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Sensitivity analysis of steel buildings subjected to column loss

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ABSTRACT

In this study, the sensitivity of design parameters of steel buildings subjected to progressive collapse is studied. To this end, design parameters such as yield strengths of beams, columns, and braces, live load, elastic modulus, and damping ratio were considered as random variables. The Monte Carlo simulation, the Tornado Diagram analysis, and the First-Order Second Moment method were applied to deal with the uncertainties involved in the design parameters. The analysis results showed that among the design variables beam yield strength was ultimately the most important design parameter in the moment-resisting frame buildings while the column yield strength was the most important design parameter in the dual system building. Sensitivity of the vertical displacement to uncertain member strength showed that progressive collapse mechanisms of the moment-resisting frame buildings and the dual system building completely differed due to different patterns of the vertical load redistribution.

1. Introduction

When a structure is subjected to unexpected loads such as explosion, impact, fire, etc. that are not considered in the normal design process, the structure may become vulnerable. The phenomenon whereby the failure of one or more load-resisting structural members due to an unexpected load leads to the collapse of the entire structure, especially in a domino-like way, is commonly called progressive collapse [1].

The collapse of the Alfred P. Murrah Building in 1995 and the World Trade Center (WTC) Tower in 2001 are examples of progressive collapse due to a car-bombing and an aircraft impact, respectively. Before the collapse of the WTC, research on progressive collapse had only been conducted by a limited number of researchers because the probability that such an abnormal loading event would occur and that it would trigger progressive collapse was very low. However, the collapse of the WTC, where more than 2000 civilians lost their lives, reminded structural engineers that the mechanism of progressive collapse needs to be thoroughly understood to prevent such a disaster recurring in the future.

To prevent the progressive collapse caused by abnormal loads, the National Building Code of Canada [2] specified requirements for the design of major elements, the establishment of connection elements, and ways of providing load transfer paths. Eurocode 1 [3] presented a design standard for selecting plan types for preventing progressive collapse and recommended that buildings should be integrated. In the United States, specific provisions related to progressive collapse have not yet been provided in design codes such as the International Building Code [4]. However, the American Concrete Institute [5] requires structural integrity (for example, continuity insurance of reinforcing bars) so that partial damage by abnormal loads does not result in the collapse of the entire structure. The ASCE 7-05 [6] also recommends a design method, a load combination, and structural integrity, as does ACI 318. The General Service Administration (GSA) presented a practical guideline for design to reduce the collapse potential of federal buildings [7]. The Department of Defense (DoD) also presented a guideline for new and existing DoD buildings [8]. These guidelines address design procedures and analysis methodology for progressive collapse.

Research on progressive collapse can be categorized according to two different approaches: (1) developing structural systems that prevent progressive collapse, and (2) developing an analysis methodology. Crawford [9] proposed the use of connection details such as Side Plate^{TM}, developed for earthquakes, the use of cables imbedded in reinforced concrete beams to activate catenary action, and the use of mega-trusses in high-rise buildings to resist progressive collapse. Suzuki et al. [10] showed that

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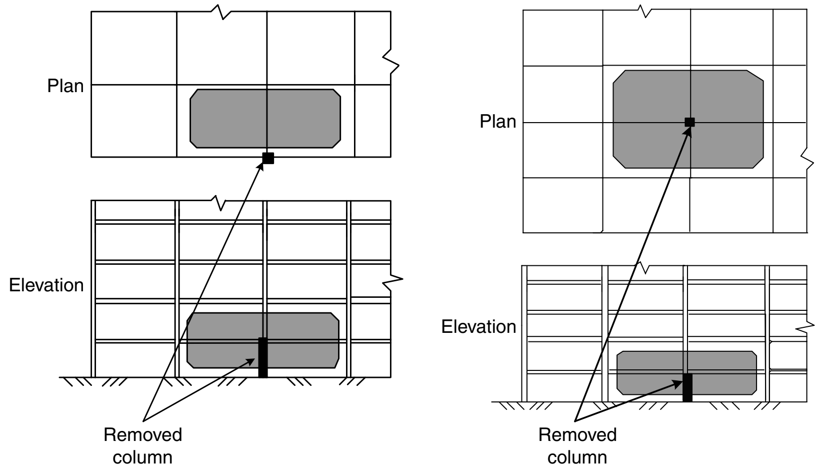

(a) Exterior consideration. (b) Interior consideration.

