ARTICLE IN PRESS
ISTRUC-00111; No of Pages 10

Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Dynamic Time-history Elastic Analysis of Steel Frames Using One Element per Member

Si-Wei Liu [*], Rui Bai, Siu-Lai Chan

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 1 May 2016
Accepted 21 May 2016
Available online xxxx

Keywords:
Time-history
Steel
Analysis
Dynamic
Beam-column
Element
Numerical

ABSTRACT

This paper proposes an efficient numerical simulation technique for dynamic time-history analysis of space steel frames by one-element-per-member model, considering geometric nonlinearity including P-Δ-δ effects, large global deflections and member deformations. The curved arbitrarily-located-hinge (ALH) beam-column element is employed for capturing members' behaviors and simulating initial imperfections, where the internal degree-of-freedoms (DOFs) are condensed for improving the computational efficiency. The consistent element mass matrix is derived based on the Hermite interpolation function, and the Rayleigh damping model is adopted for representing the system viscosity. To solve the equation of the time-history motion, a direct time-integration method via Newmark's algorithm is utilized for the step-by-step solution. A robust numerical procedure using the incremental secant stiffness method is introduced for the large deflection analysis of space frames, allowing arbitrary rotations in a three-dimensional space. Verification examples are given to validate the present model in handling dynamic behaviors of the steel frames and members under the transient actions. The distinct feature of the research is to propose an effective analytical framework using high-performance elements, dramatically improving the numerical efficiency and making the method being practical.

1. Introduction

Time-history analysis is an effective simulation-based method for evaluating the structural behaviors under the transient actions, such as earthquake attacks, accidental impacts, and progressive collapse. This method is a step-by-step integration in a time domain, bringing a rational simulation of the structure subjected to the dynamic excitations. However, this procedure is usually computationally costly, mainly since a small size of time step needs to be adopted for the precision and stability in the analysis. As reported by Nguyen [1], the most time-consuming portion in the finite element analysis (FEA) algorithm is to solve the sparse, linear equations containing the tangent stiffness matrix, incremental degree-of-freedoms (DOFs) and the external force vector. For example, if a structure is modeled by two schemes, e.g. N elements with M nodes and 4N elements with 2M nodes, the size of the stiffness matrix of the latter will be four times as large as that in the former, and the calculation time increases in line with the matrix's size. Therefore, a dramatic saving on the computational expense can be achieved when fewer elements are used in a structural system.

Some researchers have utilized the nonlinear dynamic analysis method for studying the response of steel frames under the transient motions, such as Nader and Astaneh [2], Chui and Chan [3], Awkar and Lui [4], Chan and Chui [5], Gupta and Krawinkler [6], Foutch and Yun [7], Ohtori et al. [8], Silva et al. [9] and Nguyen and Kim [10] and so on. Nowadays, the time-history analysis method has already become one of the effective tools for seismic design of structures, and is codified in the modern seismic design standards, such as Eurocode 8 [11].

The prominent emphasis in designing steel members and structures is the consideration of stability problems, and thereby, second-order effects in terms of P-Δ and P-δ effects should be properly captured in analysis. Global frame and local member imperfections should be necessarily taken into account, otherwise, the factors of instability lying in the structural system and the members cannot be effectively detected. Frame imperfection is usually applied according to the Eigen-buckling mode shapes [12], while the local member imperfection is simulated using a sine curve (see Fig. 1). The conventional method adopts several straight elements to represent the imperfection, and it causes extra manipulating efforts in offsetting the nodes. To this end, one-element-per-member model is employed in the present study, not only the computer time can be dramatically reduced, but also does it bring convenience in modeling the initial member imperfections according to the requirements in the modern design codes. This research aims to extend the application of this analytical model to the dynamic time-history analysis for seismic design.

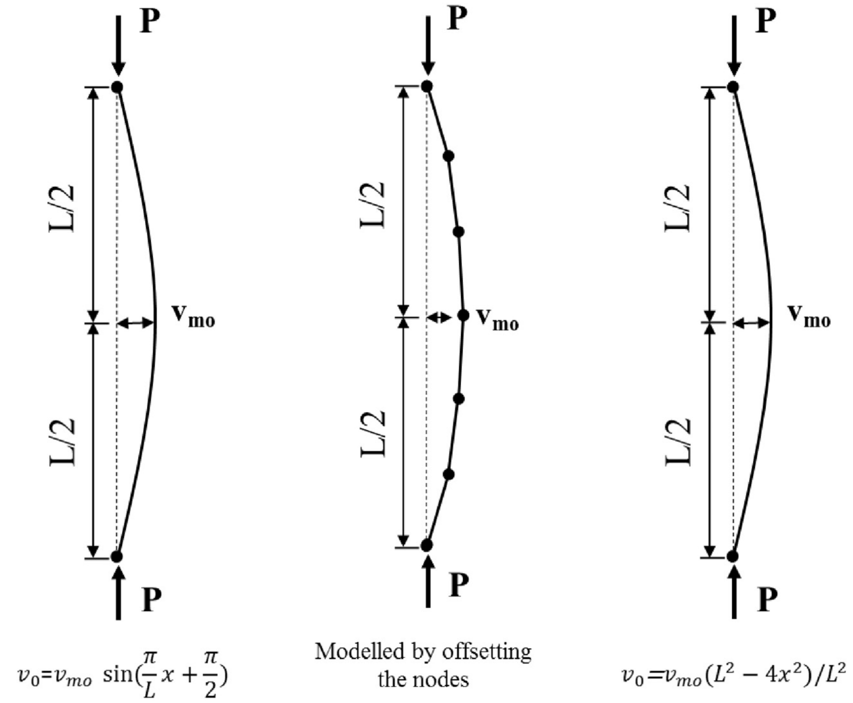
Therefore, the selection of a beam-column element, which should be initially curved and can simulate large deformation in an element, is vital and essential for a successful analysis using a one-element-per-member model. Therefore, several sophisticated elements have been developed in the recent decade, especially aiming for simulating slender members with imperfections. The Pointwise-Equilibrium-Polygonal (PEP) beam-column element with the high-order shape function is derived by Chan and Zhou [13], and has been extensively adopted in the practice over the past 16 years. Subsequently, Chan and Gu [14]

