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SOFTWARE FOR UNCERTAINTY PROPAGATION AND RELIABILITY ASSESSMENT OF INELASTIC WIND EXCITED SYSTEMS

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Abstract

This paper presents a software tool for carrying out reliability assessment of inelastic wind excited systems through direct stochastic simulation. The tool address the need for practical approaches that enable efficient evaluation of the safety of such systems in order to apply probabilistic performance-based design in wind engineering. In particular, the software application is based on a recently proposed reliability assessment framework that integrates efficient inelastic response estimation approaches with a novel stochastic simulation scheme to propagate a full range of code compliant uncertainties through inelastic systems. The eight tabs of the graphical user interface of the software are designed to offer a user-friendly environment to specify all relevant data in order to define and solve reliability analysis problems that are at the core of modern performance-based wind engineering. The potential and applicability of the software are illustrated on a 3-dimensional archetype building.

Keywords: Software, Uncertainty Quantification, Reliability Assessment, Stochastic Wind Loads, Dynamic Systems.

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1 INTRODUCTION

With the introduction of performance-based wind engineering, the potential of designing wind excited systems with controlled inelasticity has attracted growing interest and created a need for tools to efficiently evaluate the safety of such systems while considering a full range of uncertainties. To this end, an efficient framework that enables rapid uncertainty propagation has been developed for assessing the reliability of systems experiencing inelasticity [1]. In particular, in estimating inelastic responses for each sample of the stochastic simulation, strain-driven dynamic shakedown approaches have been developed to not only rapidly identify structural safety against common wind related failure mechanisms, e.g., low cycle fatigue and ratcheting, but also efficiently evaluate the plastic strains and deformations occurring at shakedown while considering both concentrated and distributed plasticity [2],[3]. To further provide information on the inelastic responses beyond shakedown as well as any nonlinear response time history of interest, an alternative adaptive fast nonlinear analysis (AFNA) approach that efficiently integrates the responses over the actual wind load history has been proposed for direct integration with the reliability assessment framework [4].

In order to help bridge the gap between state-of-the-art research and current practice in wind design, this paper presents a comprehensive software tool that enables the full transition from proof-of-concept to practice of reliability estimation through direct uncertainty propagation. The graphical user interface (GUI) of the tool consists in eight tabs that are designed for automatically carrying out all stages of the analysis, including defining the finite element model and model uncertainties, calibrating the stochastic wind load model, executing the reliability analysis by propagating uncertainty through the system by stochastic simulation, and finally providing options to display or save simulation results. An application to a full scale archetype building is presented to illustrate the practicality and efficiency of the software in propagating a full range of code compliant uncertainties for reliability assessment of wind excited structures.

2 SOFTWARE FOR UNCERTAINTY PROPAGATION AND RELIABILITY ASSESSMENT

2.1 Efficient Reliability Assessment Framework for Inelastic Wind Excited Systems

The reliability of a structure can be directly measured in terms of the failure probability against a limit state of interest. In particular, the failure limit state can be expressed as $g(\mathbf{Y}) = 0$. By convention, failure is defined as $g(\mathbf{Y}) < 0$. The associated failure probability can then be evaluated as:

$$P_f = P(g(\mathbf{Y}) < 0) = \int \cdots \int I[g(\mathbf{Y})] f_{\mathbf{Y}}(\boldsymbol{y}) d\boldsymbol{y}, \quad I[g(\mathbf{Y})] = \begin{cases} 1, if\ g(\mathbf{Y}) < 0 \\ 0, if\ g(\mathbf{Y}) \geq 0 \end{cases} \quad (1)$$

where $\mathbf{Y}$ is a vector of random variables, including uncertainties in both structural system and external loads. In this work, all random variables in the analysis were carefully chosen so as to be compliant with those considered in the derivation of load factors stipulated in design codes [5]-[7]. In order to investigate the system level reliability of the structure and the possibility of designing buildings with controlled inelasticity, a reliability assessment framework considering not only traditional limit states, e.g., component yield, but also system-level inelastic limit states has been proposed based on the concept of dynamic shakedown [1]. In particular, reliabilities are estimated for the following four limit states (LS) of interest:

1. LS1: component-level yield limit state (traditional limit state used in current design);
2. LS2: system-level first yield limit state;

3. LS3: system-level inelastic limit state (defined as the failure to achieve the state of dynamic shakedown);
4. LS4: inelastic displacement-based limit states.

