Journal of Constructional Steel Research 138 (2017) 72–78

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Modification of dynamic increase factor to assess progressive collapse potential of structures

Javad Mashhadi, Hamed Saffari *

Department of Civil Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, 22 Bahman Blvd, P.O. Box 76175-133, Kerman, Iran

A R T I C L E   I N F O

Article history:
Received 30 January 2017
Received in revised form 30 May 2017
Accepted 19 June 2017
Available online xxxx

Keywords:
Progressive collapse
Post-elastic stiffness ratio
Non-linear static analysis
Dynamic increase factor
Alternate load path

A B S T R A C T

Progressive collapse assessment of buildings against column removal requires a time consuming nonlinear dynamic analysis therefore nonlinear static analysis considering a proper dynamic increase factor (DIF) can be utilized as an alternate analysis to predict maximum dynamic response of structures. In this study, the effect of post-elastic stiffness ratio of members on DIF in nonlinear static analysis of structures against column removal is investigated, and a modified empirical DIF is presented. For this purpose, series of low and mid-rise moment frame structures with different span lengths and number of stories are analyzed. For each ratio of post elastic stiffness, a non-linear dynamic analysis and a step-by-step nonlinear static analysis are carried out. The results of analysis reveal post-elastic stiffness ratio is an efficient parameter on DIF. Therefore the new empirical formulas including moment demand, ductility and post-elastic stiffness ratio are suggested. Finally, it is shown that the proposed DIF formulas are accurate and efficient.

1. Introduction

Structures may be subject to conditions such as accident, act of terrorism or natural hazards that lead to progressive collapse, thus buildings should have enough robustness to avoid progressive collapse under extreme load events. In the commentary of the ASCE 07-10 [1], progressive collapse is defined as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it."

The collapse of the World Trade Center towers on September 11, 2001 [2], failure of three columns of the Alfred P. Murrah building in Oklahoma City in 1995 [3] and collapse of parts of the 22-storey Ronan Point tower on May 16, 1968 [4] are three most famous phenomenon of progressive collapse which generated interests to its highest level in progressive collapse. Recently, a surge of research activities on the evaluation and prevention of progressive collapse have been performed. In these researches, critical gravity load-bearing element was eliminated and then structures were designed in order to mitigate risk [5–7]. In order to minimize the risk of progressive collapse in buildings, many approaches have been suggested.

McKay [8] conducted a series of nonlinear analyses for steel and reinforced concrete frame models under various column-loss scenarios to generate regression formula for load increase and dynamic increase factors. Progressive collapse test of steel frame building located in Northbrook, Illinois was performed and four first story columns from one of the perimeter frames were removed physically and also progressive collapse simulations were carried out to compare with the experimental data [9].

The condition of energy balance between the external work and internal strain, along with the dissipated energy are considered to assess the progressive collapse potential of buildings [10,11]. Other methods such as pushdown analysis and pulldown analysis, which are based on the same principle, are presented for predicting the peak structural responses of building frames upon the sudden removal of a column [12, 13]. A multi-story steel frame structure considering catenary effect and uncertainties in the structural variables was evaluated by Chen et al. [14] in order to develop a method to predict progressive collapse resistance of steel frame buildings. Furthermore a new method based on considering partial distributed damage of element around removed column was presented for progressive collapse analysis of structures [15].

Relevant standards and design guidelines such as General Services Administration (GSA) [16] and United Facilities Criteria (UFC 4-023-03) [17] are available for designing structures resistant to progressive collapse. These standards are concerned with quantifiable and significant security methodologies to resist progressive collapse. The Alternative Path Method (APM) is proposed in both mentioned guidelines. APM is one of the most widely accepted methodologies that are applied to assess the progressive collapse potential of building structures by direct removal of a column [17]. In the following sections, alternate path method, different analysis procedures, and empirical formulas in dynamic analysis are reviewed. According to the UFC guideline in

* Corresponding author.
E-mail addresses: jmashhadi@eng.uk.ac.ir (J. Mashhadi), hsaffari@mail.uk.ac.ir (H. Saffari).

http://dx.doi.org/10.1016/j.jcsr.2017.06.038

nonlinear static analysis, the only effective parameter to obtain the DIF is θ_{pra}/θ_y, where θ_{pra} and θ_y are plastic rotation angle in acceptance criteria and yield rotation, respectively. These rotation angles depend on the material and mechanical properties of the affected structural members only. Acceptance criteria and yield rotations are defined in ASCE 41-13 [18]. Step-by-step analyses were conducted on 2D moment frames and DIF formulas for nonlinear static analysis were proposed as a function of maximum (M_d/M_p) where M_d and M_p are the factored moment demand under original unamplified static gravity load and the factored plastic moment capacity, respectively [19]. Although, gravity loads and ductility are considered for calculating the DIF in this method; however, the accuracy of proposed formula is low for structures with high level of ductility demand.

It must be noted that the effect of gravity load and post-elastic stiffness ratio is not considered in calculation of DIF in the UFC guidelines, although it has a major impact in structural response. It is predictable that the DIF value varies for structures with different gravity loads and different post-elastic stiffness ratio. Therefore, it is necessary to adjust the DIF in a manner that includes more effective structural parameter in order to match the nonlinear static analysis to the nonlinear dynamic analysis in the acceptable way.

