PUSHOVER ANALYSIS OF BUILDING STRUCTURES

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Contents

Summary

An essential requisite in performance-based seismic engineering is the estimation of inelastic deformation demands in structural members. An increasingly popular analytical method to establish these demand values is a "pushover" analysis in which a model of the building structure is subjected to monotonically increasing lateral forces. While such an approach takes into consideration redistribution of forces following yielding of sections, it does not incorporate the effects of varying dynamic characteristics during the inelastic response. One of the main challenges in a pushover procedure is the development of lateral force patterns that best represent the action of seismic forces in a building in both the elastic and inelastic phases of the response. In this chapter, several existing approaches to carrying out a pushover analysis of a building system are presented. Issues and shortcomings of existing methods are also discussed. The chapter concludes with a sample simulation using two different approaches.

1. Introduction

Seismic design of structures is currently a force-based procedure. However, it is now widely accepted that force-based design procedures do not account for force-redistribution after yielding of components nor do they take into consideration the influence of changing dynamic characteristics of the system. Since structural damage is directly related to local deformations, a more reasonable approach for seismic evaluation and design of structures should be based on inelastic displacements rather than elastic forces.

The emergence of ASCE/SEI 41-13 has laid the foundation for the development of future performance-based seismic codes. These guidelines suggest that a nonlinear static analysis is more reliable than a linear static procedure and can be applied to most regular buildings. A Nonlinear Static Procedure (NSP) involves subjecting a mathematical model of the building to a monotonically increasing *invariant* lateral force pattern until a pre-determined target displacement is reached or the building is on the verge of incipient collapse. The stiffness of elements that experience yielding is modified to reflect the post-yield behavior of the element. The capacity curve of the structure is determined in terms of base shear versus control node displacement. The term "pushover" analysis of structures can therefore be viewed as a modern variation of classical plastic “collapse” analysis of frame structures.

Given the fact that a pushover method is a static method which does not require the selection of ground motions and the modeling effort in building a computer model of a building is significantly less than for a time-history method, engineers are more comfortable with pushover procedures than nonlinear time-history methods. Given this appeal of pushover procedures, it is reasonable to assume that pushover analyses will become commonplace in seismic evaluation compared to time-history methods.

2. Overview of Current Pushover Methods

Approximate Nonlinear Static Procedures (NSPs) are becoming commonplace in engineering practice to estimate seismic demands. In fact, some seismic codes, such as the Eurocode and the Japanese Building Code have begun to include them to aid in performance assessment of structural systems. Although seismic demands are best estimated using Nonlinear Time-History (NTH) analyses, NSPs are used in ordinary engineering applications to avoid the difficulties associated with selecting ground motions and additional computational effort required by NTH simulations.

However, it is now also well-known that simplified procedures based on invariant load patterns suffer are inadequate to predict inelastic seismic demands in buildings when modes higher than first mode contribute to the response and inelastic effects alter the height-wise distribution of inertia forces. In order to overcome some of these drawbacks, a number of enhanced procedures considering different loading vectors (derived from mode shapes) have been proposed. These procedures attempt to account for higher mode effects and use elastic modal combination rules while still utilizing invariant load vectors. The Multi-Mode Pushover (MMP), for example, considers multiple pushover curves derived from different modal force patterns. The Modal

Pushover Analysis (MPA) and Upper-Bound Pushover Analysis (UBPA) procedure are also examples of this approach.

Another class of enhanced pushover methods is the adaptive pushover procedures, where the load vectors are progressively updated to consider the change in system modal attributes during inelastic phase. In this procedure, equivalent seismic loads are calculated at each pushover step using instantaneous mode shapes. The corresponding elastic spectral accelerations are used for scaling of the lateral loads which are applied to the structure in each mode independently. Several other force or displacement based pushover procedures utilizing adaptive load patterns have also been proposed.

Other alternative methods for pushover analysis include methods where deformation levels and/or the stiffness state determine the load pattern, such as using story forces proportional to the deflected shape of the structure or developing force patterns based on mode shapes derived from the secant stiffness at each load step.