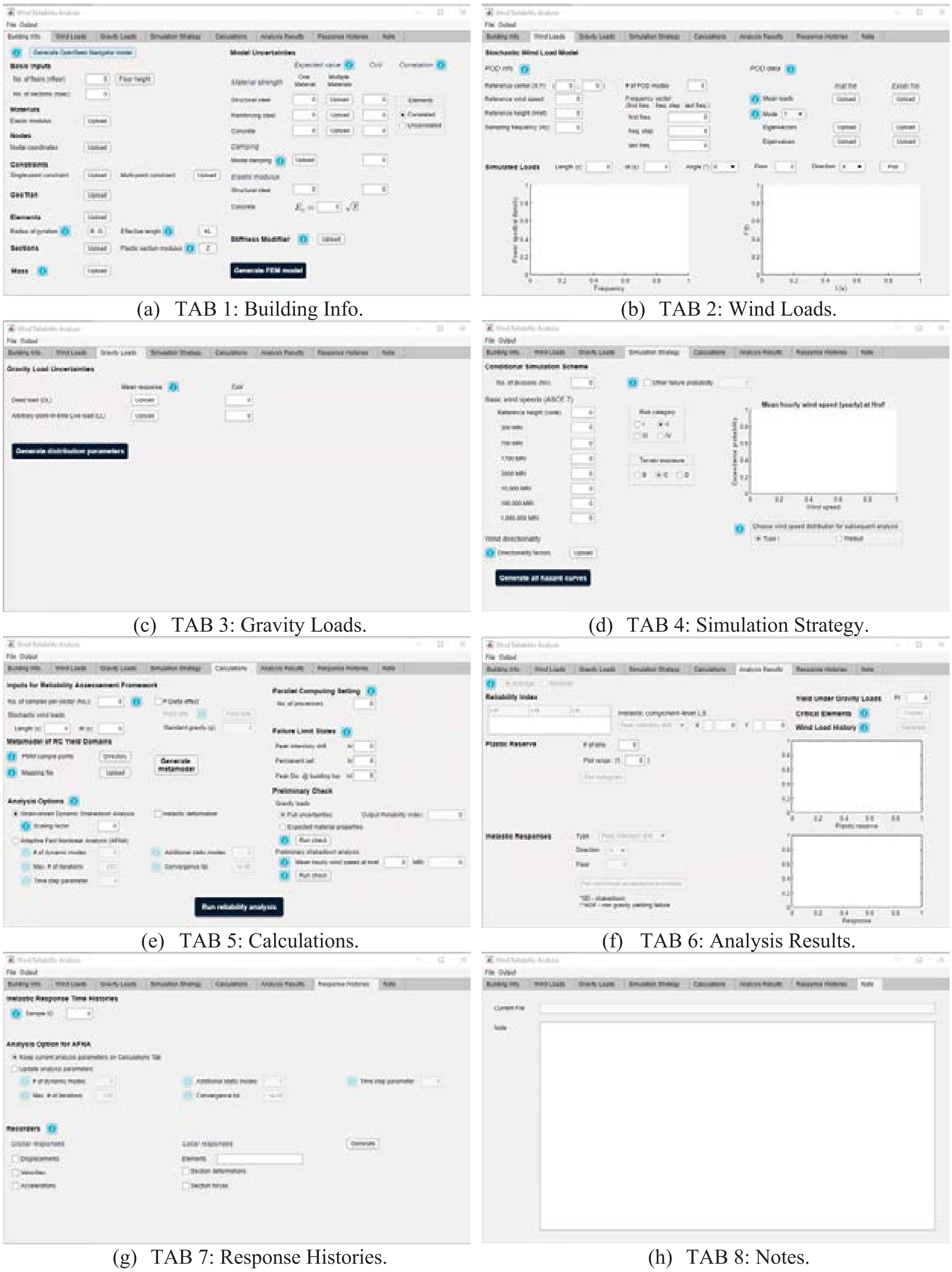
To evaluate failure probabilities associated with inelastic limit states while considering a full range of uncertainty, various efficient approaches have been developed to rapidly estimate inelastic responses of wind excited systems [2]-[4], enabling direct propagation of uncertainties through the system. The failure probability can then be solved through the integral of Eq. (1) for each limit state using simulation-based methods. In particular, an efficient stochastic simulation scheme based on conditional simulation [8] was developed to address the computational challenges associated with direct Monte Carlo simulation, especially when the reliability index of interest is associated with small failure probabilities, i.e., is in the tail of the distribution, which usually requires very large sample sizes if reasonable accuracy is to be achieved. This conditional simulation scheme is based on partitioning the wind hazard curve into a set of mutually exclusive and collectively exhaustive events, thereby enabling unbiased and high fidelity estimation of small failure probabilities (e.g., 10^{-6}) from small sample sets through the total probability theorem. To further account for extreme wind events from each wind direction, a sector-by-sector based approach, where the failure probability is defined from the most critical sector, was developed within the aforementioned conditional stochastic simulation scheme. Finally, the failure probability can be further transformed into a commonly used reliability measure in terms of the "reliability index", β, for each limit state of interest based on the assumption of the first-order reliability method, i.e., $\beta = \Phi^{-1}(1 - P_f)$.

