CHAPTER 1
INTRODUCTION

Abstract: In view of inadequacy of the existing single-objective based design optimization procedures, the concept of multiobjective optimization for seismic design of steel moment frame structures is introduced in this chapter. Focuses of the present research are described and organization of the Ph.D. thesis is outlined.

1.1 Background

Traditional seismic design codes worldwide emphasize primarily life safety and collapse prevention issues. Although buildings that were properly designed and constructed according to these codes in general survived recent moderate to major earthquake events, both direct and indirect economic losses due to structural as well as nonstructural damages were tremendous, which caused considerable concerns in the earthquake engineering community as well as in the general society. It is therefore important to incorporate damage control explicitly into the design process so that economic impacts due to seismic damages can be reduced to an acceptable level.

To address the damage control concept in seismic designs, performance-based seismic design methodologies and procedures have been systematically proposed and under continuous development as a new generation seismic design framework since 1990's (SEAOC 1995; FEMA-273 1997; FEMA-356 2000). Multiple hazard levels are defined that represent seismic intensities with varied exceedance probabilities or equivalently average return periods. Uniform hazard spectra or suites of ground motion records associated with these hazard levels may be used as seismic inputs for structural design and performance evaluation purposes (USGS; Somerville et al. 1997). Structural performance parameters are calculated at each hazard level and then checked against allowable values that result from a combination of analytical analysis and engineering judgment. Large uncertainties exist in estimating both seismic structural demands and capacities, which can best be treated in a probabilistic sense. By virtue of this multilevel multicriteria design methodology, seismic performances of a resulting structural design are hopefully under direct and explicit control, which leads to an acceptable damage level under future earthquakes.

Traditional seismic codes typically provide guidelines to design buildings with only minimum resistance requirements at designated earthquake levels (ASCE-7 1998). Taken as an example structural design of a plane steel moment frame with a fixed geometry, a number of code-conforming alternative designs exist that have distinct member proportioning patterns and seismic resistance capacities. Merits of these valid design solutions are further assessed and compared with respect to identified relevant objectives (goals, criteria); structural designs with overall better objective measures are considered more desirable than others.

Many of the merit objectives are competing in nature. For example, the initial material usage is a partial measure of the total construction expenses for a given structural design. Historically it has been the most commonly used design objective in the structural optimization community, often being computed simply as the total weight for structures built with uniform skeleton material such as steel. At the same time, a desirable seismic design should favorably reduce seismic damage impacts during a life cycle and therefore the lifetime seismic damage cost may also be used as another important merit measure. The damage cost objective is generally in conflict with the material usage objective: structural designs built with less material tend to have lower resistance to earthquakes and therefore they will most probably incur higher damage cost, and vice verse.

Another objective of practical importance for a structural design is the degree of design complexity, which affects initial construction cost in ways not reflected by the material usage alone. For example, a steel frame design with less material usage tends to require more deliberate proportioning of member sizes in order to make full use of materials while satisfying code requirements, which naturally results in use of a lager number of different steel member types. Consequently, more cost will be spent on stiffeners, splices, and other construction efforts due to sorting, staging of a vast number of different member types, additional possible cost stemming from rework due to human errors, and so on. This argument indicates that a structural design with more savings in material usage alone would likely require more construction expenses. It is therefore beneficial to seek for a desirable balance between these two kinds of design consideration.

1.2 Motivation

Structural engineers almost always tend to design a cost-effective seismic resistant structure that favorably balances initial investment and future seismic risk, in either explicit or implicit manners. In other words, future seismic damage impacts should be properly addressed in a cost-effectiveness analysis integrated seismic design procedure. In a traditional design situation where a structure is designed in accordance with minimum seismic code requirements, the safety level against future seismic threats takes what is implied in those codes. In many other cases, engineers may want to quantify future seismic impacts in terms of explicit merit objectives and see if these additional design goals could be improved by reasonably increasing the initial investment. Sometimes, engineers may be interested, for example, to find a structural design with the least initial expenses given the maximum acceptable risk measures, or to find a design solution with the lowest risk measure provided the initial cost does not exceed a prescribed amount.

Seeking for the most desirable structural design(s) based on predefined merit objective(s) leads to the design optimization problems, which by nature are multiple objectives oriented, as discussed previously. Previous research on design optimization of civil structural systems over the past several decades has focused predominately on single-objective based problems with structural material usage (volume, weight, or cost) as the most commonly cited objective function (Arora 1989). Recently a minimum expected life cycle cost criterion has been used in design optimization of seismic structures (Ang and Lee 2001; Wen and Kang 2001b). The resulting single design solution, however, may not necessarily behave satisfactorily in terms of other important merit measures, which are stated in the optimization formulation as constraints other than objective functions. This bias has hindered the traditional single-objective based optimal design concept from being widely appreciated by structural engineering professionals. Simultaneous consideration of all relevant merit objectives in the optimization process has the potential of producing better-behaved design solutions that balance different competing objectives in a preferred manner.

Numerical algorithms are needed to automatically guide the search for the posed multiobjective (or multicriteria, vector) design optimization problems. Most of conventional numerical algorithms usually work well with single-objective based optimization problems only and have nontrivial difficulties when handling multiple objective functions. For example, one approach is to lump all objectives together using prescribed weighting factors to produce a single composite objective; another approach is to consider one objective at a time only and convert other objectives into constraints. The obvious drawback of these remedy approaches is that numerous algorithm runs are necessary in order to obtain a series of final design solutions with different relative importance of conflicting objectives. In addition, one notable obstacle for many of the conventional algorithms is that gradient information is required to guide the search process and, as a result, solutions are often trapped in local optimum. Moreover, problems with discrete-valued design variables cannot be efficiently handled by many conventional algorithms that usually assume continuous design variables. Therefore, numerical algorithms that can solve multiobjective structural optimization problems without the above-mentioned numerical difficulties are desired.

