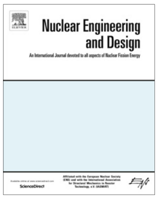
Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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



Floor response spectra for beyond design basis seismic demand

Somnath Jha *, A.D. Roshan, L.R. Bishnoi

Siting & Structural Engineering Division, Atomic Energy Regulatory Board, Mumbai 400094, India

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 23 December 2016
Accepted 4 January 2017
Available online xxxx

ABSTRACT

Vulnerability assessment of Structures Systems and Components (SSCs) of nuclear facilities for earthquake ground motion exceeding the design basis ground motion has become a key issue to ensure safety in case of highly improbable but possible extreme earthquake event beyond design basis. In order to assess seismic safety of SSCs located at different floors of the building, floor response spectra (FRS) for such beyond design basis seismic demand, taking into account possible nonlinear behavior of structure, is required. Currently used methods (e.g. IAEA Safety Series 28) do not capture softening of structure at increased demand. A performance based approach would be ideal under such situations. FRS for higher seismic demand may be developed through nonlinear time history analysis of the structure. However, this approach is complicated and cumbersome for structural configurations such as that of NPPs and requires deep insight of solution algorithm and large resources for numerical solution. In this work a simplified methodology for FRS generation for higher level of seismic demand using linear time history analysis of an equivalent linear structural model is proposed. Nonlinear behavior of structure and associated damping are estimated from Nonlinear Static Pushover Analysis. Through this approach realistic estimation of stiffness degradation of the structure and increase in damping at different levels of seismic demands can be made. Subsequently, linear time history analysis is performed on degraded structure, accounting for stiffness reduction and hysteretic damping to obtain the floor time histories which are then converted to FRS. Application of this method is shown through case studies.

1. Introduction

Seismic safety is one of the essential design requirements of a NPP structure. 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 of margins to ensure safety against beyond design basis events. With increase in demand, structure may exhibit nonlinear behavior resulting in softening (stiffness reduction) and change in natural frequencies. Nonlinear behavior of the structure also results in additional damping due to hysteresis. Conventional approaches (e.g. IAEA, 2003) address this as an extension of existing seismic analysis methodologies albeit with use of increased damping and response reduction factors due to ductility.

Performance assurance of floor mounted equipment and components is important for NPPs even under Beyond Design Basis Earthquake events. Seismic performance of these systems can only be assured if seismic demands on floors is appropriately quantified. Seismic demands on floors is generally represented through Floor response spectra (FRS). FRS for Design Basis Earthquake is developed by linear time history analysis of the structure.

Under BDBE, when structure is expected to exhibit inelastic behavior, ideally non-linear time history analysis would be required. Though non-linear time history analysis is a more rational method, its complexity of response tracking, uncertainties associated with material constitutive laws and their impact on solution accuracy are the deterrents for design office use of non-linear time history analysis. Generally, only specific purpose software like OpenSees (Gregory et al., 2007), IDARC (Valles et al., 1996) can simulate the complex behavior of concrete under cyclic loading. In addition, use of any numerical system to Nuclear Power Plants calls for stringent software related quality assurance (QA) requirements.

Abbreviations: ADRS, Acceleration Displacement Response Spectrum; BDBE, Beyond Design Basis Earthquake; CDP, Concrete Damaged Plasticity; CSM, Capacity Spectrum Method; DBE, Design Basis Earthquake; FE, Finite element; FRS, floor response spectra; GEJE, Great East Japan Earthquake; MCE, Maximum Credible Earthquake; NPP, Nuclear Power Plant; NLSPA, Nonlinear Static Pushover Analysis; PGA, Peak Ground Acceleration; SSCs, Structures Systems & Components; SSE, Safe Shutdown Earthquake.

* Corresponding author.
E-mail address: somnath@aerb.gov.in (S. Jha).

http://dx.doi.org/10.1016/j.nucengdes.2017.01.006
0029-5493/© 2017 Elsevier B.V. All rights reserved.

Please cite this article in press as: Jha, S., et al. Floor response spectra for beyond design basis seismic demand. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.01.006

Symbols

β_e	effective damping
β	viscous damping of shear wall structure
β_h	pinched hysteresis damping
β_0	hysteresis damping
E_D	energy dissipated by damping
E_{So}	maximum strain energy
f_s	secant frequency
f	elastic frequency
f_e	effective frequency
K_S	secant stiffness
K_I	initial stiffness
Z	zone factor (0.24 for Seismic Zone-IV of IS 1893 (2002))
I	importance factor (1.0 for conventional structure)
R	response reduction factor (5.0 for Shear walls)
SRF	stiffness reduction factor