2.2 Software Description

The software is equipped with a GUI where the user can, after introducing all relevant input information, estimate the reliability of wind excited systems against various elastic and inelastic limit states at both component and system levels, as defined in Section 2.1, through stochastic simulation while considering a full range of uncertainties. To carry out the pre- and post-processing for the reliability assessment, the GUI is made up of eight tabs, as shown in Figure 1, where the user can load the model, introduce the necessary information to set up the problem, perform a preliminary gravity check, run the reliability analysis, and visualize and export analysis results. The various input parameters for the problem, ranging from the finite element model, uncertainties, stochastic wind load model, simulation strategy, etc., to the analysis options are all input through the tabs. A detailed description of all menus and tabs are outlined an accompanying manual distributed with the software.

The first step to carrying out reliability analysis using the software is to define all necessary information for the building model. In particular, OpenSees (Open System for Earthquake Engineering Simulation) finite element models can be directly imported into the GUI through various *tcl* files for model generation on the *Building Info*. tab. Furthermore, to account for the uncertainties (record-to-record variability) in the wind loads, the stochastic wind load model is required. In this software, a wind tunnel informed proper orthogonal decomposition (POD) model is adopted for simulating stochastic wind loads. Hence, the user is required to introduce relevant POD data and information into the software on the *Wind Loads* tab. Statistical information for uncertainties associated with the structural system, gravity and wind loads must also be provided for running the reliability analysis.

Another key aspect of running reliability analysis through the software is that the user must set up the conditional simulation scheme [1], including the site specific wind hazard curve, for the analysis. Two wind hazard curves will be generated by fitting a Type I or Weibull distributions to a series of basic wind speeds corresponding to various mean recurrence intervals (MRI) as suggested in ASCE 7 [9] while considering the selected Risk and Terrain Exposure Category [9]. The user then has the option to choose their desired wind speed distribution for subsequent analysis based on the fitted curves displayed on the *Simulation Strategy* tab.



(a) TAB 1: Building Info.
(b) TAB 2: Wind Loads.
(c) TAB 3: Gravity Loads.
(d) TAB 4: Simulation Strategy.
(e) TAB 5: Calculations.
(f) TAB 6: Analysis Results.
(g) TAB 7: Response Histories.
(h) TAB 8: Notes.

Figure 1: Layouts for all tabs of the software.

Once the problem has been set up, two preliminary checks, namely the gravity check and preliminary shakedown analysis, can be carried out on the *Calculations* tab. Output files summarizing sample information and demand to capacity ratios for all elements will be generated automatically to assist the user in designing or modifying section sizes of the building in order to achieve a target performance.

After the preliminary check, pressing Run reliability analysis button on the *Calculations* tab starts the simulation and a wait bar is created (as a separated window) to update current progress as the analysis moves through each sample. Once the computation is finished, the analysis results are saved automatically and can be displayed on the *Analysis Results* tab. Reliability indexes, critical elements, histogram for plastic reserves and probabilistic distributions for any inelastic response of interest can be plotted selecting the corresponding button on this tab. All outputs on this tab can also be exported from the main menu in *csv* or *xlsx* format. Finally, response time histories can be generated on the *Response Histories* tab for any selected sample of interest using the AFNA approach for further review.

