction can not fail to appreciate that great structural losses are due primarily, except in the immediate region of a fault line or upon loose deposits, to faulty design, poor workmanship, and bad materials; let us hope through ignorance and a blind disregard for earthquake possibilities; yet I regret to add that I feel convinced that much of the bad work is due to a combination of criminal carelessness, viscous and cheap construction. (Derleth, 1907, pp. 21–22)

These reports imply that proper attention to design and construction inevitably results in sound buildings; there is no acknowledgment of the limitations of current knowledge or honest mistakes.

Not all reports from the 1906 San Francisco earthquake provided such untempered praise of steel frame buildings. Soulé (1907) made several prescient observations about the response of steel frames, including: the largest bending moments occurred in the middle stories; the frames developed shear stresses particularly above and near the basement; most failures were a shearing of rivets and connections, especially in the lower stories and ground floors; and "the frames in these high buildings seemed to be the most severely wrenched" (p. 144). He recommended stiffening the joints and connections, providing bracing near the ground floor, and adding more columns on the first and second floors.

In the intervening sixty-five years until the 1971 San Fernando earthquake, the field of earthquake engineering developed, including a science of seismic building response. Seismic design provisions codified earthquake engineering practice and began to define the accepted understanding of seismic building response. Now building response would be compared to the expectations defined in the building code. Albert C. Martin & Associates (1972) performed an elastic analysis of the seventeen-story, steel moment-resisting frame, Department of Water and Power Headquarters in Los Angeles following the San Fernando earthquake. They found that the simulated building response matched the recorded data, and the induced member forces "greatly exceed the code forces, although this was not considered to be a really severe earthquake, much less a maximum credible earthquake" (pp. 51–52). Bertero et al. (1978) identified large-amplitude, long-duration acceleration pulses as the cause of severe structural damage to the Olive View Medical Center. The authors recommended that the design of future structures at sites near known faults should account for the large ground velocities resulting from these near-source, acceleration pulses. Since this was a new finding, sixteen years and the 1994 Northridge earthquake transpired before this recommendation found its way into the 1997 Uniform Building Code in the form of near-source amplification factors.

The 1971 San Fernando earthquake provided information about the general seismic response of new steel frame designs. From post-earthquake observations, flexible frames, both steel and concrete, sustained primarily nonstructural damage, whereas the stiffer cores for stairs, elevators, and utilities, experienced large inter-story drifts (Steinbrugge et al., 1975). Tall steel frame buildings consistently performed better than reinforced concrete frames (Steinbrugge et al., 1971; Whitman et al., 1973). Reports differ, however, on the relative performance of shorter and taller buildings. Steinbrugge et al. (1971) observed that "there was almost always negligible or minor damage to numerous earthquake resistive multistory structures located 20 to 25 miles from the earthquake and was in sharp contrast to the comparatively rare damage to adjacent one-story non-reinforced (and non-earthquake resistive) brick structures" (p. 35). In contrast, Whitman et al. (1973) found that buildings taller than five stories sustained less damage than shorter buildings. They concluded that there was sufficient evidence from the San Fernando earthquake "to document these trends in probabilistic terms" (pp. 96–97). In a case study of twin fifty-two-story office towers in downtown Los Angeles at the end stages of construction, Steinbrugge et al. (1971) documented a 25% increase in the number of weld cracks after the earthquake. The authors cautioned: "it is premature to speculate very far into this particular case due to the lack of time and detailed information, but the potential problem of earthquake induced weld stress cracks in modern steel frame buildings is disquieting" (p. 39). These observations of building response in the San Fernando earthquake provide evidence for currently debated issues of steel frame design and construction.

The amount and type of damage to buildings in the 1994 Northridge earthquake surprised the engineering community. Engineers believed that welded steel moment-resisting frames were one of the best lateral force-resisting systems for seismically active regions. The discovery of fracture-prone welds caused engineers to reevaluate their beliefs. The engineering community wanted to understand how such a potentially devastating flaw could go seemingly unnoticed for two decades. The SAC Steel Project formed to study all aspects of steel moment-resisting frames. The reports resulting from this project document all aspects of welded steel moment frames. Reis and Bonowitz (2000) authored a report on the past performance of steel frames, and they described the evolution of welded steel moment-resisting frame design:

