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Seismic Margin Assessment for earthquake beyond design basis – Simplified practical approach

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ABSTRACT

Accentuated by recent Fukushima accident, and earthquake events that affected Kashiwazaki Kariwa and North Anna Nuclear power plants, vulnerability assessment of Structures Systems and Components (SSCs) of nuclear facilities for earthquake ground motion exceeding the design basis has become an important exercise to ensure safety in case of highly improbable but possible extreme earthquake event beyond design basis.

For seismic performance assessment of structures, three methods viz. response reduction factor based approach, nonlinear response history analysis, and nonlinear static response analysis are available (IAEA, 2011). While the first two methods are either approximate or complex, Nonlinear Static Procedure (NSP) has ability for offering a practical and accurate solution to the problem of Seismic Margin Assessment (SMA) and is simple to adopt at design office.

In the present work, step by step approach is presented for Seismic Margin Assessment of structures using nonlinear static analysis procedures. In this approach, at first, pushover analysis is performed on the structure with the appropriate load pattern (e.g. proportional to fundamental mode shape) and effect of higher modes is evaluated using an elastic response analysis. Response of higher mode is then combined to the response from pushover analysis using Modified Modal Pushover Analysis (MMPA) method (Chopra and Goel, 2004). In the second step, demand spectra for different performance objectives is evaluated by augmenting the design spectra. Hence, seismic margin of the structure is evaluated in terms of scaling factor for design spectra for different performance objectives. Material models used in this approach for pushover analysis is validated using structural response data from tests conducted on different types of structures. Application of the proposed approach is also demonstrated for Seismic Margin Assessment of a typical NPP structure.

1. Introduction

Occurrence of recent seismic events (NCO earthquake of 2007 and GEJE event of 2011) that resulted in ground motions beyond design basis at many NPP sites has emphasized the need for assessment beyond design basis and evaluation of margins. Evaluation of seismic margin calls for seismic performance assessment of the structure considering nonlinear behavior. For seismic performance assessment of structures, various procedures viz. response reduction factor based approach, nonlinear response history analysis, and nonlinear static response analysis etc. are available (IAEA, 2011). Conventional approaches (e.g. IAEA, 2003) address issue of increased seismic demand as an extension of existing seismic analysis methodologies with use of increased damping and response reduction factors to account for ductility. Nonlinear response history analysis is considered as most precise tool for Seismic Margin Assessment. However it is analytically complex and computationally expensive. Motivation for developing simplified procedures has essentially been to find an alternative approach to nonlinear response history analysis. As a good alternative to this approach, methods of performance assessment using Nonlinear Static Procedures (NSPs) proposed in ATC (1996), FEMA (2005) etc. have been applied to conventional frame structures by many researchers (Zou and Chan, 2005; Mwafy and Elnashai, 2001; Golghate et al., 2013).

Abbreviations: ADRS, Acceleration Displacement Response Spectrum; BDBE, Beyond Design Basis Earthquake; CDP, Concrete Damage Plasticity; CSM, Capacity Spectrum Method; FE, Finite Element; FRS, Floor Response Spectra; IO, Immediate Occupancy; LS, Life Safety; NPP, Nuclear power plant; NSP, Nonlinear Static Procedure; PGA, Peak Ground Acceleration; SMA, Seismic Margin Assessment; SS, Structural Stability; SSCs, Structures Systems & Components; SSE, Safe Shutdown Earthquake; SRSS, Square Root of Sum of Squares.

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Conventional approach for seismic performance assessment as per IAEA (2003) is also applied by researchers (Juraj, 2013) for Seismic Margin Assessment. However, use of prescribed damping and ductility factors renders the method approximate with respect to accuracy. IAEA (2003) recommends use of 10% damping for reinforced concrete structures after yielding. However, according to PEER/ATC-72-1 (2010) based on experiments conducted on shake table, the maximum value of damping in shear wall-frame system ranges from 6.9% to 7.5% even under significant damage conditions. Hence, use of higher damping as per IAEA (2003) for shear wall-frame system could result in un-conservative estimates of seismic capacity. Studies on application of displacement based approach for seismic performance assessment of NPP structure by NRC (2001) also indicated similar findings. It was concluded that conventional approaches usually underestimate the displacement demand on the structure primarily due to overestimated damping.

