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Nonlinear analysis of damped semi-rigid frames considering moment–shear interaction of connections

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ABSTRACT

Nonlinear vibration analysis of semi-rigid frames, considering moment and shear interaction (MVI) for the joint, is performed in this article. The numerical model of the semi-rigid frames is created using the nonlinear finite element (FE) formulation. In the numerical model, the beams and the columns are formulated based on the Euler–Bernoulli beam theory and the Partially Restrained (PR) connections are simulated as a discrete rotational springs and a parallel rotational damper. The previously formulated three-parameter model is modified and the nonlinear moment–rotation relation of the connection is tied to its shear force to assess the interaction effects of the moment and shear of the connections. An analysis algorithm is proposed to solve the eigenvalue problem of the semi-rigid frames subjected to pre-loading conditions, taking into account the MVI effects. The method is verified through comparison with analytical examples.

1. Introduction

Although there is a considerable research on the mechanical/structural characteristics of the semi-rigid frames, a less contribution deals with dynamic response analysis of the pre-loaded nonlinear semi-rigid frames. Linear dynamic response analysis of damped semi-rigid frames is performed by Kawashima and Fujimoto [1]. The results of their study showed the impact of the dynamic characteristics of the flexible connections on the vibration response of semi-rigid frames. Chan [2] developed a numerical model for vibration analysis of the semi-rigid frames with elastic connections. The method later was extended and used in the seismic analysis of semi-rigid frame with nonlinear connections [3,4]. Lui and Lopes [5] studied the vibration response of semi-rigid frames, concluding the sensitivity of their response to connection behavior and P-Δ effects. Xu and Zhang [6] studied the dynamic response of semi-rigid frames with rotational dampers at the connections. Their study showed that there is an optimal damping for a given system, at which the seismic response of the frame is minimum. Sekulovic et al. [7] analyzed the dynamic response of the semi-rigid frames considering the connection nonlinearity and damping. Dynamic analysis of two frames with different connection types showed the crucial rule of the semi-rigid beam column connections on the stability and seismic response of these frames. Sophianopoulos [8] studied the joint flexibility effect on the free vibration of elastic steel frames. The results of this work showed the considerable impact of connection response on the dynamic characteristics of semi-rigid frames. Seismic performance assessment of semi-rigid frames by using nonlinear dynamic analysis of their FE models showed the superiority of these frames to the corresponding rigid moment frames [9,10]. Da Silva et al. [11] studied the resonance response of a semi-rigid frame considering the nonlinear connection behavior. The analysis results showed that resonance does not occur in nonlinear models due to energy dissipation nature of the nonlinear connections. In reference [12] vibration and instability of semi-rigid frames with elastic joint stiffness is studied subjected to pre-loading conditions. The results of this study show the impact of connection flexibility and pre-loading conditions on the dynamic response of the slender flexible frames.

In all these studies, the rotational response of the connections is considered ignoring the interaction of the joint shear on the rotational characteristics of the semi-rigid connections and dynamic response analysis of these systems considering MVI is an unresolved issue. Herein, the eigenvalue analysis of the pre-loaded semi-rigid frames is performed considering connection nonlinearity, MVI and damping.

2. Basic assumptions

The finite element (FE) modeling of the semi-rigid frames considering MVI and establishing the new algorithm for vibration

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response analysis of these frames are based on the following assumptions:

- The prismatic beams and columns are modeled elastic according to the Euler beam theory.
- Beam-to-column PR connections are modeled as discrete zero-length joints and the connection eccentricity is ignored.
- Hysteretic damping of the PR connections is captured through a nonlinear moment–rotation relation for the joint (nonlinear rotational spring) and a linear zero-length rotational damper is defined to add additional viscous damping to the system. Hence, the nonlinear rotational spring and rotational damper act in parallel.
- The first nonlinearity source of the model is the constitutive law defined for the nonlinear rotational response of the joints (PR connections).
- The second source of nonlinearity is the relationship between the rotational stiffness of the connection and its shear.
- The implemented equations to relate the rotational response of the connection to its shear are applicable for bolted top-seat and web angle(s) connection, TSWA.
- In the free vibration response analysis, the nodal displacements due to initial pre-loading are small and the geometric nonlinearity is ignored.
- The mass source includes distributed element mass and lumped mass on the structural nodes.
- The characteristics of the viscous rotational dampers do not change within analysis.

