Structures 5 (2016) 258–273

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Probabilistic Seismic Assessment of RC Bridges: Part I — Uncertainty Models

Ricardo Monteiro [a,b,*], Raimundo Delgado [b], Rui Pinho [c]

[a] Institute for Advanced Study (IUSS) of Pavia, Italy
[b] University of Porto, Department of Civil Engineering, Porto, Portugal
[c] University of Pavia, Department of Civil Engineering and Architecture, Pavia, Italy

ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 10 July 2015
Accepted 1 August 2015
Available online 11 August 2015

Keywords:
Seismic assessment
RC bridges
Failure probability
Latin Hypercube sampling
Uncertainty models

ABSTRACT

The seismic response of structures depends on a large number of aleatory and epistemic uncertainties surrounding the estimation of the structural demand and capacity, both usually featuring considerable dispersion levels, particularly when reinforced concrete structures are being assessed. When bridges are considered, the complexity level increases, given that most of those behave irregularly in the transverse direction. Several procedures may be used for the assessment of the seismic safety of bridges, namely the ones used to estimate the demand, investigated in a companion paper, ranging from linear or nonlinear static procedures to more accurate ones, based on nonlinear dynamic analysis. This work makes use of the latter, commonly seen as more accurate, to compute the failure probability of existing bridges using a relatively simple framework. Different variables typically considered in a seismic assessment procedure (geometry, material properties, earthquake records, intensity level) are statistically characterised, enabling a global simulation process, where each iteration step is associated to an independent structural nonlinear dynamic analysis. Failure probability is then obtained through the probabilistic analysis of a safety indicator, defined as the difference between capacity and demand. An alternative uncertainty model, given by the convolution between the capacity and demand distributions, obtained independently, is also applied. A case study of seven bridge configurations, with different (ir)regularity levels, is considered together with a relatively large set of real earthquake records. The simulation process is carried out using the Latin Hypercube sampling algorithm, expected to considerably reduce the number of realisations with no reliability loss. Conclusions have allowed the identification of vulnerable configurations and shown the importance of the variable detail level when considering different uncertainty models.

1. Introduction

A typical seismic safety assessment procedure involves a set of relevant components that need to be properly defined, until the seismic safety itself is assessed. Such ultimate step may, similarly to all the other components, feature different approaching scenarios. Those will essentially consist in the comparison of the demand, coming from a properly selected seismic ground motion input, with the capacity of the structural elements, given by the geometry, material properties, and nonlinear behaviour models, among others. The deterministic approaches are the ones that practitioners are most familiarised with, as it certainly goes along with the traditional design practice or structural safety verifications. However the research trend of the past decades has been mostly addressing the employment of probabilistic approaches, which tend to gain weight, as rationally more consistent. Still, the employment of probabilistic procedures for seismic assessment by practitioners is far from being straightforward, which opens the floor to the proposal of relatively simple methodologies that do not require deep mathematical formulations but still provide accurate results.

According to Pinto [46] the probabilistic safety assessment of structures is usually simulation based, FORM-based (First Order Reliability Methods) or response-surface based. Several different proposals for implementation are available in literature within each category but the subject of probabilistic seismic assessment is still under considerable development and improvement. Such state-of-the-art is due to the growing awareness of the international community of the need for including probabilistic measures in seismic assessment practice. However, the employment of probabilistic methods is still far from large dissemination among the professional engineering community. Their main practical application may be attributed to the calibration of deterministic approaches used in codes, based on the use of partial safety factors. The reason that is mostly pointed out is the mathematical complexity and computational onus, unlike the traditional design procedures, which offer clear-cut guidance, as stated by Pinto et al. [47].

A number of probabilistic methods are becoming more common and have been systematically applied by many researchers to the seismic assessment of bridges in the past decades [e.g. 10,11,14,30,36,37,42,

* Corresponding author at: IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy.

http://dx.doi.org/10.1016/j.istruc.2015.08.002

51–53]. Provided with a solid mathematical background, such methods are not always easily approachable by practitioners and thus not necessarily appealing to the community. Indeed, the popularity of probabilistic methods has been many times restricted to the use as complement to code-based design, assessment of existing structures or design of new ones, requiring special care (critical facilities). A possible alternative to the employment of refined probabilistic methods could be the consideration of relatively simplified approaches, yet theoretically sound, which could start making their way into current design carried out by practitioners. Even if simple, any probabilistic procedure requires a substantial amount of statistical information, in comparison with the deterministic ones, to characterise the uncertainty in the structural safety problem. Such information includes the probabilistic characterisation of seismic hazard as well as the capacity and structural demand. The implementation of less complex approaches, mathematically lighter, yet probabilistically sound, can play an important role in introducing higher accuracy in current engineering seismic assessment practice.

