CHAPTER 7

Conclusions

7.1 Summary and conclusions

In this work, an analytic foundation, using basic probabilistic concepts, for design and assessment of moment-resisting frame structures under seismic loads is developed (Chapter 2). This foundation forms the theoretical basis to alternative formats suitable for implementation in design and assessment guidelines (Chapter 3). Examples of how to organize ground motion records, choose intensity levels, perform non-linear time history analyses, and, process the results, in order to obtain parameter estimates for the analytic framework, are demonstrated (Chapters 4,5,6).

7.1.1 Chapter 2: A technical framework for probability-based design and assessments

The probabilistic foundation developed, yields an analytic closed-form expression for the annual frequency of exceeding specified structural performance levels, or more briefly limit state frequency, is derived based on simplifying assumptions. The limit state frequency is derived by assuming that the parameters involved in the assessments have a stochastic nature, which is modeled by considering two different types of uncertainty. The first type identifies the more familiar "natural variability" in the parameters, and is referred to as "randomness" or more precisely the "aleatory uncertainty". The second type addresses limited knowledge and data and is referred to as "uncertainty" or "epistemic uncertainty". This second kind of uncertainty can be reduced by more acquiring data (larger sample sizes) and/or by performing more thorough research.

The derivation of the limit state frequency employs a probabilistic tool known as the total probability theorem (TPT) in order to decompose the derivations into smaller, and less complex parts. Therefore, the process of evaluating the limit state frequency involves additional "interface" variables. Two distinct approaches for deriving the expression for limit state frequency are presented, namely, the displacement-based approach, and the ground motion intensity-based approach. The displacement-based approach evaluates the limit state frequency as the frequency that a displacement-based demand variable exceeds the corresponding limit state capacity. The derivations in this case are performed in two steps: 1) Evaluating the frequency that the displacement-based demand exceeds a given value by decomposing it with respect to the ground motion intensity level and then composing the results by integration over all possible

intensity levels. This first step is done by employing the total probability theorem and an interface variable representing the ground motion intensity. This variable is referred to as the intensity measure (IM). The assumptions made in this step of the derivation include, approximating the frequency that the IM exceeds a certain level, also know as the "hazard" for the IM, by a power-law function, modeling the probability distribution of the displacement-based demand for a given level of ground motion intensity by a lognormal distribution, and assuming that this lognormal distribution is defined by a median (central value) that is itself a power-law function of the ground motion IM and a (log) standard deviation (dispersion measure) that is invariant with respect to the ground motion intensity, 2) The second (final) step is to evaluate the frequency that the displacement-based demand exceeds capacity by decomposing it into (conditional) frequencies of exceeding given values for the limit state capacity and then composing these frequencies by integration over all possible values of capacity. In this step it is assumed that probabilistic distribution of the (displacement-based) capacity can be modeled with a lognormal distribution with constant median and standard deviation and also that the capacity and demand are uncorrelated. The second or ground motion intensity-based approach evaluates the mean annual frequency that the IM variable exceeds the corresponding limit state capacity IM or more briefly the IM capacity for a specific limit state (also called limit state frequency). The derivation involves decomposing the limit state frequency into conditional limit state frequencies that the IM exceeds IM capacity for a given intensity measure and integrating the conditional limit state frequencies over all levels of ground motion intensity.

7.1.2 Chapter 3: Probability-based Demand and Capacity Factor Design (DCFD) formats

The closed-form analytic expression(s) derived for the limit state frequency can be formed into alternative formats. These formats re-shape the probabilistic expression of exceeding a certain limit state into alternative displacement-based or ground motion intensity-based design/assessment criteria. These criteria, being expressed in common engineering terms rather than the more abstract probabilistic ones, can be implemented in existing design and assessment procedures and guidelines.

Demand and capacity factored design (DCFD) represents a family of displacement-based design formats that are distinguished with regard to the type of uncertainties considered in the formulation of the limit state frequency. This format has been already implemented in, FEMA 350 for the design of new steel moment resisting frames, FEMA 351 for the assessment of the existing steel moment resisting frames, and ISO guidelines for the design of offshore structures.

