Engineering Structures 142 (2017) 137–147

Contents lists available at ScienceDirect

Engineering Structures

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

A novel reliability technique for implementation of Performance-Based Seismic Design of structures

J. Ramon Gaxiola-Camacho, Hamoon Azizsoltani, Francisco J. Villegas-Mercado, Achintya Haldar *

Department of Civil Engineering and Engineering Mechanics, University of Arizona, P.O. Box 210072, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 17 March 2016
Revised 14 September 2016
Accepted 30 March 2017
Available online 7 April 2017

Keywords:
Performance-Based Seismic Design
Structural reliability
Seismic risk
Finite element method
Response surface method
Serviceability performance functions
First-Order Reliability Method
Monte Carlo simulation

ABSTRACT

A unified Performance-Based Seismic Design (PBSD) procedure is proposed and successfully implemented. It provides an alternative to the currently used life safety design requirement. To successfully develop the concept, structures are represented by finite elements and excited by the seismic loading in time domain. A novel reliability evaluation procedure is proposed for such representation. An improved response surface based procedure is proposed by combining it with the First-Order Reliability Method (FORM) and the appropriate response surfaces are constructed by combining the saturated design and the central composite design sampling schemes. Performances are defined in terms of Collapse Prevention (CP), Life Safety (LS), and Immediate Occupancy (IO), as commonly used in the profession. The corresponding risks are evaluated by exciting a 9-story steel frame designed by experts satisfying all post-Northridge seismic design requirements. It was excited by 20 earthquake time histories for each performance level and the corresponding probabilities of failure were estimated. It took around 300 deterministic evaluations. The accuracy of the method was established using 600,000 cycles of Monte Carlo simulations. The probabilities of failure estimated using the proposed algorithm are very similar to that of simulations indicating that it is accurate. The probability of failure for two serviceability limit states (overall and inter-story drifts) are very similar, indicating that the procedure will satisfy the basic intent of PBSD. They are also similar to the values used in developing the Load and Resistance Factor Design (LRFD) guidelines used in many current design codes. Designing a structure using multiple time histories, as suggested in recent design guidelines, is a step in the right direction. From the results and the observations made in this study, the authors believe that they proposed a robust, efficient, and accurate unified PBSD procedure and documented its implementation potential.

1. Introduction

Enormous amount of property damages caused by the Northridge Earthquake of 1994 prompted the profession to find an alternative to the currently used design criteria of life safety. Although the life safety was not severely compromised during the earthquake, the structural damage was enormous. Several beam-to-column connections in steel frames fractured in a brittle manner making the buildings unusable following the earthquake. Similar damages caused by previous earthquakes indicate rooms for improvements in the current prescriptive design guidelines based on the safety factor concept as used in the Allowable Stress Design (ASD) or in the Load and Resistance Factor Design (LRFD) provisions to protect life. To address the situation, under the sponsorship of the Federal Emergency Management Agency (FEMA), a major study by SAC [a joint venture of the Structural Engineers Association of California (SEAOC), Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREE)] was initiated in the late nineties. One of the main objectives of this study was to develop recommendations for more robust design and construction of steel structures and to propose alternative design criteria to avoid adverse economic consequences. The major findings were published in a series of reports (FEMA-350, 351, 352, 353, 355C, and 355F) [1–6].

One of the major outcomes of the SAC study was the introduction of a new design concept commonly known as the Performance-Based Seismic Design (PBSD), an alternative to the life safety design concept currently practiced. PBSD is essentially a more advanced risk-based design procedure currently used in Load and Resistance Factor Design (LRFD) [7]. The dynamic responses of a structure containing many uncertainty-filled load

* Corresponding author.
E-mail addresses: jrgaxiola@email.arizona.edu (J.R. Gaxiola-Camacho), azizsoltani@email.arizona.edu (H. Azizsoltani), fcovillegas@email.arizona.edu (F.J. Villegas-Mercado), haldar@email.arizona.edu (A. Haldar).

http://dx.doi.org/10.1016/j.engstruct.2017.03.076
0141-0296/

and resistance-related design parameters are also extremely difficult to predict. At present, the required time history of the seismic loading at a given site cannot be predicted with any confidence. The authors believe that numerous sources of uncertainty cannot be completely eliminated in any realistic seismic design and thus the absolute safety of a structure cannot be assured. The SAC study made similar conclusions and advocated that the associated risk needs to be managed appropriately. To achieve this intent, the risk of real structures to satisfy specific performance requirements need to be estimated by modeling them as appropriately as possible, applying loads the best way possible, and exciting them by seismic loading in time domain. As expected, the PBSD concept is certainly a little advanced.