1.3 Objectives and scope

Steel frame building structures exhibit excellent ductile behaviors under cyclic loading, making them ideal for earthquake-resistant systems. Other advantages include light structural weight, easy prefabrication and erection, material reusability, and so on. The primary task of this Ph.D. research is to develop practical automated member sizing procedures for seismic design of unbraced planar steel special moment resisting frame (SMRF) structures while considering simultaneously as well as separately multiple competing merit objectives. Using effective numerical algorithms to solve the presently posed multiobjective structural design optimization problems, a set of optimized code-compliant tradeoff alternative designs will be produced with respect to all relevant merit objectives. Structural engineers now have much freedom to select the compromise design solution that best meets their various design goals in an overall sense. There are three major components of the present study.

The first part deals with selection of useful merit objectives that define multiobjective optimization problems for seismic steel SMRF design. These objectives should appropriately reflect either immediate construction costs or impacts from future seismic threats. One primary issue is that a merit objective candidate must be easily understood by practicing engineers so that the resulting optimized structural designs are potentially applicable in a real-world practice.

Another research effort will focus on efficient implementation of numerical optimization algorithms for the present multiobjective design problems. Genetic algorithms (GAs) will be used as the primary solver for this purpose. GA has been found effective in locating (nearly) global optimal solutions for multiobjective problems with only a single algorithm run. Moreover, GA can handle discrete-valued variables without any difficulty. There has been in the literature a wealth of structural optimization applications via GAs, most of which dealt with single-objective (i.e., structural weight) based problems only. Research efforts on structural optimization using multiobjective GAs have been very limited, many of which investigated design of simple structural systems. Applications of GA in multiobjective seismic design problems are practically non-existent. GA operators and strategies particularly suitable for the present member sizing optimization of steel SMRF structures will be used in the automated design procedures.

Numerical examples will be provided as the third major component of this Ph.D. study to demonstrate significant features of the present multiobjective seismic design optimization procedures for steel SMRF structures. Multiple merit objectives are selected to reflect steel material usage, initial expenses, degree of design complexity, seismic structural performances, and lifetime seismic damage consequences, respectively. Based on the distribution of optimized structural designs obtained from the proposed automated procedures, tradeoff analyses will be carried out to simulate how an engineer selects a compromise design that can satisfy personal preference among different merit objectives.

1.4 Organization

The Ph.D. thesis is composed of eight chapters. The remaining seven chapters are briefly described as follows.

Chapter 2 provides code provisions that are used for seismic design of steel SMRF structures in the multiobjective design optimization procedures. Specifically, AISC-LRFD steel design provisions (AISC 1994) serve as general guidelines for designing steel structures, including load combination scenarios and member strength checking. Seismic design follows the equivalent static force procedure from the 2000 NEHRP provisions (FEMA-368 2002), in conjunction with AISC seismic provisions (AISC 1997, 2000) to check the strong-column-weak-beam criterion and additional width-thickness ratio limits for structural members. These provisions form a framework to ensure code-compliant structural design solutions.

A brief review of modeling techniques for steel SMRF structures subject to seismic loads is presented in Chapter 3, including nonlinear members with point plastic hinges, panel zones, beam-to-connection connections, P-delta effects due to interior gravity loads, and other miscellaneous detailed modeling considerations; an example steel SMRF and its model used in later numerical examples is also described. Different seismic performance evaluation procedures are also compared with a focus on the nonlinear static procedure or the static pushover analysis, which will be used in this study as the primary procedure to evaluate seismic structural performance. Seismic inputs (acceleration response spectra and ground motion records) for the present steel design optimization are provided at the end.

Discussed in Chapter 4 is an introduction to numerical algorithms applicable for structural design optimization problems. First, traditional algorithms are outlined and the inherent difficulties are pointed out. GAs are then described in detail and their distinct features are compared with those of traditional algorithms, followed by an overview of GA based multiobjective optimization techniques, emphasizing various strategies such as fitness assignment, constraint handling, and elitism. The particular multiobjective GA parameters and schemes for this study are described and structural design optimization via GAs in the existing literature is summarized at the ended.

As the first numerical example, Chapter 5 provides a GA based automated procedure for design optimization of seismic steel SMRF structure that simultaneously minimizes both the steel material weight and an approximate measure of degree of design complexity while conforming to seismic design provisions described in Chapter 2.

Illustrated in Chapter 6, a numerical procedure is proposed that combines automated multiobjective optimization with the emerging performance based seismic design methodology. The selected multiple merit objectives measure either the present capital investment or the future seismic risk that is represented by appropriate structural performance parameters at various hazard levels.

The last numerical example as presented in Chapter 7 demonstrates a procedure for life cycle cost oriented seismic design of steel SMRF structures that is formulated as a multiobjective optimization problem comprising three competing merit objectives: initial cost, lifetime seismic damage cost, and degree of design complexity. User-specified confidence level on damage cost estimate is approximately considered by use of percentile limit state probabilities.

To conclude the Ph.D. thesis, Chapter 8 summarizes major findings of the present study on multiobjective design optimization of steel SMRF structures and also identifies interesting topics for future research.