Journal of Constructional Steel Research 122 (2016) 238–250

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

An evaluation method to predict progressive collapse resistance of steel frame structures

Chang Hong Chen [a,*], Yan Fei Zhu [a], Yao Yao [a], Ying Huang [b], Xu Long [a]

[a] School of Mechanics, Civil Engineering, Northwestern Polytechnical University, Xi'an 710129, China
[b] School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 19 March 2016
Accepted 21 March 2016
Available online xxxx

Keywords:
Progressive collapse
Probability
Energy
Structural reliability
Advanced first order reliability method
Robustness

ABSTRACT

In the current work, a probabilistic assessment method of a steel framed building under abrupt removal of a column due to catastrophic events is developed. A multi-story steel framed model taking into account the influence of catenary effect has been analyzed. Uncertainties in the structural variables are incorporated in the probabilistic simulation approach. Based on the changes of component internal energy, the progressive collapse sensitivity to abrupt removal of a column has been investigated. Besides, a simplified beam damage model is proposed to analyze the energies absorbed and dissipated by structural beams under large deflections. In addition, the correlation incorporating catenary action between bending moment and axial force in a beam during the whole deformation development process is studied. With the methodologies adopted for progressive collapse assessment under removal of a column, a deterministic method has been developed, framed within the Advanced First Order Reliability Method (AFORM). A robustness index (RI) is proposed to evaluate the structural robustness performance based on the acceptable probability of global failure and structural collapse probability.

1. Introduction

Progressive collapse is a catastrophic partial or total structural failure that is caused by local structural damage, which cannot be absorbed by the inherent continuity and ductility of the structural system. The local damage or failure initiates a chain reaction of failures that propagates vertically or horizontally through the structural system, leading to an extensive partial or total collapse. Virtually all the structural collapses initiate from local as opposed to system-wide damage (earthquakes being a possible exception), the key feature distinguishing progressive collapse is that the resulting damage is disproportionate to the local damage caused by the initiating event. Such collapses can be initiated by abnormal loads (e.g., gas explosions, vehicular collisions, and sabotage), fires, extreme environmental effects, human errors in design and construction. [1].

The capability of a structure to withstand damage can be developed based on structural reliability analysis and probability assessment [2]. Bassam et al. [3] proposed the probabilistic risk assessment framework to multi-story steel buildings subject to extreme loading. A brief outline of the probabilistic framework [4–6] was applied in their work, including the main requirements of describing uncertainty in the hazards, the associated local damage, as well as the consequences of global failure.

The probabilistic analysis of buildings against progressive collapse has recently been emphasized [5–6]. The probabilistic analysis will allow design engineer to decide whether further protective measures would be required to against tolerable collapse risk. The collapse risk of a building can be calculated as [5–6]:

$$P(C) = P(C|DH) \cdot P(D|H) \cdot P(H) \quad (1)$$

where: P(C) represents the probability of progressive collapse, P(H) is the probability of the occurrence of a hazard H, P(D|H) is the probability of local damage D as a result of a hazard H, P(C|DH) stands for the probability of progressive collapse of the structure as a result of local damage caused by hazard.

Starossek and Haberland [7] assigned appropriate terms for the formula as shown in Fig. 1. Based on Eq. (1) and Fig. 1, the probability of progressive collapse can be minimized in three ways: controlling abnormal events, local element behavior and/or controlling global system behavior. Predicting abnormal events is difficult; however, the local and global system behavior i.e. P(D|H) and P(C|DH) can be partially controlled.

According to the Eurocode [8] and US guidelines [9], robustness shown in Fig. 1 is defined as the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause. In terms of those codes, a localized failure due to accidental actions could be acceptable, as long as it will not endanger the stability

* Corresponding author.
E-mail addresses: changhong.chen@nwpu.edu.cn (C.H. Chen), zhuyanfei@mail.nwpu.edu.cn (Y.F. Zhu), yaoy@nwpu.edu.cn (Y. Yao), cch-by@163.com (Y. Huang), xulong@nwpu.edu.cn (X. Long).

http://dx.doi.org/10.1016/j.jcsr.2016.03.024
0143-974X/

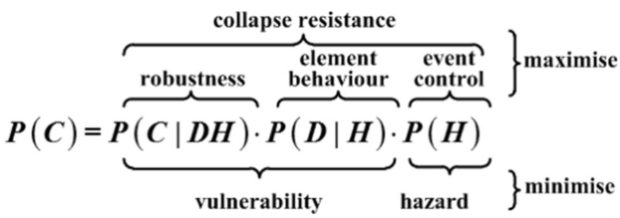

Fig. 1. Terms in context of progressive collapse.

of the whole structure, the overall load-bearing capacity of structure is maintained and allows necessary emergency measures to be taken.

