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Nonlinear inelastic time-history analysis of three-dimensional semi-rigid steel frames

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ABSTRACT

This paper presents a simple, effective numerical procedure based on the beam–column method by using the based-displacement finite element method for nonlinear inelastic time-history analysis of three-dimensional semi-rigid steel frames. The nonlinear geometry effects are considered by using stability functions and the geometric stiffness matrix. The inelasticity of material is considered by the gradual yielding of plastic hinges. A space zero-length multi-spring element is proposed to simulate the nonlinear cyclic behavior of steel connections through the independent hardening model. The Hilber–Hughes–Taylor method combined with the Newton–Raphson balance iterative algorithm is adopted to solve the nonlinear equations of motion. The results of nonlinear responses for steel frames with fully rigid and linear semi-rigid connections compare well with those of previous studies and commercial SAP2000 software. Moreover, the results of steel frames with semi-rigid connections shown in this paper can be used to calibrate similar frames in future studies.

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1. Introduction

Steel moment resisting frames have been extensively used in areas of high seismic risk for low and mid-rise buildings due to their high ductility. Conventional analysis and design of steel framed structures are usually conducted under the assumption that the beam-to-column connections are either fully rigid or frictionless pinned joints. However, in the 1994 Northridge and 1995 Kobe earthquakes, these structures, especially fully welded connections, were heavily and unexpectedly damaged. Since then, over the last three decades, several experimental and analytical studies have been conducted to investigate the dynamic behavior of alternative connection types, including semi-rigid connections.

The results of experimental studies showed that semi-rigid steel frames feature the ductile and stable hysteretic behavior of the frames when the connections are designed appropriately [1–4]. The energy is dissipated through hysteretic loops of semi-rigid connections, which are one of the important damping sources of structures. Those results also showed that if the connection stiffness increases the base shear increases but the lateral drift does not proportionally decrease. Base on the impressive characteristics of semi-rigid connections, several mathematic models were proposed to represent actual behavior of these connections. These models can be grouped into two categories: linear connection models [5,6] and nonlinear connection models [7–10]. The linear connection models cannot properly predict the connection behavior due to the stiffness of the connection being assumed to be constant during the analysis procedure; while the moment–rotation curve of connections is captured more exactly by the nonlinear connection models which fitted well in the experimental curve.

In recent years, numerous analytical studies have been conducted to investigate nonlinear inelastic dynamic behavior of semi-rigid frames under dynamic and seismic loadings by Lui and Lopes [11], Awkar and Lui [12], and Sekulovic and Nefovska [13], among others. In the studies [11] and [12], the effects of geometric nonlinearity were considered by using stability functions, the material nonlinearity was considered by refined plastic hinge approach, and the connection nonlinearity was considered by modifying the stiffness matrix of beam–column element functions that account for finite rotation at the two ends of elements. Sekulovic and Nefovska [13] presented a spring-in-series model considering both the material and connection nonlinearities, while the geometric nonlinearity was considered by using the geometric stiffness matrix obtained from approximate functions. To capture exactly the effects of geometric nonlinearity, the members need to be divided into several elements so that it consumes analysis time significantly. Though these studies considered all three nonlinear components in the same analysis, they are limited to planar semi-rigid steel frames. With the following procedure, all limitations of the above-mentioned studies are overcome by the integration of three nonlinearities in the complex time-history analysis of three-dimensional frames.

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This study aims to investigate the simultaneous effects of three nonlinear components on the dynamic behavior of different steel frame types under various dynamic loadings. The geometric nonlinearity caused by the interaction between the axial force and bending moments is considered by the use of stability functions, which can accurately capture the P–δ effect by simulating only one element per member; the P–Δ effect is considered by the use of the geometric stiffness matrix. The material nonlinearity is accounted for by using the refined plastic hinge method [14], in which the Column Research Council (CRC) tangent modulus concept is used to account for the gradual yielding due to residual stresses, while the gradual yielding due to flexure is represented by a parabolic function combined with the yielding surface proposed by Orbison [15]. An independent zero-length connection element with six different translational and rotational springs connecting two identical nodes is developed to simulate the beam-to-column connections. This is an efficient way because the modification of the beam–column stiffness matrix considering the semi-rigid connections is not necessary and the connection is ready to integrate with any beam–column model. The independent hardening model is used for considering cyclic behavior of rotational springs through employing the static mathematic models (Kishi–Chen [7], Richard–Abbott [8], and Chen–Lui [9]).

This study is based on assumptions as follows: warping torsion and axial shortening due to member curvature bending (bowing effects) are ignored; lateral-torsion buckling of members is assumed to be prevented by adequate lateral braces; a compact W-section is assumed so that the section can develop full plastic moment capacity without local buckling; the connection element length is equal to zero; a possible joint degradation due to actions of cyclic loading is not considered.

