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Progressive collapse design of seismic steel frames using structural optimization

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ABSTRACT

This paper uses structural optimization techniques to cost-effectively design seismic steel moment frames with enhanced resistance to progressive collapse, which is triggered by the sudden removal of critical columns. The potential for progressive collapse is assessed using the alternate path method with each of the three analysis procedures (i.e., linear static, nonlinear static, and nonlinear dynamic), as provided in the United States Department of Defense United Facilities Criteria (UFC) Design of Buildings to Resist Progressive Collapse. As a numerical example, member sizes of a two-dimensional, nine-story, three-bay regular steel immediate moment frame are optimally determined such that the total steel weight is minimized while the design satisfies both AISC seismic provisions and UFC progressive collapse requirements. Optimization results for the example frame reveal that the traditional minimum weight seismic design, which does not explicitly consider progressive collapse, fails to meet the UFC alternate path criteria associated with any analysis procedure. Progressive collapse design optimization using the linear static procedure produces the most conservative and consequently heaviest design against progressive collapse. In contrast, the more accurate nonlinear static and dynamic procedures lead to more economical designs with UFC-acceptable resistance to progressive collapse, at the expenses of considerable modeling and computing efforts.

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1. Introduction

Progressive collapse refers to a chain reaction of structural element failures following the initial damage to a localized portion of a building, eventually causing widespread structural damages that are disproportionate to the triggering event. The risk of progressive collapse shall be adequately mitigated during the building design process in order to safeguard the structure against this catastrophic event. In traditional structural codes, building design against progressive collapse has often been indirectly addressed by prescribing a certain level of structural integrity [1]. Recently, design guidelines have been developed to explicitly take progressive collapse into account for building design. For example, the UFC 4-023-03 (hereafter referred to as UFC) is one of the frequently referenced documents for structural design against progressive collapse [2]. Instead of preventing or limiting initial localized damages, these design guidelines try to provide satisfactory continuity, ductility, and redundancy in buildings such that the spread of local damage can be confined. Specifically, UFC allows both indirect and direct methods to be used to achieve this goal. The tie force method is an indirect design approach, with which the structure is tied together by employing the tensile capacity of floor/roof systems to improve the building's load redistribution capability. There are two direct design methods in UFC: the enhanced local resistance method and the alternate path method. The enhanced local resistance method aims to harden critical structural members (e.g., perimeter columns, wall sections) to offer satisfactory strength and ductility to resist progressive collapse. In comparison, using the alternate path method, a designer must ensure that the building is able to bridge over selected load-bearing elements that are notionally removed, one at a time, from the original intact building to simulate their sudden loss when subjected to damaging extreme loads.

Of the three different UFC design methods, the alternate path method provides a systematic way of evaluating the potential of buildings for progressive collapse. For each predetermined scenario of removing key structural elements, structural analysis is carried out for the damaged structure (i.e., the structure with an element missing). Instead of simulating the possible chain reaction of structural failures following the notional element removal, structural deformations and internal forces resulting from structural analysis are examined against the UFC acceptance criteria associated with the specific type of structural analysis being carried out. The building design is considered acceptable if these acceptance criteria are met. The UFC alternate path method can be applied by using one of the three analysis options: linear static, nonlinear static, and nonlinear dynamic. As the simplest analysis option, the linear static procedure offers preliminary, often conservative assessment of the progressive

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collapse potential. The nonlinear dynamic procedure is the most accurate and also most computationally expensive option, as it necessitates sophisticated finite element modeling and considerable computing efforts to carry out the time history analysis. As an intermediate analysis option, the nonlinear static procedure also involves modeling of both material and geometrical nonlinearities while it does not perform time history analysis to simulate the load redistribution behavior. To approximately compensate for the dynamic effects corresponding to the actual load redistribution, a dynamic increase factor is used in the nonlinear static procedure to increase the gravity loads acting on the areas that are immediately affected by the removed structural elements.

Seismic design provisions have undergone significant revisions after the recent major earthquakes that exposed deficiencies in previous generations of engineering practice. As a result, seismically safer buildings can generally be designed per the current seismic provisions. However, unless it is intentionally proportioned for enhanced resistance to progressive collapse, a seismically designed building does not necessarily have sufficient capacity to redistribute loads to other regions of the building upon the sudden loss of certain critical load-bearing elements. This is because buildings behave very differently when withstanding an earthquake and when resisting progressive collapse. While seismic design primarily focuses on lateral loads, progressive collapse design is more concerned with gravity loads acting on the structure [2]. The inherent resistance of seismic building structures to progressive collapse has been investigated using the alternate path method [3]. In order for seismic-resistant buildings to have adequate load redistribution capability, the progressive collapse requirements need to be explicitly considered during the structural design process.