To achieve the basic objectives, SAC proposed to correlate different performance levels with the corresponding risks and let the designers and/or owners decide the level of underlying risk they are willing to accept. FEMA 350 [1] defined a performance level as: "the intended post-earthquake condition of a building; a well-defined point on a scale measuring how much loss is caused by earthquake damage". To appropriately implement the PBSD concept, it is essential that the underlying risk or probability of failure of not satisfying a prescribed performance must be explicitly quantified. Obviously, just before failure, a structure is expected to develop several sources of nonlinearities. Thus, for the successful implementation of PBSD, it will be necessary to estimate the corresponding risk by applying the seismic loading in time domain in the presence of multiple sources of nonlinearity and uncertainty. Unfortunately, SAC did not recommend any specific procedure for the risk estimation and the authors believe that no such procedure is currently available.

PBSD involves a set of procedures by which a structural system is designed in a controlled manner. The concept can be implemented by following five sequential steps: (1) select performance objectives, (2) develop preliminary design, (3) assess performance capability, (4) check performance capability with allowable values, in terms of the associated risks, and (5) if risks are not acceptable, revise the initial design. The available literature on PBSD is very limited, FEMA 355F [6] suggested that PBSD guidelines can be developed by incorporating the following six items: (1) to account for uncertainty in performance associated with unanticipated events, (2) to set realistic expectations for performance, (3) to assess performance variables in similar buildings located nearby, (4) to develop a reliability framework, (5) to set representative performance levels for various seismic hazards, and (6) to quantify local and global structural behaviors leading to collapse. The authors believe that a new reliability analysis technique is required to incorporate the above items. And only then the appropriate PBSD guidelines can be developed and implemented.

Limited number of studies addressing different aspects of PBSD are reported in the literature [8–11]. However, the authors are not aware of any comprehensive study addressing all the above-mentioned 6 items. This study is expected to fill such knowledge gap. Even though the reliability approach presented in this paper is little advanced, if implemented properly, it will produce more economical and seismic-damage tolerant structures by identifying the most damage-prone structural elements and by satisfying all major failure modes or performance requirements satisfying similar pre-assigned risk levels. The authors believe that other similar studies will help to develop the appropriate design guidelines to be used by engineers in the near future.

2. Challenges in PBSD

Some of the important challenges in implementing the PBSD concept discussed above need further elaboration. The selection of performance levels and the appropriate mathematical models to represent such behavior could be very challenging. The structure is expected to develop various sources of nonlinearities following the load path to failure and the mathematical model to capture such behavior can be very demanding. To study such nonlinear behavior realistically, the structure is generally represented by Finite Elements (FEs). Considering accuracy and efficiency, representing real large complicated structural systems by FEs could be very complicated and challenging. To study the dynamic response behavior caused by the seismic loading, several methods with various degrees of sophistication are suggested in the current design guidelines [12,13]. They include pseudo-static, modal, and time domain application of the excitation. The most sophisticated analysis requires that a structure to be represented by nonlinear FEs and the dynamic seismic loading must be applied in time domain.

Since SAC did not recommend any specific risk evaluation procedure, the authors believe that the unavailability of such procedure is a major knowledge gap in realistically implementing the PBSD concept explicitly considering all major sources of nonlinearity and uncertainty. Risk is always estimated with respect to a limit state or performance function. When the Limit Performance Function (LPF) is explicit in nature, i.e., it can be expressed in terms of all Random Variables (RVs) present in the formulation and the performance requirements, the First-Order and/or Second-Order Reliability Methods (FORM/SORM) [14] can be used to extract the corresponding risk, since the derivatives of the LPF with respect to the RVs will be readily available. However, for the implementation of the PBSD concept in the presence of nonlinearity and the excitation in time domain, LPFs are expected to be implicit in nature. A considerable amount of expertize is required to extract reliability information using FORM/SORM for implicit LPFs, as reported by Haldar and Mahadevan [14]. As an alternative, the basic Monte Carlo Simulation (MCS) can also be used to estimate the reliability [15]. Unfortunately, the use of basic MCS for the reliability analysis of a real structure excited by the seismic loading applied in time domain can be impractical since one deterministic nonlinear FE-based analysis will require several hours of computing time.

Based on the above discussions, two major objectives of this paper are: (1) to propose a novel reliability analysis concept to estimate risk of a nonlinear structure represented by FEs and excited by the seismic loading applied in time domain, and (2) to showcase the implementation of PBSD to satisfy the intents of SAC.

3. A unified PBSD procedure

Some of the most basic requirements of PBSD are the deterministic evaluation of required performances as accurately as possible, the incorporation of major sources of nonlinearities in the deterministic formulation, and then estimate the risk satisfying the appropriate performance requirements. These requirements are discussed in the following sections.

3.1. Finite element representation of structures

In the most sophisticated deterministic response evaluations, structures are generally represented by FEs. In this representation, the major sources of nonlinearities can be incorporated as the structure passes through several phases before reaching the failure state. As mentioned earlier, the time domain nonlinear response analysis required to implement PBSD can be very challenging. To overcome this issue, the authors decided to use the assumed stress-based FE method in developing the deterministic FE code using concentrated plasticity model to capture material nonlinearity, specifically applicable for steel frame structures [16,17]. In this