In the nonlinear time-history analysis, an incremental-iterative scheme based on the Hilbert–Hughes–Taylor method and the Newton–Raphson method was developed for solving the nonlinear equations of motion. Viscous damping accounts for the use of Rayleigh damping matrix. Several examples are presented to verify the accuracy and efficiency of the proposed numerical procedure in predicting the nonlinear dynamic response of three-dimensional framed structures with semi-rigid connections.

2. Formulation

2.1. Semi-rigid connection element

2.1.1. Element modeling

An independent zero-length multi-spring element with three translational and three rotational springs was developed to simulate a general connection in 3-D-framed analysis. Contact or gap elements are different from the multi-spring element at their physical nature. The multi-spring element connects two nodes with coincident coordinates as shown in Fig. 1. In the scope of this study, the translational and torsional springs have linear stiffness and fully rigid, while the two rotational ones (y and z axis) have linear or nonlinear stiffness. Coupling effects between the six springs of a connection are neglected.

The relation between the incremental force vector $\{\Delta F_S\}$ and displacement vector $\{\Delta U_S\}$ of the multi-spring element corresponding to six degrees of freedom is as follows:

$$\{\Delta F_S\} = [K_S]\{\Delta U_S\} \tag{1}$$

$$[K_S] = \begin{bmatrix} R_x^{tra} & 0 & 0 & 0 & 0 & 0 \\ 0 & R_y^{tra} & 0 & 0 & 0 & 0 \\ 0 & 0 & R_z^{tra} & 0 & 0 & 0 \\ 0 & 0 & 0 & R_y^{rot} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_z^{rot} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_x^{rot} \end{bmatrix} \tag{2}$$

where $[K_S]$ is the diagonal tangent stiffness matrix for each multi-spring element, R_n^{tra} and R_n^{rot} are the component stiffness for the translational and rotational springs with respect to the n axis ($n = x, y, z$).

2.1.2. Semi-rigid connection models for rotational springs

In this study, the Kishi–Chen three-parameter power model [7], the Richard–Abbott four-parameter model [8], and the Chen–Lui exponential model [9] are used to evaluate the nonlinear behavior of semi-rigid connections. The independent hardening model is used to predict the cyclic behavior of the connections.

The Kishi–Chen model [7] is currently one of the most popular models used for semi-rigid connections since it needs only three parameters to capture the moment–rotation curve and always gives a positive stiffness. The moment–rotation relationship of the connection is presented by Chen and Kishi as follows:

$$M = \frac{R_{ki}|\theta_r|}{\left[1 + (|\theta_r|/\theta_0)^n\right]^{1/n}} \tag{3}$$

where M and θ_r are the moment and the rotation of the connection, n is the shape parameter, θ_0 is the reference plastic rotation, and R_{ki} is the initial connection stiffness.

Richard and Abbott proposed a four-parameter model [8]. The moment–rotation relationship of the connection is defined by

$$M = \frac{\left(R_{ki} - R_{kp}\right)|\theta_r|}{\left\{1 + \left|\frac{\left(R_{ki} - R_{kp}\right)|\theta_r|}{M_0}\right|^n\right\}^{\frac{1}{n}}} + R_{kp}|\theta_r| \tag{4}$$

where M and θ_r are the moment and the rotation of the connection, n is the parameter defining the shape, R_{ki} is the initial connection stiffness, R_{kp} is the strain-hardening stiffness and M_0 is the reference moment.

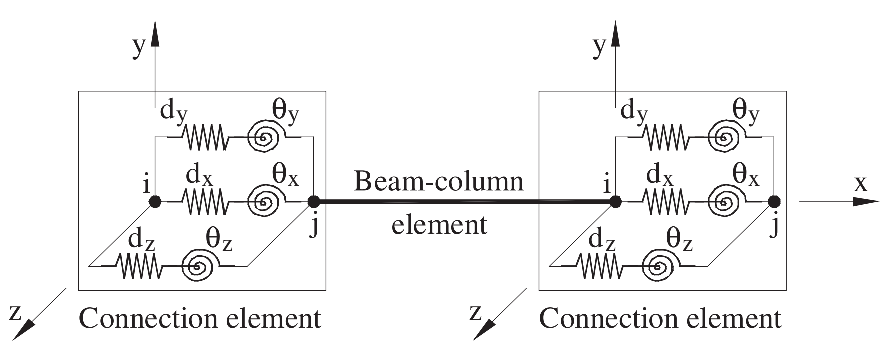

Fig. 1. A space connection element model with zero-length.

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