> With each earthquake, building codes progress. The observed performance of real buildings—especially poor performance—can have a profound impact on provisions for structural materials and systems. Though changes are sometimes written and adopted slowly even after earthquakes, they frequently take effect before thorough investigations are complete. For steel moment frames, it was more the *lack* of earthquake damage data that propelled the standards for their design. Until Northridge, [welded steel moment frame] buildings simply did not produce the multiple and repeated failures that force building codes to change. ... That was as much due to their absence as anything else. But without notable failures, seismic code provisions for steel frames developed incrementally, and almost always in ways that would encourage and broaden their use. As a result, [welded steel moment frame] design practice was shaped more by

design and construction feasibility than by code limitations. (p. 4-1)

The 1989 Loma Prieta and 1994 Northridge earthquakes caused an unexpectedly large amount of economic loss for such relatively moderate earthquakes. In response to these two events, the engineering community began development of a new philosophy of structural design (Poland et al., 1995). Existing building codes require only the preservation of life safety; if the occupants of a building survive the earthquake, the building performance is acceptable by current standards. The new approach to building design, Performance-Based Earthquake Engineering, acknowledges that standards other than life safety can apply to building performance and strives to reliably predict building performance (Applied Technology Council, 2007). The recognition of other performance levels is a direct consequence of the economic losses in the 1989 Loma Prieta and 1994 Northridge earthquakes.

The 1995 Kobe earthquake significantly damaged steel frame buildings and caused many collapses. The majority (70%) of steel buildings damaged in this earthquake were older construction. Of the damaged modern steel buildings: 300 had minor damage; 266 had moderate damage; 332 had severe damage; and 90 collapsed. Most collapsed buildings were two to five stories, and no building over seven stories collapsed (Nakashima, 2000). Engineers observed a similar weld fracture problem in 1995 Kobe buildings as in 1994 Northridge buildings. Mahin et al. (2003) compared the building performance in both earthquakes: "While Japanese construction practices differ from those used in the United States in several basic ways, [welded steel moment frame] buildings in Kobe suffered even more severe damage than observed in California; in fact, more than 10% of these structures collapsed. ... No loss of life resulted from this damage to [welded steel moment frame] structures in the United States and none of these structures collapsed." However, the largest documented dynamic ground displacements near a steel frame building in Northridge is less than 0.3 m (Somerville et al., 1995) compared to 0.5 m in Kobe (Building Research Institute, 1996). The experiences of buildings in historic earthquakes provide documentation of what happened, but that evidence is incomplete and open to several interpretations.

Following major earthquakes there is often a recognition that the damage and loss of life could have been worse. The particular fault location and orientation may have induced the largest ground motions in areas without engineered buildings (for example, Northridge) or the particular rupture induced unusually small ground motions (for example, Aagaard et al. (2004)). Engineers recognize that the experience of a moderate earthquake cannot be easily extrapolated to that of a great earthquake (for example, Frazier et al. (1971)). Satisfactory building performance in a moderate earthquake does not imply satisfactory performance in a great earthquake. After major earthquakes, interpretations of the experiences differ. Some engineers point to successfully, or unsuccessfully, designed and constructed buildings as exemplary of the general performance of that class of buildings in earthquakes. Other engineers take a more cautious tone by emphasizing the often uncertain evidence of building performance in specific historic earthquakes.

1.2.2 Computational Modeling

In addition to the experiences of building response in historic earthquakes, computational modeling provides insight into understanding seismic building response. Engineers use mathematical models of buildings which range in the level of detail from simple to quite sophisticated. Lumped element modeling with simple stiffness models characterizes the building response with one or several discrete degrees of freedom. A building can also be modeled as a continuum. This approach formulates building response as either propagating waves or as a modal superposition. A third modeling technique is finite elements which can have sophisticated material models and detailed descriptions of element behavior. Each method of modeling building response contributes to the general understanding of building behavior.

Lumped element models form the basis of the conceptual understanding of building response. Basic engineering training uses single-degree-of-freedom oscillators to explain the fundamental behavior of a variety of systems. In practice, the initial design of buildings is based on the response of a series of single-degree-of-freedom oscillators (that is, the response spectra). Thus, using single- or multiple-degree-of-freedom oscillators to model building response is natural and instructive for engineers. Since the oscillator model is general, it can be used to describe the response of many building types in different kinds of ground motion. I limit this discussion, however, to a brief overview of studies that employ oscillators to describe general structural response in pulse-like, near-source ground motions.

