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Contribution to transient analysis of inelastic steel frames with semi-rigid connections

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Abstract

Dynamic behavior of multistory flexibly connected steel frames under earthquake excitations is studied in this paper. The numerical model that simultaneously includes nonlinear connection behavior, member yielding and geometrical nonlinearity of the structure is developed. Flexibility of connection is idealized by nonlinear rotational spring and dashpot in parallel. The refined-plastic hinge method is adopted to simulate member plasticity, for which it is assumed to be lumped at the ends of beam elements and base end of columns. A plastic hinge is idealized by nonlinear rotational spring, which is then combined with connection spring to form a resultant spring (spring-in-series). Transient response of the ductile seven-story steel frame under different intensities of the earthquake excitation is investigated. Characteristic results are presented and discussed.

Keywords: Steel frame; Semi-rigid connections; Inelastic dynamic analysis

1. Introduction

Most connections in real steel structures are more or less flexible or semi-rigid. It has been proven so by numerous experimental investigations that have been carried out in the past [1–3]. Dynamic behavior of frames with semi-rigid connections may be significantly different from rigidly connected frames, particularly those subjected to strong earthquake excitations. Therefore, the conventional methods of analysis and design of frame structures with ideal connections (fully rigid or pinned) are inadequate, as these often cannot represent real structural behavior.

Flexible connection has an ability to take over a part of input energy imparted to the structure when subjected to an earthquake excitation and dissipate it through hysteretic loop, without remarkable damage, like friction. In such a way, semi-rigid connections may reduce and improve seismic response of the structure. Therefore, significant potential for passive control of seismic response of frame structures exists in semi-rigid connections, such as lumped dissipative elements.

Behavior of steel frames under earthquake excitations generally is nonlinear. Only for a low-intensity excitation, behavior may be linear. Primary sources of nonlinearity are: connection behavior, material yielding and geometrical nonlinearity of the structure and its members. These three types of nonlinearity are generally coupled and interactive, so it is necessary to take care of combined effects of these sources on the frame structures dynamic response. The first two sources, connections and material yielding are located in the joints or at the ends of beam members as lumped dissipative elements, while the third, geometrical nonlinearity, is a combined result of both external loads and deformed geometry of the frame.

The purpose of our investigation is the development of a nonlinear numerical model for simulating the dynamic (seismic) behavior of steel frames according to the aforementioned major sources of nonlinearity. The present study relies on the author's former papers, Sekulovic et al. [4–7]. This paper is an extension of the author's work [5] regarding dynamic analysis of elastic steel frames with semi-rigid connections on the more general case of inelastic dynamic analysis.

In the former paper [5], a new beam element with flexible eccentric and viscous damping connection has been presented. For a uniform beam with nonlinear rotational springs and dashpots attached at its ends, complex dynamic stiffness matrix

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has been obtained based on analytical solutions of the second-order equations, so each beam corresponds to one finite element. Nodal displacements and rotations of element ends are eliminated via static condensation procedure. Thus, number of degrees of freedom is the same as for a beam element with fully rigid connections. Consistent mass and damping matrices have also been derived based on physical properties of the member. The numerical model and computer program for dynamic analysis of frames that includes both nonlinear connection behavior and geometric nonlinearity of the structure have been developed. The program has been tested and verified to be valid and efficient through the comparison with other analysis results and the benchmark solutions [5,7].

In this paper, the refined-plastic hinge model proposed by Chan and Chui [8] is adopted and incorporated into previously developed computer program in order to enable transient analysis of flexibly connected inelastic frames. The combined effect of material yielding and connection flexibility on seismic response of multistory frames when subjected to different intensities of earthquake ground motion is investigated.

Two types of nonlinear analysis are applied, conventional direct structural response analysis and energy response analysis. They are in correlation as two complementary and comparable approaches. In recent years, energy approach has gained great attention used for identifying where and how the energy is dissipated within the structural system. Moreover, a part of the external (input) energy dissipated through hysteretic inelastic behavior is directly related to damage of the structure, thus the energy approach may be rational and reliable way to estimate damage that can be used as a design parameter. On the other hand, connection hysteretic energy, like friction, may even be present since joints of real structures are always more or less flexible.

