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Efficient methodology for the probabilistic safety assessment of high-speed railway bridges

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ABSTRACT

The efficiency of different probabilistic methodologies for the safety assessment of short span railway bridges is compared in the current paper. Two different simulation methods, namely the Monte Carlo and the Latin Hypercube, are combined with two different procedures to enhance the efficiency of the assessment. One of the methods is a tail modelling approach based on the extreme value theory that uses the Generalized Pareto Distribution to model the tail of the obtained distribution. The other one is an Enhanced Simulation procedure which uses an approximation procedure based on the estimates of the failure probabilities at moderate levels for the prediction of the far tail failure probabilities by extrapolation. A composite bridge with six simply supported spans of 12 m and ballasted track is selected as case study for the crossing of the TGV-double high-speed train. The variability of parameters related to the bridge, the track and the train is taken into account along with the existence of track irregularities. The running safety of trains due to loss of contact between the wheel and the rail and the track instability due to excessive deck vibrations are the two safety criteria analyzed, providing examples of limit state functions with different degrees of complexity. The obtained results are extremely promising and indicate the feasibility of the application of this type of methodology in common practice due to the very reasonable computational costs that are required.

1. Introduction

Safety has always been one of the main engineering concerns, particularly for important structures such as bridges. Due to the generalized use of computers and their continuous evolution, the safety assessment techniques have become increasingly sophisticated and complex, allowing more realistic and accurate analysis. In recent years, the use of probabilistic methods to assess the safety of new and existing structures has become more frequent. Due to the degree of complexity of the safety assessment of railway bridges the use of such methods is not very common. However, some examples of application of probabilistic approaches can be found in [1–4].

Due to the complexity involved in the safety assessment of railway bridges the problems generally need to be addressed through simulation methods. The Monte Carlo method [5,6] is usually selected, but more refined methods like the Latin Hypercube [7] can also be applied. Regardless of the selected method, the objective is always to obtain an accurate assessment using an efficient methodology. The efficiency of a methodology represents its capacity to reduce computational costs without compromising accuracy. Besides accuracy, the quantification of the uncertainties in the predictions is also important.

Despite the potential of the simulation methods, it is observed that for several problems the use of such a technique by itself may be computationally prohibitive. For this reason several authors proposed complementary procedures in order to enhance the efficiency of such methods. Naess et al. [8] proposed an approach that estimates the probability of failure by extrapolating the tail probabilities based on the estimates of the failure probabilities at moderate levels. Ramu et al. [9], on the other hand, proposed the estimation of the probability of failure by modelling the tails of the obtained distributions.

In the present study the safety assessment of a short span composite high-speed railway bridge is performed. In previous research works the safety due to track instability caused by excessive deck vibrations [10] and the running safety of trains [11] on this type of bridge have already been studied using probabilistic approaches. The current paper is focused on the analysis of the efficiency of different probabilistic methodologies in the safety assessment of short span railway bridges. Besides the standard Monte

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Carlo simulation, that has been used in previous works, in this paper a more refined simulation technique, namely the Latin Hypercube sampling method, is also applied. Furthermore, both simulation methods are combined with two different approaches to enhance efficiency. One is based on the extreme value theory and used the Generalized Pareto Distribution to model the tail of the distribution. The other uses an approximation procedure based on the estimates of the failure probabilities at moderate levels to estimate the target probability of failure by extrapolation.

Two different failure modes are assessed: the running safety of trains due to loss of contact between the wheel and the rail and track instability due to excessive deck vibrations. This provides examples of limit state functions with different degree of complexity and enables the understanding of how this complexity affects the efficiency of the assessment. In the end, the results are compared in order to identify the most efficient approach.

2. Structural reliability analysis

The use of analytical techniques for the reliability analysis of complex structural systems, which are often characterized by non-linear limit-state functions, can be extremely difficult. In this section, several alternatives to assess this problem are presented and discussed. The different investigated techniques are used in the safety assessment of a short span high-speed railway bridge presented in Section 3. The obtained results are compared in order to identify the most efficient approach.