Fewer studies have focused on the evaluation of P(C|DH). Recently Bassam [3] investigated the failure probability of a structure, a probabilistic risk assessment framework to multi-storey buildings subject to extreme loading is developed based on the First Order Reliability Method (FORM). However, according to SSC-351 [10], the FORM method has the following shortcomings: Firstly, if the performance function g (.) is non-linear and the linearization takes place at the mean values of x_i, errors may be introduced by neglecting higher-order terms. Secondly, the method is not consistent with different equivalent formations for the same problem, which means that the reliability index β depends on the formulation of limit state equation. Thirdly, in the FORM method the reliability index β represents failure probability when the variable x_i is normally distributed and the performance function g (.) is linear in x_i. It is noted that many variables follow other distribution types, such as Weibull or exponential distribution, not just normal distribution. Therefore, an advanced First Order Reliability Method (AFORM)is adopted in the current study to establish the conditional probability of failure. Structural reliability theory allows some uncertainties to be quantified and included explicitly in the analysis. Considering these uncertainties, structural reliability analysis yields a quantifiable measure of structural safety, the failure probability, as shown in Fig. 2 [11–12]. Structural reliability methods can be employed to determine the characteristic values.

Assuming that the ultimate limit-state criterion can be expressed in terms of the resistance *R* (capacity) and the effect of the loading *S* (demand). The values of *R* and *S* are assumed to be uncertain and can be described by probability density functions $f_R(r)$ and $f_S(s)$. The safety limit-state will be violated if:

$$Z = g\ (R, S) = R–S \le 0 \tag{2}$$

As shown in Fig. 3, the probability of failure is given by

$$P_f = P(R-S \le 0) = P(g(R,S) \le 0) < P_d \tag{3}$$

where: g (.) is 'limit-state function' with negative values defining the failure scenario, P_d is the predefined probability of failure level equaling to acceptable probability of failure.

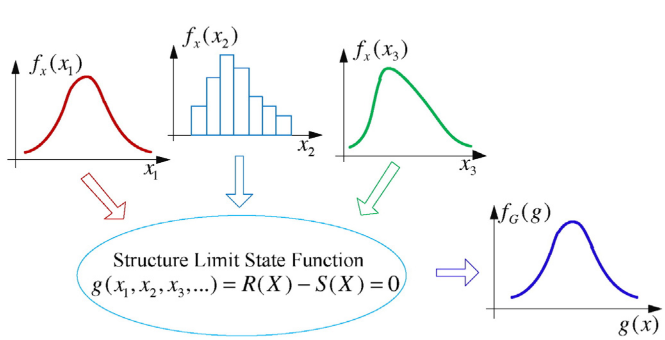

Fig. 2. Reliability analysis of a structure with random parameters.

The main objective of the current study is to develop an evaluation method to predict progressive collapse resistance of steel frame structure based on probability and energy principle.

2. The probabilistic model of progressive collapse

2.1. The sensitivity structural analysis

The component's internal energy (elastic deformation work) is defined as:

$$E_{i,\text{int}} = \iiint_{V_i} u_i\, dV \tag{4}$$

where *i* is the number of the undamaged component; u_i and V_i are elastic strain energy density per unit volume and the volume of a member, respectively. If a component is formed by a single material and has a uniform section

$$u_i = \frac{E_{i,\text{int}}}{V_i}. \tag{5}$$

The change in the elastic strain energy density per unit volume is given by:

$$\Delta u_i = \frac{\left|\Delta E^d_{i,\text{int}}\right|}{V_i} = \frac{\left|E^d_{i,\text{int}} - E^0_{i,\text{int}}\right|}{V_i} \tag{6}$$

where $E^0_{i,\text{int}}$ is the internal energy (elastic deformation work) of a member before being damaged, $E^d_{i,\text{int}}$ is the internal energy (elastic deformation work) of a member after being damaged, and $\Delta E^d_{i,\text{int}}$ is the variation of internal energy caused by abrupt removal of a column.

Furthermore, the relative variation of the elastic strain energy density per unit volume is:

$$\Delta u_{i,rel} = \frac{\Delta u_i}{\max_i\{\Delta u_i\}}. \tag{7}$$

The sensitivity index of all structural components is defined as:

$$SI_{i,j} = \Delta u_{i,rel} \tag{8}$$

where: *i* is the number of a undamaged component, *j* is the number of a removed component.

According to the sensitivity index of a structural component, a sub-structure resisting progressive collapse can be obtained. Thus, the proposed sub-structure becomes the analysis target, instead of a single beam or column in the traditional analysis. The whole structural performance resisting progressive collapse is characterized by analyzing the behavior of the sub-structure in a column removal scenario. Thus, the analysis process proposed in the current study is closer to the realistic collapse scenario.

2.2. A simplified beam damage model

A steel frame beam under normal load is mainly subjected to the combined effect of moment and shear force, and the axial force in steel beam is usually ignored. With the increase of load, bending moments at midspan and ends of the steel frame beam increase accordingly, which develop plastic hinges at these locations and large deflection at the beam midspan. In this case, the steel beam endures considerable axial force, which cannot be neglected. As the total cross section yields, the axial force in the steel beam can further increase to resist the additional external loading, which results in decreasing of the bending moment at plastic hinge section. Finally, the steel beam mainly depends on the axial force to resist external loading and the steel beam fails at midspan or ends