Mylonakis and Reinhorn (2001) derive a closed-form description of the response of a single-degree-of-freedom oscillator to acceleration pulses. The authors find that severe structural damage may occur if the pulse duration is long compared to the structural period and if there is not sufficient ductility. Chopra and Chintanapakdee (2001) compared the acceleration-, velocity-, and displacement-sensitive regions of the response spectra for near- and far-source ground motions in order to reconcile the different structural behaviors in each type of ground motion. MacRae et al. (2001) compared the responses of short-, medium-, and long-period inelastic oscillators to determine the structural demand as a function of distance to the fault. Mavroeidis et al. (2004) performed a parametric study of elastic and inelastic oscillators to determine what ground motion characteristics affect structural response. They found that pulse duration most significantly affected structural performance. These studies use simple oscillators to inform the general understanding of seismic building response and to provide evidence for recommended changes to the building code.

Continuous models of building response are more complex than lumped element models, but they provide additional insight into the physics of seismic building response. Todorovska and Trifunac (1989) modeled buildings as continua in two dimensions and derived closed-form solutions for harmonic, horizontal shear wave excitation. The authors describe the contributions of symmetric and antisymmetric (with respect to the vertical centerline) modes of vibration to the building response. They also show that the phase velocities of incident seismic waves affect the transfer of energy from the ground to the building. Safak (1999) developed a layered media building model that treats each building story as a distinct layer. The wave propagation through the building is described by each layer's wave speed and by transmission and reflection coefficients at the layer interfaces. Huang (2003) used a continuous shear beam to model tall building response in near-source ground motions. The author found that higher modes affect building response when the fundamental structural period is long compared to the pulse duration. The author also proposed an "effective response spectrum" to incorporate this phenomenon in design calculations.

A third way to model building behavior, specifically framed buildings, is with finite elements. The framing members are modeled with one or more elements, and the physical behavior of these pieces are defined with simple or complex models. Hall et al. (1995) used finite element models of steel moment frame buildings to study their behavior in near-source ground motions. The authors described the dynamic deformed shape of the buildings as well as the collapse mechanism in pulse-like ground motions. Gupta and Krawinkler (2000a) studied the responses of frame models of three-, nine-, and twenty-story buildings in ground motions representing various seismic hazard levels. Employing finite element models allowed the authors to consider the performance of important structural members, such as panel zones, columns, and column splices.

One important advantage of finite element modeling is the ability to model collapse of buildings. In strong ground motions, large inter-story drifts can develop, inducing a second-order moment due to the eccentric load (that is, the P-Δ effect). Simple oscillators do not explicitly account for this effect. Challa and Hall (1994) studied the severity of ground motions required to collapse a regular plan, twenty-story, steel moment frame building. The authors concluded that the ground motions that caused collapse were "quite severe," and it was unclear at the time whether such strong ground motions were plausible. Gupta and Krawinkler (2000b) studied the P-Δ conditions that indicate collapse of tall steel buildings. The authors found that the buildings became sensitive to P-Δ effects consistent "with the attainment of a drift at which the global pushover curve shows a clear negative slope." They proposed a design procedure to check for designs sensitive to P-Δ effects in the assumed seismic hazard. Villaverde (2007) summarized the current literature on building collapse experiences and modeling.

Another advantage of finite element modeling techniques is the ability to model building response in three spatial dimensions. Carlson (1999) developed a nonlinear finite element program to model severe deformations in steel buildings. The author verified the program with case studies and then studied the three-dimensional effects on an irregular-plan building. The author found that peak-to-peak ground displacement predicted damage to tall buildings better than peak-to-peak ground acceleration. MacRae and Mattheis (2000) compared the response of a three-dimensional, three-story building model to the response of the equivalent two-dimensional model. The authors found that the two-dimensional model neither overestimated nor underestimated the three-dimensional drifts. However, the methods to measure drift in ground motions with two horizontal components depended on the assumed axes. The authors also found that excitations in the orthogonal direction increase drift in the principal direction. In companion papers, Liao et al. (2007a,b) studied the responses of three-dimensional models of steel moment frame buildings. The first paper developed the finite element model and found that torsional effects are important because structural members failed asymmetrically. The second paper quantified the reliability and redundancy of these buildings.

1.2.3 End-to-End Simulations

With the advancement of ground motion simulation and improved computational power, end-to-end simulations are feasible. These simulations begin with an earthquake source model, propagate the seismic waves on a regional scale, apply the resulting surface ground motions to building models, and record the building responses. These studies presently assume the same building model at all locations in the simulation domain, but future studies may consider a mix of buildings more consistent with existing or proposed building inventories. The results of these studies map the building responses on the simulation domain, thereby identifying sites where the buildings perform well or poorly.