Fig. 1. Allowable collapse zone [7].

the use of hat-bracing at the top of structures may increase the resistance to progressive collapse. Hayes Jr. et al. [11] investigated the relationship between seismic design and the blast or progressive collapse-resisting capacity. They mentioned that the seismic design details developed for special moment frames in high seismic zones would provide better resistance to external explosion or impact load than the less-rigorous design details of ordinary moment frames. Khandelwal et al. [12] also investigated the mechanism of the progressive collapse of seismically designed braced steel frames.

Both linear and nonlinear analysis methods can be used to simulate progressive collapse. The linear analysis method can be readily adopted to the alternative path method [7] where the demand-capacity ratio of the structure is evaluated repeatedly. However, Powell [13] proposed that the nonlinear analysis method should be used for progressive collapse because the result of the linear analysis can be too conservative and is sensitive to input parameters.

For realistic simulation of structural performance, the analysis process needs to include uncertain characteristics of material properties. Nevertheless, most recent research on progressive collapse of structures has been conducted based on deterministic approaches where the nominal or average values of the design parameters were used [14]. An application of the theory of probability to the structural analysis is one of the ways to deal with uncertain material properties which are considered as random variables [15]. The effect of variability of uncertain design parameters on structural behaviors can be estimated by a sensitivity analysis. Sensitivity analysis has been used for earthquake engineering to estimate sensitive design parameters to the seismic response of buildings [15]. Recently Park and Kim [16] carried out fragility analysis of steel structures subjected to progressive collapse considering the probability distribution of material properties. The progressive collapse mechanism and the capacity of structures can be affected by the probabilistic properties of the design parameters and load combinations. The sensitivity analysis is necessary to understand which design parameters are more important to progressive collapse than others.

The objective of this study is to determine the important design parameters and structural members for the progressive collapse mechanism of buildings. To this end, three different probabilistic approaches were used on steel moment frame buildings and dual system buildings of various stories. Uncertainties associated with material properties and member capacities were considered in order to determine the influential material properties and members for the progressive collapse of the analysis model buildings.

2. Analysis methodology

2.1. Analysis method for progressive collapse

Progressive collapse refers to the phenomenon whereby local damage of structural elements caused by abnormal loads results in global collapse of the structure. To carry out analysis for progressive collapse, it is necessary to track progressive member failures. In the design guidelines of the GSA and the DoD, an analysis method for progressive collapse, called the alternative path method, is presented. In this method, damaged structural members are removed from the model structure and the loads originally supported by the lost members are redistributed to neighboring members. In this way, progressive member failures can be evaluated. However, this procedure requires repetitive analysis until progressive member failure stops and the structure is stabilized.

The guidelines define the allowable collapse zone, as shown in Fig. 1, such that if a member fails outside of this zone, the probability of progressive collapse is considered to be high. In this study, the onset of progressive collapse was determined by the failure of a structural member located outside of the allowable collapse zone when a column located in the zone was removed.

For numerical simulations of the progressive collapse, nonlinear static and dynamic analyses were conducted [17,18]. An incremental vertical displacement was applied downward of the node, where the damaged column was removed and the corresponding applied vertical load was recorded. The gravity load is a combination of dead load (DL) and live load (LL). The load combination was assumed to be DL + 0.25LL, as shown in Fig. 2. For dynamic analysis, all member forces were first obtained from the full structural model subjected to the applied load (DL + 0.25LL). The structure was then re-modeled with a column removed and its member forces applied to the structure as a lamp force to maintain equilibrium (Fig. 3). The forces were suddenly removed after 7 seconds to initiate progressive collapse as shown in Fig. 3, where W denotes member forces of the lost column. In this way, the progressive collapse analysis started from the moment the structure was already deformed by the applied load.