3 CASE STUDY

An example building will be presented in this section to demonstrate the potential of the presented software. All input and files necessary for running the reliability analysis are distributed with the software and described in detail in the user's manual.

3.1 Description

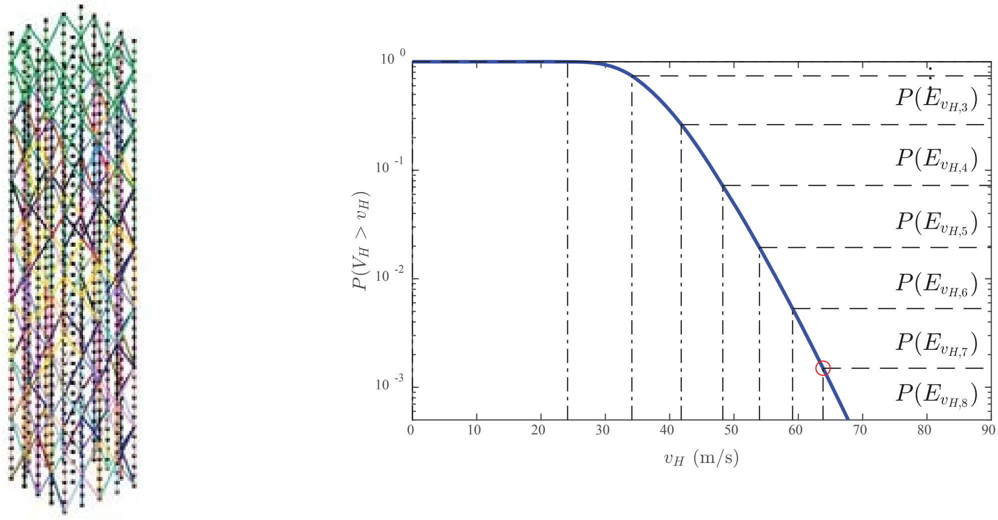
A 45-story archetype building, as shown in Fig. 2(a), is presented to demonstrate the potential of the presented software. The layout consists of 45 levels of office space, floor system composed of 63.5 mm (2.5 in.) of light-weight concrete over 76.2 mm (3 in.) of composite deck supported by steel beams and columns. The columns and braces are wide angle W14 sections except for the corner columns at lower levels, which are square box sections. Each floor is considered to act as a rigid floor diaphragm for horizontal movements. The story height is 4 m for all levels. The overall height of the structure is 180 m. In estimating elastic responses, the first six modes are considered in the modal analysis with damping ratios of 2%. The steel composing the frame is assumed to be elastic perfectly plastic with nominal yield stress $F_y = 345$ MPa. The nominal Young's modulus E_s and shear modulus G_s are taken to be 200 GPa and 77 GPa respectively. Nominal floor loads including self load, superimposed dead load and live load are summarized in Table 1. Uncertainties in the structural system as well as in the gravity and wind loads are considered in the reliability analysis (Table 2).

Self Load	Superimposed Dead Load	Live Load
2.4	0.72	3.1

Table 1: Nominal floor loads of the 45-story archetype building (Units: kN/m^2).

	Nominal	Mean/Nominal	Coefficient of Variation	Distribution
F_y	345 (MPa)	1.1	0.06	Normal
E_s	200 (GPa)	1	0.04	Lognormal
ξ	2%	1	0.3	Lognormal
D	-	1.05	0.1	Normal
L_{apt}	-	0.24	0.6	Gamma

Table 2: Description of random variables considered for the 45-story archetype building.



(a) (b)

Figure 2: (a) 3D view of the 45-story archetype building and (b) site specific 50-year non-directional mean hourly wind speed at the reference height of the archetype building.