Currently there are a limited number of end-to-end studies of building response. Hall et al. (1995) used simulated ground motions from a scenario magnitude 7.0

earthquake on a blind thrust fault in the Los Angeles basin. They applied the ground motions to two types of flexible buildings: a twenty-story steel moment frame which satisfies the seismic provisions of the 1991 and 1994 Uniform Building Codes; and a three-story base-isolated building. The authors found that the ground motions induced steel frame responses larger than those anticipated in the building code and identified the possibility of collapse. This early study emphasized the preliminary nature of the findings, but subsequent studies have supported and elaborated these initial results.

Krishnan et al. (2006) studied the responses of tall steel moment frame buildings in scenario magnitude 7.9 earthquakes on the southern San Andreas fault. This work used three-dimensional, nonlinear finite element models of an existing eighteen-story moment frame building as is, and redesigned to satisfy the 1997 Uniform Building Code. The authors found that the simulated responses of the original building indicate the potential for significant damage throughout the San Fernando and Los Angeles basins. The redesigned building fared better, but still showed significant deformation in some areas. The rupture on the southern San Andreas that propagated north-to-south induced much larger building responses than the rupture that propagated south-to-north.

Krishnan and Muto (2008) used the same building models as the previous study, as well as a building with an L-shaped plan, to simulate the response of steel moment frames in a magnitude 7.8 scenario earthquake on the southern San Andreas, also known as "ShakeOut". The authors recommended using the following estimates to characterize the damage in ten- to thirty-story, steel moment frame buildings: 5% (of an estimated 150 existing buildings of this type) collapse; 10% are red-tagged, or deemed unsafe to enter; 15% with enough damage to cause loss of life; and 20% with visible damage requiring building closure.

Olsen et al. (2008) simulated the responses of twenty-story steel moment frames in earthquakes on the northern San Andreas fault. The authors studied the building responses to ground motions based on the 1989 Loma Prieta and 1906 San Francisco earthquakes. This thesis presents some of the results used in this paper and also considers the steel moment frame responses as functions of intensity measures.

1.2.4 Building Design and Weld State

Several studies considered different designs of tall steel buildings, arguing that one type of design performs better than another in seismic areas. In seismic design provisions for ductile buildings, the strength can be reduced by a factor R, since it is assumed that the post-yield strength of ductile buildings provides sufficient lateral force resistance to preserve life safety. Designs with lower-strength tend to be more flexible as well. Lee and Foutch (2006) considered several designs of three-, nine-, and twenty-story steel moment frames using different R factors. They used an incremental dynamic analysis to determine the inter-story drift ratio capacity of the moment frames. For the twenty-story buildings, this capacity was reduced from 7.7% for designs with an R factor of 8 (the stiffest considered) to 5.6% for designs with an R factor of 12 (the most flexible considered); twenty-story, more flexible designs tended to collapse at lower inter-story drift ratios compared to stiffer designs. The authors concluded, however, that maintaining the lower bound on the reduced design response spectrum, C_s, safely allows the design of more flexible buildings without compromising life safety. Hall (1998) studied the relative performance of four steel moment frame designs: short versus tall; and stiffer, higher-strength versus more flexible, lower-strength. The author employed nonlinear finite element models of the designs in time history analyses with simulated strong ground motions. He found that, of the four considered designs, the shorter, stiffer building performed best in the moderate (magnitude 6.7) and large (magnitude 7.0) earthquakes considered. Naeim and Graves (2006) used strong ground motions from a magnitude 7.15 scenario earthquake on the Puente Hills fault at eighteen sites to generate response spectra with an elastic-perfectly plastic material model. The authors concluded that taller, more flexible buildings are "substantially safer" than shorter, stiffer buildings, assuming both classes of buildings are properly designed and constructed. These studies draw different conclusions about the relative performance of different steel moment frame designs.

The problem of fracture-prone welds in welded steel moment frame buildings has been well documented. In addition to comparing the relative performance of four steel moment frame designs, Hall (1998) considered the effect of brittle welds on building response. He found that the presence of brittle welds increases the story drifts and increases the likelihood that the buildings lose lateral force-resisting capacity (that is, collapse). The SAC Steel Project generated several reports documenting fractured welds in existing buildings, testing welded connections in laboratories, and modeling the response of buildings with fracture-prone welds. Luco and Cornell (2000) compared the response of steel moment frames with brittle welds to those with sound welds and studied the effect of changing the parameter values of the assumed weld fracture model. The authors found that the presence of brittle welds is significant in the strongest ground motions that induce severely nonlinear behavior. The assumed weld fracture material model only affected the results in moderate ground motions; in smaller ground motions there were not enough weld fractures, and in larger ground motions significant damage accumulated for all fracture models. Rodgers and Mahin (2006) performed scaled laboratory testing on, and computational modeling of, two-story steel moment frames with brittle welds. The authors concluded that the ground motion amplitude and character most significantly affected the response of the moment frames with brittle welds. The problem of brittle welds in older, welded steel moment frames is well known.