Different simplified approaches, as via media, are proposed in the literature for estimation of seismic demands on floors (Igusa and Der Kiureghian, 1985; Villaverde, 1997; Miranda and Taghavi, 2006; CEN EC8, 1998) among others). Limitations of these methods have been extensively reviewed by Sullivan et al. (2013). It is noted that, most approaches in the literature do not consider the impact of different levels of elastic damping and non-linear behavior of the primary structure on floor spectra. These approaches are either simple but not reliable or reliable but require relatively advanced analysis capabilities (Calvi and Sullivan, 2014). Calvi and Sullivan (2014) proposed a simplified method for generation of FRS and validated it by comparing predicted spectra with those obtained from time-history analyses of a case study building. The method proposed in Calvi and Sullivan (2014) could be applied to multi-story structures only in linear range, but it is possible to adjust elastic damping values over a wide range.

Development of a simplified approach, which is capable of addressing the non-linear behavior of the primary structure and increased damping that influences the shape and intensity of floor spectra, is quite challenging.

The methodology proposed in this work for generation of FRS utilizes state of the art seismic performance assessment procedures viz. Nonlinear Static Pushover Analysis (NLSPA) for accounting non-linear behavior of the structure. Simplicity of pushover analysis makes it more appealing for design office use to calculate degraded stiffness of the structure at different levels of seismic demand exceeding design basis. Hysteretic damping due to nonlinear behavior of the structure could also be evaluated from pushover curve using empirical approaches given in various international guidelines (ATC-40, 1996; Kennedy et al., 1984). The main postulation of the proposed method is that linear time history analysis on equivalent linear structure, after accounting for stiffness degradation and enhanced hysteretic damping can yield floor response spectra for seismic demand, corresponding to Beyond Design Basis Earthquake (BDBE).

Industrial standard software platform such as ANSYS (2015) and Abaqus (2010) are being used in nuclear applications after satisfying software quality assurance requirements. The implementation of proposed methodology is shown through the use of Abaqus software.

2. Methodology for generation of FRS using pushover analysis

NPP structures may exhibit nonlinear behavior if subjected to ground motion higher than the design basis. FRS required for seismic qualification of floor mounted equipment and components for beyond design basis ground motion should be developed taking into account possible degradation of the structure and expected level of damping. Static pushover analysis is a tool by which stiffness degradation of the structure and expected damping at different levels of seismic demand can be evaluated.

In this work, pushover analysis is proposed to be used to determine stiffness degradation of structure and modified damping at different levels of seismic demand. This is done by seismic performance assessment of the structure using Capacity Spectrum Method of ATC-40 (1996). Finite element (FE) model of structure is then modified to take into account the stiffness degradation and modified damping expected at any specified level of seismic motion beyond design basis. Modified FE model of the structure may be named as equivalent linear model. Linear time history analysis of the degraded structure (reduced stiffness) is performed for the modified damping to generate FRS.

2.1. Seismic performance assessment

In Capacity Spectrum Method, capacity of structure is compared with seismic demand in Acceleration Displacement Response Spectrum (ADRS) format to assess the seismic performance of structure for a given seismic motion. The procedure seeks to find out a point on the capacity spectrum that also lies on the appropriate demand spectrum, scaled down for nonlinear effects. This point is called performance point. Hysteretic damping and stiffness degradation for the ground motion under consideration is estimated in correspondence of the evaluated performance point.

2.2. Estimation of hysteretic damping

Damping that occurs when the earthquake ground motion derives the structure into inelastic range can be viewed as the combination of viscous damping that is inherent in the structure and the hysteretic damping. Hysteretic damping is dependent on area of hysteretic loops formed when the earthquake force (base shear) is plotted against the structure displacement. Hysteretic damping can be represented by equivalent viscous damping using equations available in the literature (ATC-40, 1996; Kennedy et al., 1984; Gülkan et al., 2005).

An approximate effective (hysteretic) damping is calculated based on the capacity curve, the estimated displacement demand and resulting hysteresis loop. Probable imperfections in real building hysteresis loops, including degradation and duration effects, are accounted by reducing theoretically calculated equivalent viscous damping values.

Equivalent viscous damping of frame structures (i.e. with beam and columns), can be estimated using bilinear hysteretic model given in ATC-40 (1996) and reproduced as Eq. (1). Based on studies of nonlinear response of short period structures, Gülkan et al. (2005) reported that equation given in ATC-40 significantly underestimates the displacement demand of short period structures such as shear walls due to overestimation of viscous damping. High damping values are not expected for shear wall structures due to considerably lower ultimate displacement demand than frame structures and existence of pinching in the hysteresis loop. For experiments conducted on shake table under significant damage

Please cite this article in press as: Jha, S., et al. Floor response spectra for beyond design basis seismic demand. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.01.006