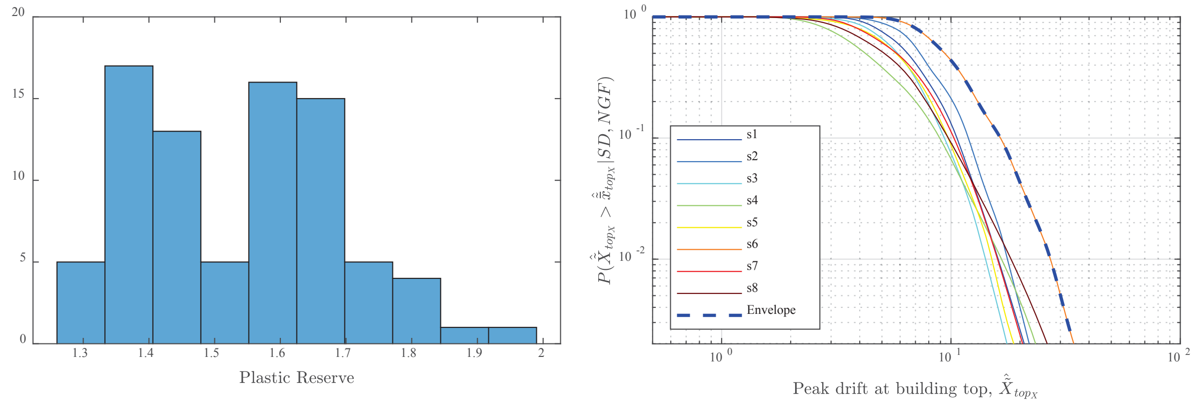
Wind tunnel driven stochastic wind loads of $T = 3600$ s were considered with random wind speeds generated from the site specific hazard curve, as shown in Figure 2(b). In modeling wind directionality, eight sectors, specifically NE, E, SE, S, SW, W, NW and N, were considered in the analysis. To further model the uncertainty in wind direction within each azimuthal sector in the stochastic simulation, the wind direction is assumed in the software to be uniformly distributed between the upper and lower bounds of each azimuthal sector.

3.2 Results

The reliability for the archetype building was determined for four failure limit states outlined in Section 2.1. In particular, peak interstory drift ratio of 1%, peak drift at the building top of 0.5% and permanent set of 0.1% were considered as deformation limits for LS4. The analysis was carried out for a total of 3200 samples, i.e., 400 samples for each wind direction sector. Figure 3 reports the reliability indexes for all limit states in a format that can be exported from the software. By comparing the reliabilities associated with all limit states, it can be observed that this structure is more susceptible to failure due to excessive inelastic deformations, peak displacements at the building top and peak interstory drifts, rather than the inability to shakedown. In addition, figures for plastic reserve of the system and probability distribution of any response parameter of interest can also be plotted on the *Analysis Results* tab, as shown in Figure 4 for the histogram of the plastic reserve of the system and the distribution associated with the peak displacements at the building top in the X-direction.

Limit State	Description		Reliability Index (Average)	Floor (Average)		Reliability Index (Sectorial)	Floor (Sectorial)
LS1	First component yield	=	3.38	-	=	2.84	-
LS2	First system yield	=	3.31	-	=	2.81	-
LS3	Non-shakedown	=	3.90	-	=	3.50	-
LS4	Peak interstory drift-X	=	4.14	43	=	3.63	43
	Peak interstory drift-Y	=	3.97	43	=	3.36	43
	Permanent set-X	=	3.97	11	=	3.52	12
	Permanent set-Y	=	4.23	19	=	3.76	21
	Peak displacement @ Top-X	=	3.46	-	=	2.94	-
	Peak displacement @ Top-Y	=	3.65	-	=	3.03	-

Figure 3: Reliability indexes for the 45-story archetype building exported from the software.



(a) (b)

Figure 4: (a) Histogram of plastic reserve and (b) probability of exceedance of the peak displacements at the building top in the X-direction for the 45-story archetype building.

4 CONCLUSIONS

This paper presented a software tool for carrying out reliability analysis of inelastic wind excited systems through direct stochastic simulation with the aim of enabling the full transition from proof-of-concept to practice of reliability estimation considering a full range of uncertainty. The tool is equipped with a GUI that consists in eight tabs that are designed for automatically carrying out all stages of the analysis including: importing the OpenSees finite element model; calibrating the stochastic wind load model; executing the reliability analysis based on efficient conditional stochastic simulation; and finally providing options to display/save the results from the analysis and rerun samples of interest to have a comprehensive understanding of the nonlinear response of the system. The potential of the presented software was demonstrated on a 45-story archetype building subject to stochastic wind loads.

5 ACKNOWLEDGEMENT

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