Chapter 6
Seismic Reliability Analysis in the Framework of Metamodelling Based Monte Carlo Simulation

ABSTRACT

A comparative study of various metamodelling approaches namely the least squares method (LSM), moving least squares method (MLSM) and artificial neural network (ANN) based response surface method (RSM) are presented to demonstrate the effectiveness to approximate the nonlinear dynamic response of structure required for efficient seismic reliability analysis (SRA) of structures. The seismic response approximation by the LSM, MLSM and ANN based RSMs are explained with a brief note on the important issue of ground motion bin generation. The procedure adopted herein for SRA is based on the dual response surface approach. In doing so, the repetition of seismic intensity for SRA at different intensity levels is avoided by including this as one of the predictors in the seismic response prediction model. A nonlinear SDOF system has been taken up to elucidate the effectiveness of various metamodels in SRA.

INTRODUCTION

Seismic Reliability Analysis (SRA) of structures is basically a structural reliability analysis problem in which the limit state of interest is the difference between seismic demand (D) and capacity (C) considering uncertainty due to earthquake motions, structural properties, physical damage, economic and human losses etc. The problem can be envisaged as a time dependent structural reliability analysis problem in which the limit state of interest can be expressed as,
Seismic Reliability Analysis in the Framework of Metamodelling Based Monte Carlo Simulation

\[ Z(X_C, X_D, t) = C(X_C, t) - D(X_D, t) \]  

(1)

where, \( X_C \) and \( X_D \) are the variables governing the capacity and demand and \( t \) is the time parameter. The computation of probability that the limit state function is negative means to evaluate the seismic risk of the structure i.e.

\[ Z < 0 \rightarrow Failed, Z = 0 \rightarrow Limiting and Z > 0 \rightarrow Safe \]  

(2)

Thus, the seismic risk analysis is the evolution of the following multi-dimensional integral to obtain the probability of failure \( (P_f) \),

\[ P_f = \int_{Z < 0} f_Z(X) dZ \]  

(3)

where \( X \) is an ‘n’ dimensional vector having variables involving \( X_C \) and \( X_D \), \( f_Z(X) \) is the joint probability density function (pdf) of the involved random variables. The exact computation of the above is often computationally demanding. In fact, the joint pdf of \( f_Z(X) \) is hardly available in closed form. Various approximations are usually adopted to obtain the probability of exceeding a response parameter for different limit states of damage.

The more accurate and conceptually straightforward but computationally demanding methodology for SRA is based on Monte Carlo Simulation (MCS) technique. The robustness and better accuracy of MCS based SRA is well known (e.g. Dymiotis et al. 1999; Kwon & Elnashai, 2006; Kazantzi, Righiniotis & Chryssanthopoulos, 2008). The SRA by non-linear performance based analysis using random field theory in the framework of statistical simulation is notable (Au & Beck, 2003; Kwon & Elnashai, 2006). The approach is always preferable as it does not require an assumption about the shape of the failure surface. However, such full simulation approach needs a large number of replications to obtain acceptable confidence in probabilities of failures of structures, which are typically very small in magnitude. For each replication in the simulation process, the computation of maximum response requires to perform complete nonlinear time history analysis (NLTHA) which is computationally demanding for large complex structural models. Various metamodelling techniques are found to be useful in this regard to replace the complex model. In fact, response surface method (RSM) based MCS simulation using various sampling technique for reliability analysis of structures is studied extensively (Faraveli, 1989; Bucher, & Bourgund, 1990; Rajashekar& Ellingwood; 1993; Bucher and Most, 2008). This approach is found to be useful to replace a complex mechanical model of the actual structure for seismic response analysis involving large computational need (Iervolino, Fabbrocino & Manferedi, 2004; Towashiraporn, 2004; Park & Towashiraporn, 2014). A comparative study of various RSMs for SRA of structures involving NLTHA is performed by Möller et al. (2009). Simulation based SRA using Latin hypercube sampling technique for generation of RSM is also notable (Unnikrishnan et al., 2013). Generally, the RSM is based on the global approximation of scatter position data, usually through a second order polynomial function obtained by using the least squares method (LSM) of regression. The efficiency of the approach largely depends on the selection of the basic functions and should be chosen to resemble the basis function as closely as possible to the actual variation of the response within the domain. Such a selection is not