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Computationally efficient framework for probabilistic collapse analysis of structures under extreme actions

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ABSTRACT

Currently there is a growing need for a versatile framework consisting of analytical and surrogate models to ensure both accuracy and computational efficiency of collapse analysis under extreme actions. However training metamodels for highly nonlinear structural responses requires large number of samples to achieve enough accuracy. In this research a method is developed to achieve computational efficiency by implementing the adaptively shifted integration-Gauss technique in conjunction with a core neural network metamodel. The analytical model is validated by experimental data and its accuracy is further evaluated by detailed finite-element analysis. The applicability and efficiency of the provided tool for highly nonlinear analyses are investigated using collapse assessment of a steel framed structure subjected to code-stipulated vehicle impact loads. Thorough probabilistic analyses are carried out including reliability assessment, fragility analysis, and two different sensitivity tests. The analysis results show the superiority and precision of this framework compared to detailed finite-element analysis.

1. Introduction

Undoubtedly there is a growing trend towards probabilistic collapse assessment of structures in recent years [1–3]. Evaluating a structure under such condition needs intensive finite-element (FE) analyses to find collapse probability. The problem becomes worse for fragility and global sensitivity analysis. To overcome this problem, various techniques and soft computing methods have been used such as artificial neural networks (ANN), response surface methods, Kriging, etc. The comparison of these methods for application in seismic fragility analysis has been done recently by Wang et al. [4]. ANN metamodels are universal estimators and their accuracy does not depend on the dimension of the input space compared to polynomial response surface methods [5]. In the latter case, the accuracy is highly dependent on the number of input parameters. Furthermore, response surface methods are based on a specified function in advance while activation functions in ANN metamodels can be adjusted by some coefficients based on inputs and outputs in order to minimize the error. Thus response surfaces might not be able to capture highly nonlinear responses [4]. It has been also shown that nonlinear regression using ANNs has sometimes superiority over Kriging [4]. Based on the aforementioned advantages, ANN has gained a prominent position among optimization techniques [6–8]. However preparing samples for training ANNs using FE analysis is very costly in terms of computational time, and highly nonlinear problems generally require thousands of samples to achieve adequate approximation using ANN metamodels. On the other hand, simulating the collapse behavior of a structure under one specific scenario needs a detailed analytical model to capture inherent nonlinear and non-monotonic structural responses which in turn is quite time-consuming [9]. In addition to applications to plane frames, trusses, or simple structures [7,8,10,11], neurocomputing has been successfully applied to analysis of large scale structures [12,13]. However collapse simulation under extreme actions is still a matter of debate, especially when a probabilistic analysis is involved. Analyzing structures under such condition may directly result in numerical instability or need time consuming numerical methods for convergence.

In order to partly deal with this problem, the alternate path method (APM) recommended in the design guidelines [14,15] has been employed in many studies to investigate the collapse behavior of different structures [2,16–20]. The prevalent assumption in these studies is based on the speculation that the sudden column removal approach gives conservative results; however this assumption does not hold for every case. For instance, Kang and Kim [21] investigated collapse behavior of moment frames subjected to vehicle collision. The study showed that as a result of large lateral loads during collision, the maximum vertical displacement of the beam-column joint above the impact location is