Considering the above mentioned limitations of conventional analysis methods and full scale nonlinear dynamic analysis, nonlinear static analysis procedure appears to be more viable option. Detailed performance evaluation of different Nonlinear Static Procedures (NSPs) viz. Capacity Spectrum Method (CSM) (Freeman et al., 1975), Modified Pushover Analysis (Chopra and Goel, 2002), Adaptive CSM (Casarotti and Pinho, 2007) and Adaptive Modal Combination (AMC) (Kalkan and Kunnath, 2006) was carried out recently by Pinho et al. (2013). Sixteen planar buildings with different structural and material properties were analyzed in the study. Nonlinear Static Procedures were validated using results of dynamic analysis for large number of input motions. The evaluation indicated that nonlinear static analysis procedures can accurately predict displacements and produce reasonable estimates for other response parameters when compared to non-linear dynamic analysis results. Limited dispersion was observed among prediction by different methods.

Jha et al. (2017) performed validation exercise of nonlinear static analysis procedure for shear wall structures widely used in nuclear power plants. In this study response parameters obtained from shake table testing on a shear walls were compared with those predicted using Nonlinear Static Procedures. The work concluded that performance of the structure could be predicted with reasonable accuracy using NSP.

In the present research work, step by step approach is presented for Seismic Margin Assessment of structures using nonlinear static analysis procedures. In this approach, at first, pushover analysis is performed on the structure with the appropriate load pattern (e.g. proportional to fundamental mode shape) and effect of higher modes is evaluated using an elastic response analysis. Response of higher mode is then combined to the response from pushover analysis using Modified Modal Pushover Analysis (MMPA) method (Chopra et al., 2004). In the second step, demand spectra for different performance objectives is evaluated by augmenting the design spectra. Hence, seismic margin of the structure is evaluated in terms of scaling factor for design spectra for different performance objectives. Material models used in this approach is validated using structural response data from tests conducted on different types of structures (Barda et al., 1977; Lefas et al., 1987). The validated approach is applied to a typical Indian NPP structure for evaluating viability of the approach for such structures. Simplified method proposed in this work can be used for Seismic Margin Assessment of reinforced concrete structures to ensure safety under earthquake beyond design basis.

2. Seismic performance assessment using pushover analysis

The static pushover analysis (ATC, 1996) provides reasonably good estimate of the maximum seismic demand that can be imposed on structures characterized by inelastic behavior distributed along the height and the seismic response is predominantly governed by the fundamental mode of vibration. An important condition for obtaining accurate results is selection of appropriate material models, which are computationally efficient as well as provides accurate results in nonlinear domain.

Two key points of a performance based analysis are demand and capacity. Demand is the representation of earthquake ground motion to the structure and capacity is the structure's ability to resist the seismic demand. Once capacity curve of the structure is established, performance assessment of the structure can be conducted using Capacity Spectrum Method (CSM) (ATC, 1996). In this method capacity of structure is compared with seismic demand in Acceleration Displacement Response Spectrum (ADRS) format to assess the seismic performance of structure. However, this methodology is primarily applied to frame (beam-column) type flexure dominant structures. For short period structure like shear walls, effectiveness of Nonlinear Static Procedure was assessed and suitable modifications were applied by Jha et al. (2015) to adopt it for Seismic Margin Assessment (SMA). The study showed that damping values estimated for squat shear wall type structures are un-conservative if ATC (1996) equations are utilized.

2.1. Material modeling for pushover analysis

Nonlinear Finite Element analysis is being increasingly used to predict inelastic response of Reinforced Concrete (RC) structures. In the present work, pushover analysis is carried out using Finite Element software Abaqus (2010). Nonlinear behavior of the structure is captured through an appropriate non-linear material model for beam and shell Finite Elements. For beam elements, nonlinearity is modeled using nonlinear moment-curvature (M-phi) relations. M-phi relations are derived considering nonlinear concrete and steel properties using characteristic strength of material. Validation study for use of M-phi relations for modeling nonlinearities in beams and columns for use in pushover analysis is provided in Section 4.1.

Computationally efficient material models which would generally be less complex, have limited accuracy of behavior predictions in nonlinear regime. On the other hand complex models may pose convergence issues in solution phase. Validation of the material model with the available experimental data prior to its application is necessary from this perspective. In this work, shear walls are represented by shell elements and concrete material nonlinearity is modeled using damaged plasticity model for concrete (Abaqus, 2010). Behavior of reinforcing steel is modeled using elasto-plastic model. Validation of adopted material models and related aspects are covered in Section 4.2.

Due to high in-plane rigidity, floor slabs do not contribute to nonlinear lateral load-deformation response of the structure and hence these are modeled with elastic properties.

2.2. Lateral load distribution for pushover analysis

Pushover analysis is carried out with lateral load distribution corresponding to fundamental mode of vibration. Incremental lateral loads are applied in both the orthogonal horizontal direction, proportional to mass normalized mode shape.

2.3. Performance objectives

Seismic margin of the structure is evaluated with respect to certain pre-defined performance objectives. Acceptable performance criteria for these objectives are formulated at global response of the structure (inter storey drift, roof displacement etc.) and local (element) levels.

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