---

[*] Corresponding author. Tel.: +852 2334 6389; fax: +852 2334 6389.
E-mail address: siwei.liu@connect.polyu.hk (S.-W. Liu).

http://dx.doi.org/10.1016/j.istruc.2016.05.006

Please cite this article as: Liu S-W, et al, Dynamic Time-history Elastic Analysis of Steel Frames Using One Element per Member, Structures (2016), http://dx.doi.org/10.1016/j.istruc.2016.05.006



$v_0 = v_{mo} \sin(\frac{\pi}{L}x + \frac{\pi}{2})$

(a) Codified requirement

Modelled by offsetting the nodes

(b) Conventional method

$v_0 = v_{mo}(L^2 - 4x^2)/L^2$

(c) Proposed method

Fig. 1. Modeling of initial member imperfections.

refined the classical stability function element by incorporating the member imperfections to the formulations, which is suitable for analyzing the extremely-slender columns. Recently, the Arbitrarily-Located-Hinge (ALH) element with initial curvatures has been developed by Liu et al. [15,16], being possessed of an internal node to reflect inelastic behavior and the large deformation along the member length. In the present study, the ALH element is employed and extended its application to the dynamic time-history elastic analysis of steel frames.

Two main approaches are popularly utilized for solving the structural dynamic problems [17], e.g. response spectrum and time-history analysis methods. The former approach provides an approximated solution to estimate the peak values of displacements and forces for a system, ignoring all the nonlinear effects, e.g. geometric and material nonlinearities. This method is usually adopted in the conventional design with a small-scale excitation due to its simplicity. However, in order to obtain the 'exact' time-history response of the structure at a specified moment, time history analysis method seems to be the only option. In the current study, a time integration approach using Newmark's algorithm is introduced, which is unconditionally stable numerical integration method [18] and widely adopted for solving structural dynamic problems to show its reliability and validity. For an accurate reflection of accelerated motions within members, the consistent mass matrix [17] is derived based on the Hermite interpolation function. To represent the system viscosity, an approximated method using the Rayleigh [19] damping model is adopted.

Structural members might exhibit large deformations in a nonlinear dynamic analysis. In this paper, the incremental secant stiffness method [20] based on the co-rotational description is employed for achieving arbitrarily nodal rotations during the numerical procedure. In this method, each element has its own local axes system. The element deformations and axes' rigid-body movements are separately considered, and the final nodal rotations are calculated by a gradual transformation process instead of a summation. The method has been proven to be accurate and efficient by extensive research, e.g. So and Chan [21], Ho and Chan [22], and Liu et al. [23,24].

In this paper, the element formulations, e.g. tangent stiffness, mass and damping matrixes, are derived and presented with details, and direct time-integration method using the Newmark's method is elaborated. For describing the kinematic motion of elements during the incremental-iterative procedure, the incremental secant stiffness approach is introduced. Finally, several examples are given for the verifications and validations.

2. Assumptions

The following assumptions are taken in the deriving the element formulations and given as: (1) the Euler–Bernoulli's assumption is made, where the plan section before and after deformations are kept being normal to the centroid axes; (2) strains assume to be small, while the displacements and rotations can be arbitrarily large, using the incremental secant stiffness method [25]; (3) material's behavior is assumed to be elastic throughout the whole analysis procedure; (4) warping and shear deformations are not included in the element formulations; and (5) the applied forces are conservative and added to the nodes, remaining to be independent of the loading history.

3. Element formulations

To capture reliably the structural behavior under loads, the influential effects inherent to the beam-column members are considered, and namely they are the initial imperfections, large deflection and P-δ effect and so on. The arbitrarily-located-hinge (ALH) element proposed by Liu et al. [15,16] is used in the present study. This element explicitly simulates the initial member curvatures, and it is also capable of modeling the large member deformation by one element. A review of the ALH element is presented herein, and detailed formulations should be referred to the original paper proposed by Liu et al. [15,16]. Furthermore, the mass and damping matrixes for the ALH element are derived in this section.

Please cite this article as: Liu S-W, et al, Dynamic Time-history Elastic Analysis of Steel Frames Using One Element per Member, Structures (2016), http://dx.doi.org/10.1016/j.istruc.2016.05.006