2.1. Invariant Load Methods

2.1.1. FEMA Displacement Coefficient Method

The *Displacement Coefficient Method* (DCM) was adopted by National Earthquake Hazard Reduction Program (NEHRP) in their Pre-standard for Seismic Rehabilitation of Buildings (FEMA-356) as the preferred method to determine the expected maximum displacement (or target displacement) for the nonlinear static analysis procedure. The target displacement (δ_t) is computed by modifying the spectral displacement of an equivalent SDOF system as follows:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \,. \tag{1}$$

The factors $C_0, C_1, C_2,$ and C_3 are modification factors that account for spectral displacement, inelasticity, hysteresis shape, and P-Δ effects, respectively. S_a is spectral acceleration and T_e is the effective fundamental period computed as follows:

$$T_e = T_i \sqrt{\frac{K_i}{K_e}} \,, \tag{2}$$

where T_i is the elastic fundamental period, K_i is the initial elastic stiffness and K_e is the stiffness at a base shear strength equal to 60% of the yield strength of the structure. Since the nonlinear static response of the structure is extremely sensitive to choice of load pattern, FEMA-356 recommends using at least two load patterns that approximately bound the distribution of the inertia forces along the building height in a seismic event. The first is a profile based on lateral forces that are proportional to the total mass at each level called the uniform pattern. The second pattern can be a triangular pattern that is dependent on the fundamental period of the structure in the direction under consideration or a pattern resulting from a modal combination using

SRSS (Square-Root of Sum of Squares) or CQC (Complete Quadratic Combination) modal response combination.

2.1.2. Capacity Spectrum Method

The *Capacity Spectrum Method* (CSM) uses a pushover analysis to establish the base shear vs. control node displacement and then converts these quantities into spectral acceleration and spectral displacement that is plotted in ADRS (Acceleration-Displacement Response Spectrum) format. Load patterns based on higher modes are used to generate a series of pushover curves. The following relationships are used to make the conversion to ADRS format:

$$S_{\mathrm{a},m} = \alpha_m (V_m / W)\,, \tag{3}$$

Where $S_{\mathrm{a},m}$ is the spectral acceleration for mode 'm' (expressed in units of 'g'), V_m is the base shear for mode 'm', W is the seismic weight of the building, and

$$\alpha_m = \frac{\sum_{i=1}^{N} w_i \Phi_{i,m}^2}{\left(\sum_{i=1}^{N} w_i \Phi_{i,m}\right)^2}\,, \tag{4}$$

$$S_{\mathrm{d},m} = \frac{\Delta_{\mathrm{c},m}}{\beta_m \Phi_{\mathrm{c},m}}\,, \tag{5}$$

$$\beta_m = \frac{\sum_{i=1}^{N} w_i \Phi_{i,m}}{\sum_{i=1}^{N} w_i \Phi_{i,m}^2}\,, \tag{6}$$

where

N = number of floors in the building

$S_{\mathrm{a},m}$ = spectral acceleration for mode 'm'

$S_{\mathrm{d},m}$ = spectral displacement for mode 'm'

V_m = base shear for mode 'm'

W = seismic weight of building

w_i = seismic weight of floor at level 'i'

$\Phi_{i,m}$ = modal amplitude at level 'i' for mode 'm'

$\Delta_{\mathrm{c},m}$, $\Phi_{\mathrm{c},m}$ = displacement and modal amplitude of control node for mode 'm'

The ADRS format of the response spectrum represents the demand side of the equation. A debated issue in CSM is the representation of damping when developing the demand curve to account for inelastic effects. When the structure is in the inelastic range under the action of seismic forces, much of the dissipated energy is due to yielding of the structure. The net effect of yielding is to increase the overall damping of the system. Hence a series of ADRS curves for different damping values should be generated. The pushover curve (the capacity side of the equation) is then superimposed on these demand curves. The intersection of the pushover curve with one of the demand curves at an appropriate damping value represents the "performance" point. This is shown graphically in Figure 1 where it is assumed that 20% damping is the final damping value which establishes the performance point (typically this is an iterative process).