In this study, effect of post-elastic stiffness ratio on DIF is evaluated and empirical DIF formulas are proposed. The new DIF formulas consider ductility demand, gravity loads and post-elastic stiffness ratio of member for assessing the progressive collapse potential of structure. For this purpose, series of three-dimensional moment frames with three and ten-storey buildings as low and mid-rise buildings, with different span lengths are provided. These structures are designed for different seismic ground motion intensities to cover a wide range of structures with varied section members. Therefore, nonlinear dynamic and step-by-step nonlinear static analyses are carried out for each assumed post-elastic stiffness ratio. Maximum ratio of M_d/M_p in damaged structure is considered for obtaining DIF, where M_d and M_p are the member moment demand under unamplified gravity loads and the plastic moment of each member, respectively. This parameter indicates the nonlinearity level of member under unamplified gravity loads in damage building. Finally, a new empirical DIF as a function of post-elastic stiffness ratio and maximum ratio of M_d/M_p for each member is presented. This ratio can be used for nonlinear static analysis of structures.

2. Analysis procedure

The Alternate Path Method (APM) is one of the most extensive methods to assess progressive collapse of the structure. In APM, one of the vertical load-bearing elements at the specific location of plan and elevation is removed, and the capability of structures to bridge across a removed element is evaluated [16,17]. In this method, one of the three analysis procedures consisting of linear static (LS), nonlinear static (NLS), or nonlinear dynamic (NLD) analyses can be implemented. NLD analysis is the most accurate but time consuming procedure. Moreover, NLD analysis widely depends on some parameters such as gravity loads, damping ratio, time step, plastic hinge definition and post-elastic stiffness ratio. The design guidelines allow using NLS and LS analyses in replace of NLD analysis with considering some limitations [16,17]. The simplest analysis procedure is LS, in which the actual nonlinear dynamic response of structure cannot be predicted accurately. Another method which can be employed is NLS analysis. In this approach, material and geometrical nonlinearities are considered in the model with the vertical load-bearing element being removed. In order to consider both effects of dynamic and nonlinearity in model, the loads in the bays immediately adjacent to the removed element and at all floors above it, are amplified [17].

3. Overview of proposed formulas for DIF

In recent years, several empirical DIF formulas have been proposed (Table 1), which can be used for structures with sudden column removal in nonlinear static analysis.

Table 1 shows a summary of recent studies that were conducted to present DIF formulas. These researches have been based on the approaches which achieve the most accurate equations.

Stevens et al. [20] proposed an empirical DIF formula for steel structures. This equation depends only on m parameter which is the plastic rotation divided by yield rotation. This parameter represents the critical structural performance level of component or connection in the area which is loaded with the amplified gravity load. Similar procedure was utilized for a wide range of steel frame models under various column removals in order to present an empirical DIF formula for steel moment frames [21]. This equation is dependent on the ratio of $\theta_{all}/\theta_{yield}$, where θ_{all} and θ_{yield} are the minimum nonlinear acceptance criteria and yield rotation of members, respectively, (according to ASCE 41-13 [18]). Series of low and mid-rise building were designed and analyzed to assess the effect of damping ratio on the DIF [23]. Step-by-step analysis using similar procedure [21] was conducted. An empirical formula considering damping ratio and ductility for steel structures was presented [23]. In this equation, ζ is the damping ratio of the model and θ_p/θ_y is the maximum ratio of plastic and yield rotations of member in affected bay of the structure.

An analytical DIF based on a bilinear load-displacement relationship for the Single Degree of Freedom (SDOF) model was presented which relays on post-elastic stiffness ratio (α) and the ductility demand (μ) of model [22].

The mentioned proposed formulas depend on maximum ductility of critical member, damping ratio and post-elastic stiffness ratio of model. However, the gravity loads and ductility demand of member are not considered in those formulas, although they are effective parameters.

Liu [19] proposed a new DIF which includes gravity loads for nonlinear static alternate path analysis. The proposed DIF is a function of maximum ratio of M_d/M_p. Based on Liu's work [19], three DIF equations were presented based on different locations of column removal, and maximum ratio of M_d/M_p. Table 1 shows the DIF for both exterior and interior column removal scenarios where the maximum ratio of $(M_d/M_p) \geq 0.5$. In this method, function of $1 - M_d/M_p$ measures the percentage level of the overall residual capacity of a building frame to remain essentially elastic. The proposed formula [19] is not accurate for structures with

Table 1
Proposed formulas for DIF calculation in nonlinear static analysis.

Researchers	Formulas	Descriptions
Stevens et al. [20]	$DIF = 1.44\,m^{-0.12}$	Empirical formula for steel structures depending only on ductility.
McKay et al. [21]	$DIF = 1.08 + \frac{0.76}{(\theta_{all}/\theta_{yield})+0.83}$	The UFC formula for steel structures that relates only to ductility.
Tsai and Lin [22]	$DIF = \frac{2\mu[1+\alpha(\mu-1)]}{1+\alpha(\mu-1)^2+2(\mu-1)}$	Analytical DIF relating to ductility and post-elastic stiffness ratio.
Liu [19]	$DIF = 0.84 + \frac{1.23}{2.95\ \max(M_d/M_p)-0.28}$	Empirical formula based on residual capacity of model considering gravity loads and ductility demands.
Mashhadi and Saffari [23]	$DIF = (2-2.54\zeta) - \frac{(0.9-1.81\zeta)(\theta_p/\theta_{yield})}{(0.84-2.15\zeta)+(\theta_p/\theta_{yield})}$	Empirical formula depending on ductility and damping ratio for steel structures.

Note: m = plastic rotation divided by yield rotation; θ_{all} = minimum nonlinear acceptance criteria; θ_{yield} = yield rotation; μ = ductility demand; α = post-elastic stiffness ratio; M_d = factored moment demand under original unamplified static gravity load; M_p = plastic moment; θ_p = plastic rotation; ζ = damping ratio.