One important issue in progressive collapse design is how to achieve cost-effectiveness in proportioning structural components to facilitate load redistribution. Use of the alternate path method requires structural analysis and acceptance evaluation of trial designs under different scenarios of removing critical elements, making the design process very repetitive in nature. The efforts to obtain an economical design can be formidable if a manual trial-and-error design approach is employed. However, this process can be efficiently handled by computerized structural optimization, which uses appropriate numerical search algorithms to maximize or minimize predefined objective function(s) by selecting appropriate values for a set of design variables while conforming to relevant design constraints. For design of practical building structures, design constraints are usually derived from structural criteria set forth in relevant code standards. The commonly used design variables are often discrete-valued, such as cross-sectional dimensions in concrete design and commercially available standard sections in steel design. The material cost is usually used as an objective function subjected to minimization. For steel design, the material cost is often simply expressed as the total steel weight, recognizing that this weight metric alone may not completely quantify the actual expenses associated with construction of a steel building [4]. Because objective functions and design constraints are typically non-differentiable with respect to discrete-valued design variables, most gradient-based optimization algorithms are not readily applicable. In contrast, heuristic search algorithms are particularly effective for solving practical steel design optimization problems. These algorithms include simulated annealing [5], genetic algorithm (GA) [6], tabu search [7], particle swarm optimization [8], and ant colony optimization [9].

The ever-increasing concerns over the susceptibility of building structures to progressive collapse have spurred extensive research to accurately simulate such a chain reaction and understand the underlying mechanisms (e.g., [10–13]). Design optimization against progressive collapse provides a promising approach to achieving economy in building design while mitigating such rare yet devastating events. Grierson and Khajehpour carried out earlier, relevant research [14]. They considered the progressive collapse risk by defining a single load-path redundancy factor, which is a function of bay numbers and degree of connectivity between the floor system and columns/shear walls in each story. They emphasized the importance of enhancing structural safety against progressive collapse in achieving an overall cost-effective design. However, integration of structural optimization techniques with the progressive collapse design by direct approaches (e.g., alternate path method) has not been available in the literature.

In this paper, a GA-based structural optimization is presented to cost-effectively design code-compliant seismic-resistant steel frame structures that simultaneously satisfy the UFC progressive collapse criteria associated with the alternate path method. A number of column removal scenarios are considered per the UFC guidelines. The load redistribution capability is assessed by using each of the three analysis procedures (i.e., linear static, nonlinear static, and nonlinear dynamic) provided in UFC. To illustrate the usefulness of the present progressive collapse design optimization, a numerical example is provided, in which member sizing of a planar nine-story, three-bay seismic steel moment frame is carried out in order to minimize the total steel weight while possessing UFC-acceptable resistance to progressive collapse. Designs thus obtained using different UFC analysis procedures are critically compared. In order to demonstrate the importance of intentionally considering progressive collapse in the structural design process, the traditional minimum weight design of the same example frame without explicitly accounting for progressive collapse is also obtained as a baseline design.

2. Problem statement

2.1. Overview

The present progressive collapse-resistant design optimization of seismic steel frame structures can be conceptually stated as

Objective: To reduce the total steel weight, which acts as an approximate indicator of frame construction cost.
Subject to: AISC-LRFD seismic provisions [15];
UFC progressive collapse design requirements associated with the alternate path method.

The design variables considered in the optimization are steel member sizes that are selected from commercially available hot-rolled, wide-flange standard steel sections. A standard GA is used as a numerical solver to find the optimized combination of section types for beams and columns of the frame. Fig. 1 gives a flowchart for this structural optimization framework. GA strategies and AISC-LRFD seismic requirements are briefly described in the next two sub-sections. The UFC alternate path method is discussed in Section 3.

2.2. Genetic algorithm

A GA scheme that was previously developed for optimal design of steel frames [4] is used for the present member-sizing problem. Specifically, a steel frame design is encoded into a two-portion string of pointers, which are associated with two subsets of commercially available standard sections used for column and beam members, respectively. GA starts with a set of initial trial frame designs that are generated from an exhaustive combination of different section types, one from the column section subset and the other from the beam section subset. Each of the following

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