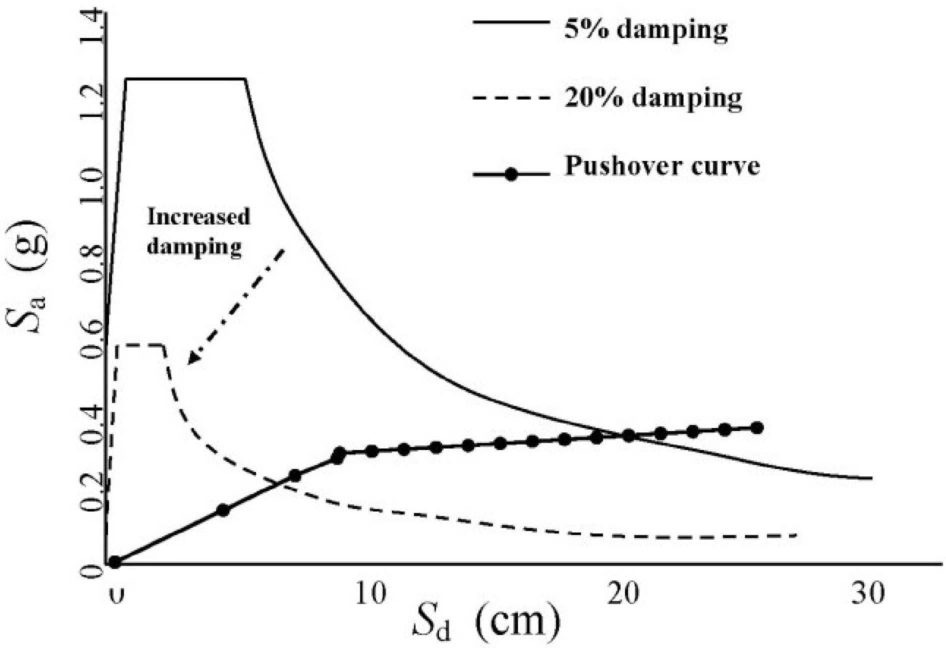

Figure 1. Capacity spectrum procedure to determine performance point of the structure.

2.1.3. N2 Method

The N2 method was initially proposed by Fajfar and Gaspersic (1996). A slightly modified version of the method has been included in the Eurocode 8 (CEN 2004). Conceptually the method is a variation of Capacity Spectrum Method that instead of a highly damped spectra, it uses an R–μ–T relationship (in which R is the strength reduction factor, μ is the ductility and T is the period of the structural system). The method consists of the following steps:

i. Perform pushover analysis and obtain the capacity curve in terms of base shear versus roof displacement of the building

ii. Convert the pushover curve of the Multi-Degree-Of-Freedom (MDOF) system to the capacity diagram of an Equivalent-Single-Degree-Of-Freedom (ESDOF) system and approximate the capacity curve with an idealized bilinear relationship

iii. Using the relationships proposed by Vidic et al. (1994), determine the seismic demand for the ESDOF system – this includes the displacement demand and the dissipated hysteretic energy.

iv. Transform the ESDOF demands into global seismic demands of the MDOF model. The process is outlined in Fajfar and Gaspersic (1996).

v. Perform a pushover analysis of the MDOF model up to the displacement demand computed in the previous step. Evaluate performance of the building at this displacement demand.

The N2 procedure has been shown to reasonably predict seismic demands based on comparison with nonlinear time-history simulations of several Reinforced Concrete (RC) multi-story frame-wall and frame structures.

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Biographical Sketch

Sashi Kunnath is Professor in the Department of Civil & Environmental Engineering at the University of California at Davis (UCD). He received his undergraduate degree from Bangalore University (India), his Master's Degree in Structural Engineering from the Asian Institute of Technology (Thailand) and his PhD at the University at Buffalo of the State University of New York. His research interests include performance-based seismic engineering, nonlinear modeling of structural behavior and structural response evaluation under extreme loads. He has published over 200 technical papers and reports, chaired and/or co-chaired international symposia, technical sessions at international conferences and workshops, and delivered invited/keynote lectures in China, Hong Kong, India, Italy, Japan, Korea, Mexico, Portugal, Slovenia and Thailand. He has served on numerous technical committees of ASCE and ACI including the SEI/ASCE Standards committee on Disproportionate Collapse and ACI Committee 377, Performance-Based Structural Integrity & Resilience of Concrete Structures. He formerly served as the Editor-in-Chief of the ASCE *Journal of Structural Engineering* (2003 – 2010) and also chaired the ASCE Technical Administrative Committee on Dynamic Effects and the Technical Committee on Seismic Effects. He has received various research and service awards including: the 2012 Norman Medal from ASCE, the Richard Torrens Award in 2009, the Raymond Reese Research Prize from ASCE in 2008, and the American Concrete Institute (ACI) Structural Research Award in 2001. He is Fellow of the American Concrete Institute (2007), the American Society of Civil Engineers (2010) and the ASCE Structural Engineering Institute (2013).