In light of the above, this paper presents two different methodologies for the seismic safety assessment of structures, applied to bridges, which foresee the computation of the failure probability. This is achieved through a relatively straightforward process, which can be used in current practice for seismic assessment purposes, without significant computational onus. In order to accomplish so, as well as to duly incorporate the uncertainty associated to all the considered variables of the safety problem, both capacity and demand are statistically characterised by means of assumed and/or adjusted distributions. Such statistical definition makes use, when necessary, of random samples obtained with the Latin Hypercube sampling (LHS) technique. On the one hand, the safety assessment of a single structural system can be carried out through a safety indicator statistically characterised by multiple aleatory deterministic differences between the capacity and the demand (global uncertainty). On the other hand, a failure probability obtained from the independent statistical characterisation of the variables that are part of the process (local uncertainty) could be considered. Therefore, the difference between the two proposed methodologies lies on the way of dealing with the uncertainty of the different variables, which yield distinct failure probabilities. The distinction is established between accounting for uncertainty locally or globally, which depends on the number of considered variables characterised statistically (higher for the latter) and on the approach for the convolution between capacity and demand. Both uncertainty modelling approaches are tested for a case study of seven bridge configurations, featuring different deck lengths and regularity levels. The same approaches, herein validated, are then tested in a companion paper addressing the relative accuracy of different nonlinear analyses (static and dynamic) to estimate the seismic demand.

2. Safety assessment

2.1. Failure probability

The failure probability of a structural element, considering a single failure mode, may be obtained according to Eq. (1), where X is a vector containing the basic random variable x, in which the structural safety is settled; $g(X)$ is the limit state function associated to the failure mode under consideration and $f_X(x)$ is the joint probability density function of the vector X, characterising the way the variables define the structural safety problem. This is, according to Ferry-Borges and Castanheta [17], a commonly employed procedure, corresponding to the simplest basic problem of structural safety.

$$p_f = \int_{g(X)\le 0} f_X(x)dx \tag{1}$$

The solution of Eq. (1) will involve multidimensional integration in agreement with the number of variables in vector X (e.g. the physical variables such as loading, material properties or geometrical data), which incorporate the uncertainty associated to the regarded failure mode. In a structural engineering context the safety problem will essentially depend on two continuous and independent assumed variables: R, standing for a measure of resistance (capacity) and S, the structural response (demand). In this case the limit state function is simply given by, in other words, the difference between the capacity and the demand as shown in Eq. (2).

$$g(X) = R - S \tag{2}$$

By taking the corresponding joint probability density function, $f_X(x)$ and assuming that R and S are independent variables, the failure probability will be given by Eq. (3), where $f_S(s)ds$ is the probability of S within the interval $[s, s + ds]$ and $F_R(s)$ is the cumulative distribution function of R i.e. the probability of R being less than the value of S corresponding to s.

$$\begin{aligned} p_f &= prob(R - S \le 0) = \iint_F f_{R,S}(r,s)dr\,ds \\ &= \int_{-\infty}^{+\infty} f_S(s)\cdot\int_{-\infty}^{S} f_R(r)dr\,ds = \int_{-\infty}^{+\infty} f_S(s)\cdot F_R(r)dr\,ds \end{aligned} \tag{3}$$

Furthermore, as R and S are independent, the probability of both occurring at the same time is given by the product of each of the probabilities of occurring separately, i.e. $f_S(s)\cdot F_R(s)ds$. The sum for all the values of S yields the convolution integral in Eq. (3) [21]. It is thus necessary to define the statistical distributions for the capacity (R) and demand (S). As far as capacity is concerned, F_R function in Eq. (3), numerical simulation is used to characterise ultimate ductility in curvature (μ) which is in turn expressed as a function of the material properties, concrete and steel, which assume their own statistical distributions. The distribution of μ is obtained using a simulation scheme, which can be pure Monte Carlo or improved Latin Hypercube. On the other hand, the estimate of the distribution of the demand (S) depends on a higher number of analysis steps and variables. The input ground motion is well known for its aleatory uncertainty hence several analyses need to be carried out for a sufficient number of intensity and nonlinearity levels to cover the record-to-record variability.

2.2. Seismic hazard — intensity level probability density function

The intensity level probability density function represents, at each intensity measure level (e.g. peak ground or spectral acceleration) the density of probability at each point in the sample space of that random variable. The probability of the variable falling within a specific set is given by the integral of its density over the set. To characterise an event such as the occurrence of an earthquake, highly unusual, it is common to use the extreme value theory, a branch of statistics dealing with the extreme deviations from the median of probability distributions. Within such theory, the generalised extreme value distribution has been defined, combining three types of distinct distribution families, also known as type I, II and III extreme value distributions. In the earthquake engineering context, if the seismic hazard would be defined by means of peak ground acceleration, a maxima-related extreme value distribution will be definitely suitable. On the other hand, if a resistance-side variable should be the goal, a minima extreme value distribution would, instead, be more suitable. The generalised extreme value distribution is a flexible three-parameter model that combines the aforementioned maximum extreme value distributions and types I, II and III are often referred to as the Gumbel, Fréchet and Weibull extreme value distribution families. Type I distribution, Gumbel related, has been early used in applications of extreme value theory to engineering problems and, as related to the maxima, is the one frequently chosen to characterise seismic hazard intensity. Its probability density function is given by Eq. (4), where $\mu \in \Re$ is the