Fragility/hazard format represents a ground motion intensity-based family of design formats, also capable of considering both types of uncertainty. The fragility/hazard has a graphic representation based on fragility and hazard curves and forms of it have been implemented in the DOE 1020 seismic criteria (Kennedy and Short, 1994). The consideration of the epistemic uncertainty in the development of these formats may result in designing the structure with certain degree of confidence or assess the level of confidence in the design of an existing structure.

7.1.3 Chapter 4: Alternative non-linear demand estimation methods

Non-linear displacement demand estimation methods can be used in the context of the DCFD format in order to design and assess the performance of the structures under seismic loads. It is demonstrated how alternative non-linear dynamic analysis procedures can be implemented in order to assess the performance of an existing (older) reinforced concrete frame for a specific limit state, using DCFD's displacement-based criteria. These non-linear procedures involve, selection of intensity levels, performing non-linear time history analyses, and post-processing the results. Special attention is given to the estimation of the displacement-based demand parameter, which is compared to the limit state capacity in the framework of DCFD assessment criterion. The demand estimations obtained using the analytic DCFD format (based on the analytic assumptions outlined above), are compared to the results obtained by numerical integration (based on empirical probabilistic representations of the parameters). In order to be able to compare the accuracy of the alternative demand estimation methods, the DCFD displacement-based design/assessment criterion is extended to a more general equivalent form. Hence these methods are compared in the light of the equivalent probabilistic demand estimations they provide.

It was desirable to lay out the methods based on the range of ground motion intensity levels included in the dynamic analyses performed. Therefore, these methods are discussed in two categories, namely, the "wide-range" and "narrow-range" demand estimation methods. In general the non-linear procedures discussed are employed in order to obtain local demand parameter estimates for the DCFD format. The narrow-range methods, provide parameter estimations with relatively small number of non-linear dynamic analyses. It is shown that the accuracy of these methods is significantly improved when the range of the ground motion intensity levels are slightly increased to accommodate the estimation of a demand parameter related to the gradient of displacement-based demand with respect to ground motion intensity level. The wide-range

methods involve more extensive analysis efforts in order to provide local parameter estimations as a function of the ground motion intensity level. Although the derivation of the DCFD design format is based on certain analytic assumptions about the parameters, (e.g., constant standard deviation and power-law median for the displacement demand), it is shown that incorporating the local estimates, provided by the wide-range methods, into the DCFD formulation provides accurate results. However, the non-linear nature of the displacement-based demand at higher intensity levels make the resulting parameter estimates subject to potential (local) irregularities in displacement response in the non-linear range. Hence, the resulting (local) parameter estimates should be treated with care and with intuition of the actual physical behavior at the corresponding intensity level. The "wide-range" methods can also be used in order to obtain parameter estimates related to limit state capacity. An application of such methods to the estimation of the global dynamic instability limit state is discussed.

7.1.4 Chapter 5: Probabilistic seismic assessments in the region of global dynamic instability

One of the main assumptions leading to the derivation of the DCFD format is that the displacement-based response of the structure for a given ground motion intensity level can be adequately modeled by a lognormal distribution. However, this assumption may not be true for displacements close to the onset of global dynamic instability, also referred to as "collapse", in the structure. The three-parameter distribution is an alternative probability distribution that is defined by using the total probability theorem (TPT) to decompose the displacement-based demand into two mutually exclusive states of "collapse" and "no collapse", where the lognormal distribution is still is applied only in order to model the "no-collapse" part. Alternative methods for incorporating the three-parameter distribution or parallel probabilistic models based on empirical distributions, other than the lognormal distribution, into the demand assessments are discussed. As a special case, an alternative formulation for the DCFD format, representing the displacement-based demand (for a given intensity measure) by the three-parameter distribution, is derived. It is important to note that the alternative DCFD formulation is only applicable to assessments for limit states other than the so-called "collapse" limit state (also called the "exogenous" limit states). It is demonstrated that wide-range methods can also be used to provide parameter estimates (as a function of the intensity level) for the alternative DCFD formulation in the range of collapse. Alternatively, a "pseudo" lognormal distribution can be constructed based on the three-parameter distribution. This pseudo lognormal distribution can be used to make local

parameter estimations in the range of global dynamic instability in the original DCFD formulation.