2.1. Monte Carlo method (MC)

Simulation techniques have emerged as an interesting alternative to analytical approaches as they are much simpler to use and almost unaffected by the complexity of the studied problem and the number of basic random variables [5]. The Monte Carlo method is the basis of most simulation methods and is generally selected for the analysis of complex systems. In this method values are generated for the random variables, $X^{(i)} = (X_1^{(i)}, X_2^{(i)}, \ldots, X_n^{(i)})$, according to their distribution. Some application examples of this methodology to the safety assessment of railway bridges can be found in [2,4,12]. Usually, the safety is assessed by a simple process that consists on counting the number of cases where the safety limit is exceeded over the total number of simulations. However, since the entire sample space, S, must be adequately represented and particularly due to the rather small probabilities that are typically used in structural safety engineering problems [13], the computational costs of this method can, in some cases, be prohibitive.

2.2. Latin Hypercube method (LH)

As an alternative to the Monte Carlo approach, the use of variance reduction techniques enables refining the sampling process and increase the efficiency of the simulation. An example of such techniques is the Latin Hypercube sampling, which is a stratified sampling method [7]. In this method the range of each variable X_n is divided into N strata of equal marginal probability, ensuring that each variable X_n has all portions of its distribution represented by input values, sampling once from each stratum. Stein [14] shows that this method is superior to standard MC with respect to precision of estimators provided that the response is a monotonic function of the statistic variables. The sampling process allows several possible configurations of the sample space. Therefore, the proper selection of samples representing the stratified sampled space is decisive for the efficiency of the method. In the present paper the Matlab Latin Hypercube sampling routine [15], which has implemented a function that attempts to optimize the sample with respect to an optimum euclidean distance between design points, is used.

2.3. Tail modelling – Generalized Pareto Distribution (GPD)

Since structural reliability problems are determined by the tail of the obtained statistical distributions, the computational cost can be significantly reduced if an extrapolation of the Cumulative Distribution Function (CDF) is made using tail modelling techniques [9]. The classical tail modelling is based on the extreme value theory and consists on approximating the tail portion of the CDF above a certain threshold, u, by the Generalized Pareto Distribution [16]. The approximation function, $F_{\xi,\psi}(z)$, can be written as [9]:

$$F_{\xi,\psi}(z) = \begin{cases} 1 - \left(1 + \frac{\xi}{\psi} \cdot z\right)^{-\frac{1}{\xi}} & \text{if } \xi \neq 0 \\ 1 - \exp\left(-\frac{z}{\psi}\right) & \text{if } \xi = 0 \end{cases} \quad (1)$$

where z is the exceedance, ξ and ψ are the shape and scale parameters, respectively. This method has been applied in previous research works [10] and proved its efficiency in the analysis of complex multi-modal response problems. However, the tail needs to be modelled accurately, as small variations in the tail of the distribution can result in a variation by an order of magnitude of the safety level. Furthermore, the method relies significantly in the most extreme values, which are the ones that present the largest uncertainty. For this reason the estimated probability of failure may require, in some cases, a larger number of simulations until it stabilizes. Two different limits for the variation of the estimated reliability index were used in this paper to validate the accuracy of the estimated probability of failure: a 0.5% limit (previously used in [10]) and a 1% limit. The comparison allowed seeing that there are no substantial differences between the two limits, apart from the expected, although slight, reduction of the number of simulations required to achieve stability with the larger limit. Since the accuracy of the estimation was not compromised, the results presented in the following sections correspond to the values obtained using the 1% variation limit.

2.4. Enhanced Simulation method (ES)

Naess et al. [8] proposed an Enhanced Simulation method which is able to overcome some limitations of high computational cost due to large samples needed for a robust estimation as in the previously presented method. It exploits the regularity of the tail probabilities to set up an approximation procedure based on the estimates of the failure probabilities at more moderate levels for the prediction of the far tail failure probabilities. The safety margin, M, represents the difference between the capacity and the demand to define the probability of failure as $p_f = \text{Prob}(M \leqslant 0)$ and is extended to a parameterized class of safety margins in the following way:

$$M(\lambda) = M - \mu_M \cdot (1 - \lambda) \quad (2)$$

where μ_M is the mean value of the safety margin M and λ is the scaling parameter that assumes values in the interval $0 \leqslant \lambda \leqslant 1$, putting the emphasis on the more reliable data points. Thus, the original system is obtained for $\lambda = 1$ while $\lambda = 0$ represents a system highly disposed to failure.

For a sample of size N an empirically estimated probability of failure is given by:

$$\hat{p}_f(\lambda) = \frac{N_f(\lambda)}{N} \quad (3)$$