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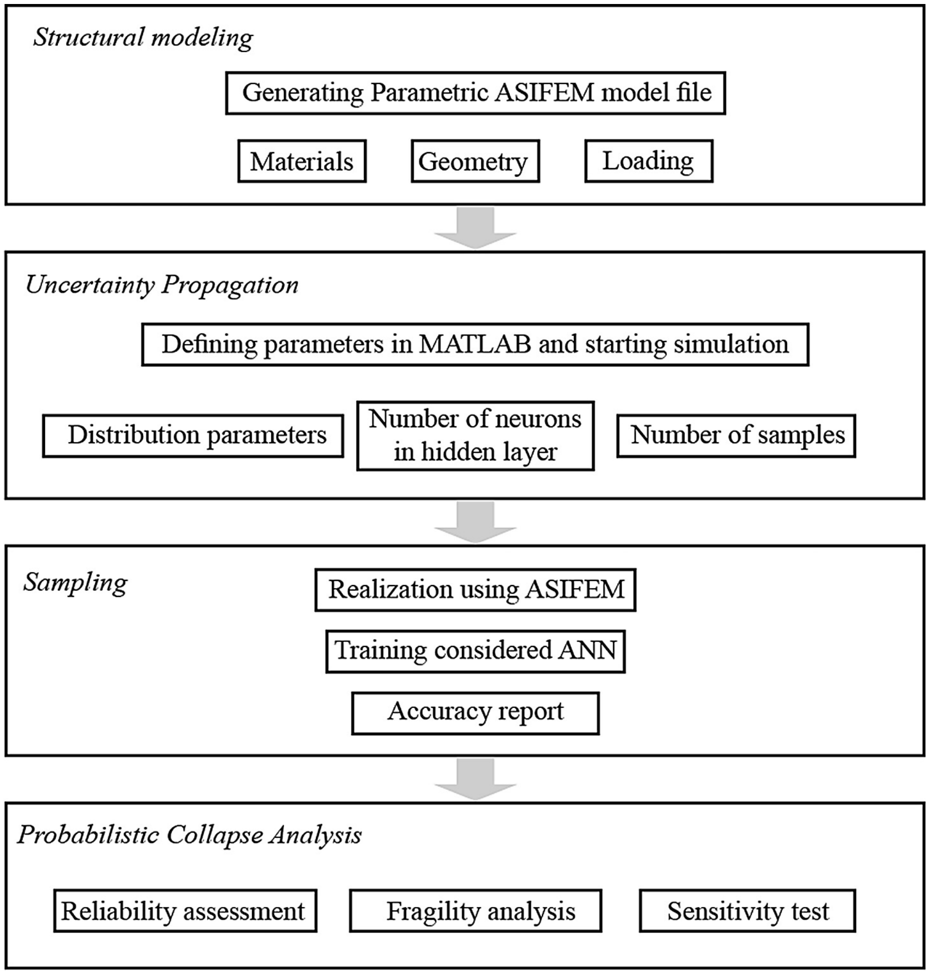

Fig. 1. Representation of the developed framework.

much larger than displacements obtained from APM. Fu also [22] reported that using APM in the collapse assessment of building structures fails to consider large shear actions on column members.

Therefore, a versatile framework including both analytical and surrogate models is required to provide enough accuracy and computational efficiency for collapse assessment under extreme actions. The overall scheme of the framework developed in this study is shown in Fig. 1. A reliable modeling approach called the adaptively shifted integration (ASI)-Gauss technique is utilized to fulfill the requirements for a precise collapse simulation of framed structures under any loading condition. The analytical model is first validated using experimental data, and then the structural modeling procedure is embedded in *MATLAB* programming [23] to generate the analysis model parametrically. A core ANN metamodel is implemented in the code which is trained by the samples from the parametric model structure. Accordingly uncertainty propagation, assigning ANN parameters, and defining the number of samples for training procedure can be done in the developed framework. The number of samples and ANN parameters can be changed based on the accuracy report to get the adequate approximation. At the next stage, samples from the analysis model are implemented with a proper neural network architecture to conduct further probabilistic analyses at a low computational cost. To show the applicability of the presented method for probabilistic collapse analysis under large deformations, a steel structure subjected to code-stipulated vehicle impact loads is investigated when uncertainties in loading, geometry, and material properties are present.

Most studies about collapse analysis of structures under vehicle impact have assessed the impact behavior of column members, though the post-collision behavior of the structure at hand is of great interest. For instance, El-Tawil et al. [24] evaluated the behavior of bridge piers under vehicle collision and found that current standard provisions in this field are non-conservative. Sharma et al. [25,26] assessed shear capacity of reinforced concrete columns probabilistically and developed methods for estimating the fragility curves under vehicle collision. Kang and Kim [27] studied effects of different footing connection details on impact behavior of a steel column. Here, a whole structure is investigated using reliability and fragility analysis under vehicle impact loads on a corner column according to the European code [28]. The accuracy of the model structure is further evaluated by comparing its collapse behavior with a detailed FE model. To find the most influential uncertain variables, the tornado diagram analysis (TDA) is carried out and the results are compared with a variance-based global sensitivity test. By taking advantage of the presented framework Monte Carlo simulations (MCSs) are carried out efficiently.

The present research may provide a framework for different types of probabilistic and reliability-based collapse analysis under extreme loads, which is of great interest in practice. Furthermore, the comparison of different sensitivity tests will show the tradeoff between efficiency and accuracy which is helpful for researchers.

2. Computationally efficient analytical model

2.1. ASI-Gauss technique

To get the response of the structure under extreme loads, the *ASIFEM* code [29] is employed which takes advantage of the ASI-Gauss