Journal of Constructional Steel Research 117 (2016) 161–174

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Dynamic analyses of bolted-angle steel joints against progressive collapse based on component-based model

Qiuni Fu [a,b,c], Bo Yang [a,b,*], Ying Hu [a,b], Gang Xiong [a,b], Shidong Nie [a,b], Weifu Zhang [a,b], Guoxin Dai [a,b]

[a] Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing, 400045, PR China
[b] School of Civil Engineering, Chongqing University, Chongqing 400045, PR China
[c] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore, Singapore

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 27 September 2015
Accepted 17 October 2015
Available online 26 October 2015

Keywords:
Progressive collapse
Alternate Path Method
Component-based model
Dynamic performance

ABSTRACT

Some design methods have been proposed to prevent progressive collapse of building structures. Alternate Path (AP) Method is the most effective and popular one among them. Based on component-based joint models, this paper takes AP Method to study the dynamic performance of two-dimensional (2D) bolted-angle steel joints under a sudden column removal scenario. The comparison between the quasi-static and dynamic responses of the component-based models simulated by finite element software and the experimental test results shows that the component-based models are reliable. After that, based on the validated component-based models, parametric study was conducted in order to study the dynamic responses of bolted-angle steel joints subjected to different levels of sudden gravity loads. These 2D steel joints employ two types of beam–column connections, including web cleat connections and top and seat with web angle connections. Dynamic increased factors (DIFs) are obtained by comparing the acquired dynamic responses with the corresponding nonlinear static responses of the bolted-angle steel joints. Finally, DIFs calculated in this study are compared with the regulations of Department of Defense (DoD) in United States and a simplified energy balance method. As a conclusion, it is found that the numerical results in this study are in good agreement with the energy balance method.

1. Introduction

The design provisions of building structures to resist progressive collapse in many standards and design guidelines, e.g. ASCE [3], GSA [6] and DoD [5], provide two types of design approaches, including direct design and indirect design methods. The former involves Specific Local Resistance Method and Alternate Path (AP) Method. In AP Method, it is assumed that one or more vertical structural members are removed, followed by redistribution of gravity loads, and then the remaining structure system is reanalyzed under updated internal forces. Concerns of the AP Method focus on the response of the remaining structure after the accident rather than initial abnormal loading. Indirect design approach is a kind of notional reinforcement measure during the structural design process through the provision of minimum level of strength, continuity and ductility to resist progressive collapse without considering the direct action on the structures from the abnormal loading. Tie Forces Method belongs to indirect design approach.

Progressive collapse is absolutely a nonlinear dynamic process considering its real time effect. Under a sudden column removal scenario, a typical building structure exhibits a highly nonlinear dynamic response, and thus the maximum dynamic response of the structure should be taken into account in assessment. In order to take account of dynamic effect, there are usually two simplified approaches, i.e. linear and nonlinear modeling with different Dynamic Increased Factors (DIFs) and direct dynamic analyses. Nevertheless, the direct dynamic analysis on the damaged structure is overly complicated for office design environment. Wisely, the dynamic response can be established with nonlinear static response under magnified loads. Thus, nonlinear static design approach is also allowed by DoD [5] by amplifying the static loads with a DIF. This idea is relatively convenient and has high accuracy, which has been studied by other researchers, such as Izzuddin [10]. Specifically, the General Services Department in the USA [6] adopts linear static method with a coefficient of 2.0 for static loads to consider the dynamic effect caused by accidental loading. In the loading method of dynamic analyses in [6], the original loads are applied onto the structures without amplification. Similar to [6]; DoD [5] assigns the same factor 2.0 on static loads for linear static design to cover dynamic effect. However, DoD [5] also recommends that static loads should multiply DIF for nonlinear static design, and the DIFs here decrease with the

* Corresponding author at: School of Civil Engineering, Chongqing University, Chongqing 400045, PR China.
E-mail address: yang0206@cqu.edu.cn (B. Yang).

http://dx.doi.org/10.1016/j.jcsr.2015.10.010
0143-974X/

increase of allowable deformation rather than a constant of 2.0 in linear elastic static analyses. The DIF for nonlinear static design can be calculated by Eq. (1):

$$DIF = 108 + \frac{0.76}{\theta_{pra}/\theta_y + 0.83} \quad \text{(for still frame)} \tag{1}$$

where θ_{pra} is the plastic rotation angle, and θ_y is the yield rotation.

There are increasing research works, which have found that the difference between linear elastic static approach and nonlinear dynamic approach is obvious and cannot be negligible. Nevertheless, dynamic analysis is inapplicable in practical design work about progressive collapse. Therefore, the idea of DoD [5], i.e. nonlinear static design with DIFs, is rather valuable, although some defects exist in the DoD [5] in terms of the specifications on DIF, which is deduced from seismic studies. Liu et al. [9] conducted dynamic experimental tests of planar steel frames with web cleat connections subjected to a middle column removal scenario. According to their conclusions, the DIFs could be greater than 2.0, unlike the conventional knowledge that the force-based DIFs should be less than 2.0. Izzuddin et al. [10] proposed a simplified dynamic assessment approach based on the equivalence between external work and internal energy with the assumption of single degree of freedom mode. On basis of that, further analyses were conducted [11]. According to the conclusions of Izzuddin et al. [10], for an elastic–plastic system, the DIFs reduce monotonically with available ductility, which is in accordance with DoD [5]. On the other hand, for an elastic–plastic hardening system, the DIFs can increase with the ductility increase to high values, which are much greater than those values adopted by DoD [5]. Li [7] pointed out that Eq. (1) was obtained from curve fitting and thus lacks a theoretical basis. The dynamic effect has also been studied by other researchers [2,8,12].