7.1.5 Chapter 6: Non-linear response dependence on ground motion characteristics with implications for ground motion record selection

The closed form expression for the limit state probability was derived by adopting an interface variable referred to as IM in order to represent the ground motion intensity. It was implicitly assumed that the adopted IM can provide an adequate presentation of the ground motion characteristics, such as magnitude and source-to-site distance. On the other hand, the non-linear dynamic analysis procedures implemented for making probabilistic assessments involve selecting a suite of ground motion records. Inevitably, it is of interest to know what a representative ground motion selection is, what are the criteria for creating such selection, and whether it depends on the ground motion intensity level. It is demonstrated that the criteria for selecting a representative suite of ground motion records are related to the criteria measuring the adequacy of an adopted IM in representing the ground motion characteristics. Adequacy of an IM is measured through its "sufficiency" and "efficiency". A sufficient IM is one that renders the structural response (here the displacement-based response) conditionally statistically independent of the ground motion characteristics, such as moment magnitude and closest source-to-site distance, for any given intensity level. An efficient intensity measure predicts the structural response with relatively small record-to-record variability (i.e., minimizes the dispersion due to randomness). Theoretically speaking, careful selection of the ground motion records is not essential if the adopted IM is shown to be sufficient with respect to the ground motion characteristic variables. A first-order approximation to the sufficiency criterion states that the expected value of the response is functionally independent of the ground motion characteristics for any given intensity level. In this context, a suite of linear regressions can be used to establish (linear) first order sufficiency of the adopted IM for various intensity levels. In the cases where sufficiency is not established, a weighted linear regression scheme based on the results of seismic hazard disaggregation may be used to enhance the probabilistic demand estimations.

It was demonstrated that, for the structure studied when maximum inter-story drift angle is adopted as the displacement-based demand, the spectral acceleration at the first-mode frequency (FMF) is a sufficient IM with respect to the ground motion magnitude, source-to-site distance, and the "epsilon" of the attenuation law. The sufficiency was established for different ductility levels through the case study of two structures with very short and long first-mode periods,

subjected to a suite of more-or-less arbitrarily selected ordinary (i.e., no near-source recordings) ground motion recordings on stiff soil. It was also demonstrated for both cases that the displacement-based response (for a given FMF spectral acceleration) depends on the shape of the elastic response spectrum. The short-period SDOF system demonstrated dependence on the shape of the spectrum at longer periods, whereas for the long-period MDOF system the response was dependent on the shape of the spectrum at shorter periods (i.e., higher frequencies). This could be explained by the elongation of the natural period for the short-period system in the nonlinear range and the effect of higher modes for the long-period system. The observed sufficiency with respect to ground motion characteristics may contradict the common perception that the ground motion magnitude is likely to affect the structural response specially for systems with very long natural periods. This perception seems in tune with the observed correlation between the spectral shape at higher frequencies and magnitude, together with the demonstrated dependence of the response of the long-period structure on spectral shape. It can be argued that the although these two pair-wise correlations exist (as measured by the slopes of the fitted lines), they are not strong enough to induce (statistically) significant correlation between response and magnitude (in part due to large variability of data points around the fitted line).

The peak ground acceleration (PGA) is shown to be insufficient with respect to the ground motion magnitude for the long-period system in the non-linear range of response. A weighted regression scheme based on the results of the disaggregation of seismic hazard for PGA with respect to magnitude is used in order to take into account the magnitude-dependence. The displacement-based demand estimations (demand hazard) based on the weighted regression show very good agreement with those based on adopting the pair [PGA, M] as a vector-valued intensity measure.