3. Formulation of the beams and columns

Beam/column elements are formulated according to the Euler beam theory ignoring the shear deformations. The corresponding stiffness matrix, K_b, is in the form of Eq. (1).

$$K_b = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} \\ & & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & -\frac{2EI}{L} \\ & & & \frac{EA}{L} & 0 & 0 \\ & sym. & & & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ & & & & & \frac{4EI}{L} \end{bmatrix} \tag{1}$$

in which E, I, A and L are the modulus of elasticity, moment of inertia, sectional area and the length of the member, respectively.

4. Modeling of the flexible connections

Taking into account the rotational flexibility of the PR connections can be achieved either modifying the flexural stiffness of the beam or modeling the connection as a discrete joint element. A two-node zero-length element with three degrees of freedom (DOF) for each node is implemented to model the flexible connections in this study. This element is placed between the coincident end nodes of beam and column members/components (nodes i and j shown in Fig. 1-a). A rotational damper is also defined between these nodes as shown in Fig. 1-a. The stiffness matrix of the joint, K_{joint}, is in the form of Eq. (2).

$$K_{jo\ int} = \begin{bmatrix} k_a & 0 & 0 & -k_a & 0 & 0 \\ & k_s & 0 & 0 & -k_s & 0 \\ & & k_T & 0 & 0 & -k_T \\ & & & k_a & 0 & 0 \\ & sym. & & & k_s & 0 \\ & & & & & k_T \end{bmatrix} \tag{2}$$

Where, k_a and k_s denote the elastic axial and shear stiffness of the connection. The nonlinear moment–rotation (M–θ) response of the joint is defined by Eq. (3), according to the previously defined three-parameter power model [13]. The tangent rotational stiffness of the connection, k_T, is differential of the connection moment (M) with respect to its rotation (θ) and calculated by using Eq. (4). Fig. 1-b) schematically shows the connection response and its mechanical characteristics. Herein, the original three-parameter equation is modified to consider the effects of the joint shear force by using R_{stiff}, the reduction factor for the rotational stiffness of the connection.

$$M = \frac{k_0^* \theta}{[1 + (\theta/\theta_0)^n]^{(1/n)}} \tag{3}$$

$$k_T = \frac{dM}{d\theta} = \frac{k_0^*}{[1 + (\theta/\theta_0)^n]^{(1/n)}} \left(1 - \frac{(\theta/\theta_0)^n}{1 + (\theta/\theta_0)^n}\right) \tag{4}$$

$$\theta_0 = \frac{M_u}{k_0} \tag{5}$$

$$k_0^* = R_{stiff} \times k_0 \tag{6}$$

as stated, M and θ in the above equations are the applied moment and the corresponding rotation and θ_0 is a reference rotation defined by Eq. (5). Also, M_u, n and k_0 are the ultimate moment capacity of the connection, a shape parameter and the initial rotational stiffness of the connection, respectively. $k_0^*$is the reduced initial rotational stiffness of the connection due to existence of shear force in the connection. Details on calculating the reduction factor for the initial rotational stiffness, R_{stiff}, are discussed in the following section.

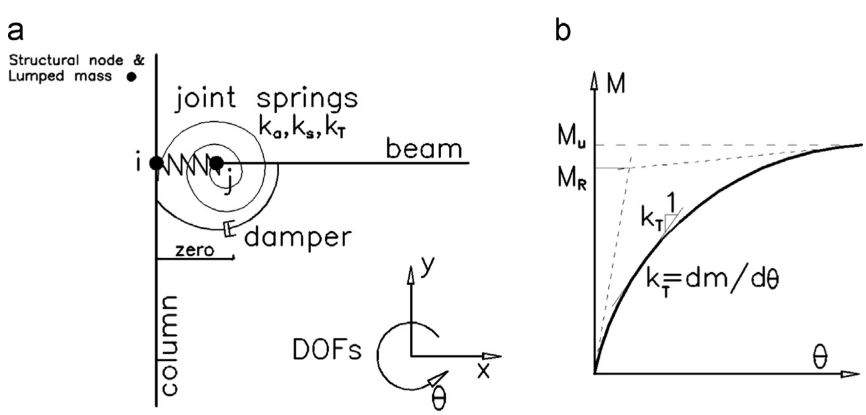

Fig. 1. Modeling of the semi-rigid connections (a) and nonlinear moment-rotation response of the PR connections (b).