2. Semi-rigid connection modeling

Numerous experimental results have shown that the connection moment–rotation relationships are nonlinear over the entire range of loading for almost all types of connections. To describe nonlinear connection behavior different mathematical models have been proposed. In this study, the three-parameter power model proposed by Richard and Abbott [9] is used for representing moment–rotation behavior of connection under monotonic loading. The model can be formulated as:

$$M = \frac{k_o \theta}{[1 + (\theta/\theta_o)^n]^{1/n}}, \tag{1}$$

where k_o is initial connection stiffness, n is shape parameter of M–θ curve, $\theta_o = M_u/k_o$ is reference connection plastic rotation and M_u is ultimate moment capacity of the connection, as it is shown in Fig. 1(a). Connection stiffness k_c which is tangent slope of M–θ curve according to (1) is given by

$$k_c = \frac{\mathrm{d}M}{\mathrm{d}\theta} = \frac{k_o}{[1 + (\theta/\theta_o)^n]^{(1+n)/n}}. \tag{2}$$

Connection stiffness k_c decreases from the initial values k_o

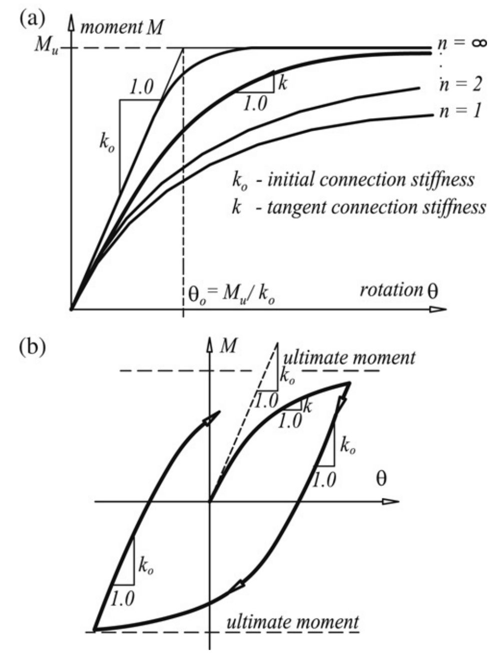

Fig. 1. Connection modeling. (a) Richard–Abbott model, (b) independent hardening model.

to zero, when moment M reaches ultimate capacity moment M_u. Values for initial connection stiffness k_o, ultimate capacity moment M_u, and shape parameter n are determined from empirical expressions, Kishi and Chen [10]. The independent hardening model has been adopted to simulate inelastic connection behavior under cyclic loading. In this model, characteristics of connection are assumed to be unchanged throughout loading cycles. Moment–rotation curve under the first cycle of loading, unloading and reverse loading remains unchanged under the repetition of loading cycle. Skeleton curve used in the model is obtained from three-parameter power model, which provides a smooth M–θ function with its positive first-derivative (i.e. a value of connection stiffness). Cyclic moment–rotation curve based on this model is schematically shown in Fig. 1(b). The independent hardening model is simple and easily applicable to all types of steel frames connection models. Experiments carried out by Popov and associates [11–13] show that hysteretic loops under cyclic loading are very stable so the moment–rotation functions obtained by static tests may be extended to dynamic analysis. More recently, experimental studies [14,15] on flexibly connected frames show that properly designed semi-rigid connections can exhibit reliable hysteretic response thus making flexibly connected frames suitable for use in seismic regions.

3. Plasticity modeling

To simulate inelastic frame behavior, two approaches exist: distributed plasticity approach or plasticity zone method and lumped plasticity approach or plastic hinge method. Although plastic zone method is generally more accurate than plastic hinge method, it is less suitable for inelastic analysis of complex multistory frames due to extensive computational time required.