7.2 Limitations and future work

This work presents an analytic framework for probabilistic seismic assessments of moment-resisting frame structures. Examples of how to organize ground motion records, intensity levels, perform non-linear dynamic analyses, and process the results in order to perform probabilistic seismic assessments are also demonstrated. At every step, certain assumptions were made. These assumptions define the limitations and the scope of this work as well as possible schemes for future research.

The assumptions underlying the derivation of an analytic closed-form framework for probabilistic assessments were outlined above. They consist of assuming that 1) the IM hazard can be modeled as a power-law function of the IM, 2) the conditional distribution of the displacement-based demand can be modeled by a lognormal distribution with its median approximated as a power-law function of the IM and constant standard deviation, 3) the distribution of the displacement capacity can be modeled by a lognormal distribution with constant median and standard deviation, 4) the displacement-based demand and capacity are independent, and 5) the epistemic uncertainties in hazard, demand and capacity were represented by lognormal distributions.

Some of these assumption were relaxed later by obtaining local estimates of the IM hazard and/or by implementing nonlinear dynamic methods in order to obtain local estimates of the conditional median and standard deviation of the displacement-based demand. It was demonstrated that the closed-form framework was still able to provide reasonable estimates even though the underlying assumptions were not strictly correct. It is important to note that the accuracy of the closed-form framework for seismic assessments was compared to numerical solutions based on non-parametric probabilistic distributions. These numerical solutions were in turn obtained based on certain assumptions, such as, 1) the suite of ground motions used were the same for all different IM levels considered. 2) these records did not include near-source recordings, 3) it was assumed that scaling is justified 4) a limited number of ground motion records were used, 5) the IM hazard calculations did not include directivity parameters, and, 6) the numerical integration was carried out assuming that the adopted IM is sufficient with respect to ground motion characteristics. Finally, all of these studies in Chapters 4 and 5 used a single structural model. While it was intentionally chosen to include characteristics such as cyclic strength degradation, it would be desirable to extend these studies to a broader population of structural models to seek any limits to the conclusions drawn here.

It was demonstrated how to measure the epistemic uncertainty associated with limited sample size, i.e., number of ground motion records. However, future work should demonstrate how the uncertainties associated with specific parameter estimations can be propagated into the derivations. Also, the validity of assuming a lognormal presentation for the epistemic uncertainty was not investigated.

The presented framework is based on the mean annual frequency of exceeding limiting states that are defined in terms of structural response parameters . It is also important to derive analytic

frameworks based on life-cycle costs, since the probabilistic performance objectives are ideally based on life cycle considerations.

As it was mentioned before, the sufficiency investigations for FMF spectral acceleration were done by using a suite of scalar linear regressions. Therefore, the sufficiency of FMF spectral acceleration was established for one ground motion variable at a time. Ideally, sufficiency should be established for all the effective ground motion variables simultaneously, meaning that multi-variable regressions are more appropriate for this purpose. However, it is believed that the method presented in this work is capable of distinguishing any major dependence on ground motion characteristics. Also the linear regression scheme used can only establish *linear (first-order)* sufficiency for the range of intensity that the ground motion records cover. Also, the conclusions are specific to the suite of ground motion records used, which do not include near source recordings. It is important to investigate the sufficiency with respect to the ground motion variables that include directivity variables and based on a suite of records that does include near-source recordings. In order to establish the sufficiency of FMF spectral for the long-period system for different ductility levels, the ground motion records were scaled. A thorough investigation that would confirm scaling for long-period structures is needed.

As a general note, the structural systems used in this work are intended to serve as case studies and the accuracy of the modeling assumptions and their limitations were not the focus of this thesis. Furthermore, while the structures in Chapter 6 were specifically chosen to be "extreme cases" with respect to the periods and higher-mode effects, the limits of applicability of the conclusions made here have not been established.