1.2.5 Building Response Prediction

Several intensity measures have been proposed to predict the response of buildings in seismic ground motions. Anderson and Bertero (1987) described the inherent uncertainties of predicting building response from ground motion records of the same earthquake. They showed that peak ground acceleration is not a good intensity measure to predict building response. They recommended considering incremental velocity (the area under an acceleration pulse) and peak ground displacement as better intensity measures. Makris and Black (2004) argued that peak ground velocity is not an adequate intensity measure because it does not distinguish between long-duration acceleration pulses and a series of large spikes in acceleration. The authors used a dimensional analysis to conclude that acceleration pulses better predict the response of buildings than do velocity pulses.

Spectral values are commonly used to predict seismic building response. Gupta and Krawinkler (2000c) studied the use of spectral displacement to predict the total roof drift and peak inter-story drift of frame structures. The authors developed modification factors for the spectral displacement at the fundamental structural mode to account for "[multiple-degree-of-freedom] effects, inelasticity effects, and P-Δ effects." Then they found a relationship to predict total roof drift from the peak inter-story drift. Baker and Cornell (2005) studied a vector of intensity measures consisting of spectral acceleration and a parameter, ϵ, that measures the difference between the observed spectral acceleration and that predicted by a ground motion prediction equation. The authors argued that using both parameters to scale ground motions resulted in more accurate predictions of building response than using spectral acceleration alone. The literature is not clear on what intensity measure best predicts steel moment frame building response.

1.3 Outline of Chapters

Chapter 2 describes the steel moment frame buildings used in this thesis. The buildings have four distinct designs: six or twenty stories designed to the 1992 Japanese Building Code or the 1994 Uniform Building Code seismic provisions. With these four building designs, shorter versus taller buildings and stiffer, higher-strength versus more flexible, lower-strength buildings can be compared. Chapter 2 also describes the nonlinear finite element models of these designs. The buildings are characterized in terms of their elastic modal periods and pushover curves. Different modeling assumptions, such as how to apply the ground motions and how to model brittle welds, are studied to understand their effect on the simulated building responses.

The next three chapters present the results of applying simulated ground motions to steel moment frame building models. Chapter 3 considers two sets of earthquakes in the San Francisco Bay area: one set simulates the ground motions in the 1989 Loma Prieta earthquake and a second set models three magnitude 7.8 earthquakes on the northern San Andreas fault, based on a scenario of the 1906 San Francisco earthquake. Chapter 3 compares the responses of the stiffer, higher-strength versus the more flexible, lower-strength designs and compares the responses of models with fracture-prone (brittle) welds versus sound (perfect) welds.

Chapter 4 considers studies of fault ruptures in the Los Angeles basin. One study generated ground motions on ten faults and a second study generated broadband ground motions from ruptures on the Puente Hills fault system. (This second study is the only study I consider that produced broadband (periods greater than 0.1 s) ground motions; all other studies produced long period (periods greater than 2 s) ground motions.) Chapter 4 uses the broadband ground motions to compare the responses of the shorter and taller buildings. This chapter also compares the building responses in the Los Angeles basin for simulations on the Puente Hills fault system from the two studies and for multiple realizations of the same earthquake (that is, the same magnitude and same fault).

Chapter 5 shows the building responses to simulations on the southern San Andreas fault. These simulations generate building responses to distant earthquakes with ground motions amplified by sedimentary basins, as well as building responses to near-source ground motions from great earthquakes. This chapter also presents the building responses as measured by the permanent total drift ratio in addition to collapse and peak inter-story drift ratio.

Chapter 6 brings the building responses of Chapters 3–5 together and develops probabilistic building response prediction equations based on intensity measures. This chapter compares several proposed relationships based on pseudo-spectral acceleration, peak ground displacement, and peak ground velocity.

Chapter 7 concludes this thesis with a discussion of the significant findings from this study. This chapter identifies the significant conclusions and suggests how to expand on this work.