Speaking of modeling approaches, huge computational cost of micro-modeling (continuum elements) let macro-modeling to be a worthwhile choice on the premise of certain accuracy. Yang [13,14] developed a macro-modeling, component-based model, to simulate the behavior of bolted angle connections withstanding tension under large deformation. The accuracy was validated by the static tests. The proposed component-based model of bolted-angle connections shown in Fig. 1 is an aligned model. The basic components include bolt in tension (*bt*), top, web and seat angle in bending (*tab*, *wab*, *sab*), angle in bearing (*abb*), bolt in shear (*bs*), beam flange in bearing (*bfbb*), bolt slippage model (*bsm*) and beam web in bearing (*bwbb*). As shown in Fig. 1, the component-based model has been simplified by combining all the components at one bolt row as one equivalent spring. For example, all the components located at the bottom bolt row including *bt*, *sab*, *bsm*, *bfbb*, *bs* and *abb* have been combined as one spring k1. In this model, it is assumed that the springs of k1, k3-1, k3-2 and k3-3 can sustain tensile forces while all the compression forces are sustained by the spring of k2. More details can be found in Yang and Tan [13].

In view of the background mentioned above, this paper takes AP Method to study the dynamic performance of two-dimensional (2D) steel frames under a sudden column removal scenario. Firstly, the prototype of the models and the details of the modeling method are presented. After that, the component-based models are validated by static and dynamic test data. And then, the validated component-based models are used to study the dynamic behavior of bolted-angle beam–column joints under sudden column removal scenarios. Finally, the DIFs are investigated via comparing the component-based model predictions, energy balance approach numerical results with DoD [5] recommendations.

2. Prototype model

2.1. Test specimens

Fig. 2 shows the test set-up both used in Yang and Tan [13] and Liu et al. [9]. As shown in Fig. 2, after the removal of the middle column, the internal forces and deflections of the *middle* and the *side* connections are anti-symmetric about the middle of the beam span. Thus, the inflection point is located at the middle of the beam span during the deflection process. Therefore, only one-half of the beam span on both sides was simulated using pin conditions, as shown in Fig. 2. The behavior of the *middle* and the *side* connections, including load-carrying and rotation capacities, can be represented by the specimens. The specimen prototypes in this paper stem from the tests of Yang and Tan [13] and Liu et al. [9]. Based on AP Method, the idea of the dynamic tests of Liu et al. [9] is shown as Fig. 3. Firstly, uniform loads were applied on the beam with quick-release device supporting at the middle point. Then,

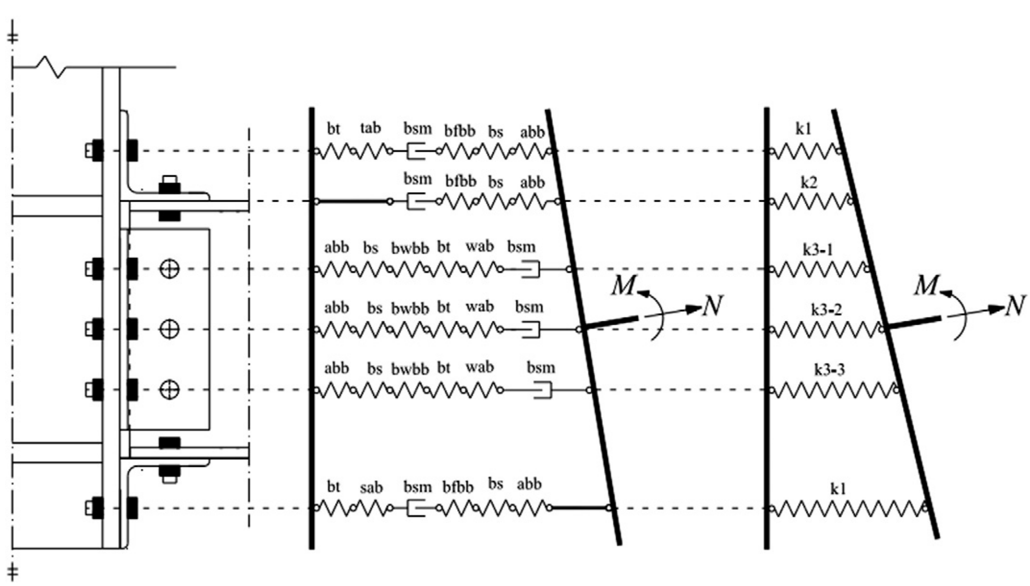

Fig. 1. Component-based model of bolted-angle connections of beam–column joints [13].