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Sensitivity analysis of steel moment frames accounting for geometric and material nonlinearity

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Abstract

A procedure for sensitivity analysis of planar steel moment frameworks accounting for second-order displacement effects and inelastic material behavior under combined bending moment and axial force is presented in the context of performance-based design for seismic loading. Analytical formulations defining the sensitivity of nodal displacements to modifications in member cross-section sizes are derived. A nine-story moment frame example illustrates the applicability and accuracy of the developed formulations.

Keywords: Nonlinear analysis; Displacement sensitivity analysis; Performance-based design; Steel moment frameworks; Second-order analysis; Nonlinear sensitivity analysis

1. Introduction

Since the publication of FEMA-273 [1], the Performance-Based Design (PBD) concept has quickly gained popularity in professional practice for the design of building structures under seismic loading. With the emergence of the PBD methodology, there is a need to develop corresponding analytical methods. Four possible analytical methods are identified by FEMA-273: linear static, linear dynamic, nonlinear static and nonlinear dynamic analysis. Among them, the non-linear static procedure (so-called pushover analysis) is widely accepted as a viable tool to compute earthquake demands under various earthquake hazards. This is primarily because of the simplicity and ability of pushover analysis to estimate component and system deformation demands with acceptable accuracy without the intensive computational and modeling effort of a dynamic analysis.

The essential feature of pushover analysis is that it is a nonlinear procedure in which monotonically increasing lateral loads along with constant gravity loads are applied to a framework until a control node (usually referred to the building roof) sways to a predefined target lateral displacement corresponding to an earthquake hazard level. Structural deformation and member forces are monitored continuously as the model is displaced laterally. Numerous researches e.g., [2–4] on pushover analysis have been conducted recently.

Pushover analysis can be used for an iterative design process in which the structure is repeatedly modified until code-and designer-specified requirements are met. One such method is to incorporate pushover analysis together with a PBD optimization algorithm [5]. The application of optimization techniques to structural design involves using structural response sensitivity coefficients (gradients) to explicitly formulate constraint functions. Each coefficient defines the change in a structural response, such as a displacement, due to a unit change in a design variable, such as a member cross-section area. The calculation of sensitivity coefficients is called design sensitivity analysis

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and constitutes a significant part of the computational effort in an optimal structural design process.

The design sensitivity analysis of linear elastic structural systems is well-developed [6,7]. However, the sensitivity analysis of nonlinear inelastic structural systems, such as steel moment frames loaded into the plastic response range, is far more complicated and computationally intensive because the state of internal forces at any given load level depends on the prior loading history. There has been substantial study since the mid-1980's on history-dependent sensitivity analysis. Ryu et al. [8] compared the difference between linear and nonlinear sensitivity analyses and pointed out that the direct differentiation method and adjoint variable method were suitable for nonlinear sensitivity calculations. Wu and Arora [9] recognized that a response sensitivity at a given time required the calculation of partial derivatives of internal forces with respect to the design variables. However, since analytical expressions were not available, the finite difference method was used in their study to compute the partial derivatives of internal forces taking into account inelastic material behaviour (called the semi-analytical approach). Haftka and Mroz [10], Choi and Santos [11], Cardoso and Arora [12] developed variational formulations for nonlinear design sensitivity analysis, in which constraints were formulated as functions while perturbations of the design variables were treated as pseudo-initial strains. The variational approaches are suitable only for simple continuum structures. Vidal et al. [13] presented an incremental direct differentiation method for the sensitivity analysis of history-dependent materials. Their study showed it was critical to utilize the consistent tangent operator in sensitivity formulations in order to obtain reliable results. Haftka [14] concluded that the semi-analytical approach by Wu and Arora could be viewed as an overall finite difference approach based on a single Newton iteration. Ohsaki and Arora [15] obtained sensitivity coefficients from incremental equilibrium equations. The sensitivities of the incremental displacements were calculated and accumulated to obtain the sensitivities of the total displacements at the current loading level. In this procedure, the yielding load (so-called 'yielding time') of each member is considered to be a function of the design variables. These 'yielding times' were recorded and differentiated with respect to the design variables in order to solve the sensitivity discontinuity problem. This procedure is path-dependent and extremely difficult for problems where 'yielding times' and their sensitivities are hard to find. Lee and Arora [16] investigated the discontinuity of response sensitivities that occur when inelastic behavior is governed by a piecewise linear constitutive law. They pointed out that sensitivity coefficients along the loading path could be obtained by differentiating the total equilibrium equations. This is an important discovery because it obviates the need for 'yielding times' and their sensitivities. Yamazaki [17] suggested that incremental equilibrium equations could be differentiated to find incremental sensitivities that accumulate to give total sensitivities. The sensitivity discontinuity at material transition points is overcome by using the differentiated constitutive law at the yielding points. Bugeda and Gil [18] described some considerations for analytical shape sensitivity analysis when material nonlinearity is accounted for in the finite element analysis. While significant advances have been made, the literature reveals that applications of nonlinear design sensitivity analysis have been primarily limited to bar trusses and simple continuum structures such as plates, shells and single beams, under static loading alone.

Gong et al. [19] presented a procedure for PBD sensitivity analysis of planar steel moment frameworks accounting for first-order inelastic behavior due to bending stresses caused by seismically induced inertial loading. Analytical formulations defining the sensitivity of displacements to modifications in member sizes were derived based on a load-control pushover analysis procedure. The adjoint variable method was found to be extremely efficient when accounting for material nonlinearity under a single stress state alone (i.e., bending moment). Although the formulations were derived based on continuous design variables, they are readily extended to the case of discrete sizing variables for commercially available steel sections. A 3-story moment frame example illustrated the applicability and accuracy of the developed methodology.

This paper is the further development of the above noted previous study by the authors [19]. The pushover design sensitivity analysis is extended to account for second-order displacement effects and inelastic material behavior under combined bending moment and axial force. A nine-story moment frame example illustrates the applicability of the developed sensitivity formulations.

2. Pushover analysis

Based on a procedure originally conceived for the elastic analysis of steel frameworks with semi-rigid connections [20–23], this study adopts a pushover analysis procedure recently developed by Hasan et al. [24] to predict seismic demands for steel frameworks. 'Fictitious plastic hinge connections' are introduced at both ends of beam-column elements (e.g., see Fig. 1 for a planar member), and the conventional elastic and geometric stiffness matrices for the elements are progressively modified to account for the progressive degradation of the post-elastic stiffness of the framework structure under incrementally increasing loads.

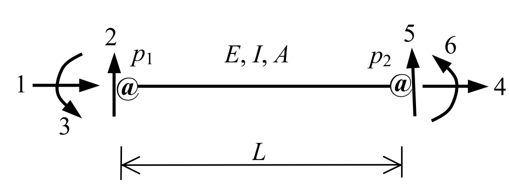

Fig. 1. Planar beam-column element.