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Performance-Based Wind Design of Tall Buildings Considering the Nonlinearity in Building Response

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ABSTRACT:

Tall buildings exhibit complex structural responses under dynamic loads such as the actions of wind. In addition to the dependence on complex and dynamic nature of wind actions, the responses are influenced by numerous characteristics of the buildings itself such as its shape, height, and setback and tapering along the height etc. Difficulty in transferring the complex nature of wind and interaction it's with buildings led to the development of mathematical models and analysis techniques defining minimum design requirements to ensure safety of the occupants during specific design events. Progressive research and increased computational efficiency over the past couple of decades has produced more elegant solutions to the analysis and design of buildings such as Performance Based Design (PBD). PBD proposes that the structure be designed to meet specific performance objectives set forth by the stakeholders. PBD has become a mainstream approach to assess and reduce the risks in rehabilitation of existing structures. Application of PBD philosophy for design of tall buildings and other structures excited by wind loads has received much attention recently. The significant wind related economic losses incurred every year around the world has prompted the researchers to develop methods to reframe wind engineering to fully embrace the concepts of PBD. The main objective of Performance Based Wind Engineering (PBWE) is to assess the adequacy of a structure in terms of the decision variables (DVs) set forth by the stakeholders. Each DV is defined to satisfy specific performance levels such as operational, immediate occupancy, life safety, and collapse prevention. The performance levels are defined based on acceptable levels of strength and serviceability requirements of both structural and non-structural components. They also reflect the probable levels of damage, casualties, downtime, and costs of repair.

With the advancements in the computational capacity available, this study implements the proposed PBWE methodology by following the true nature of the PBD philosophy considering the nonlinearity in response of buildings and associated uncertainties in the wind loading. Furthermore, the study makes contributions to the field of PBWE by providing prediction of turbulent wind loads at each level of the building and also by developing the formulation to account for along- across- and torsional- wind loading along the height of the building. The aerodynamic load coefficients and aeroelastic load functions are obtained from wind tunnel experiments conducted on a scaled section model in the AABL Wind and Gust Tunnel at the Wind Simulation and Testing (WiST) laboratory at Iowa State University. The aerodynamic load (drag, lift and moment) coefficients and their derivatives with respect to angle of attack are obtained for three different mean angles of attack of wind (0°, 34° and 90°) using section model tests in a wind tunnel. The aerodynamic load coefficients and their derivatives are then used to calculate buffeting load time histories for the building based on Quasi-Steady formulation, corresponding to synthetically generated wind speed time histories that are based on empirical Power Spectral Density (PSD) functions (Kaimal Spectra).

The wind hazard for a specific site is defined in terms of maximum wind velocity experienced at the specified height of the building over the given averaging time (i.e. gust) while accommodating the factors accounting for terrain roughness and other topographic factors. For a given body immersed in wind flow, the wind velocity fluctuations are to be converted into time varying forces to be able to conduct nonlinear time history analysis in such a way that decision variable (*dv*) can be generated to ease communications with stakeholders and owners. Tall buildings are subjected to non-uniform time varying wind loads along their height which vibrates at random frequencies. The winds

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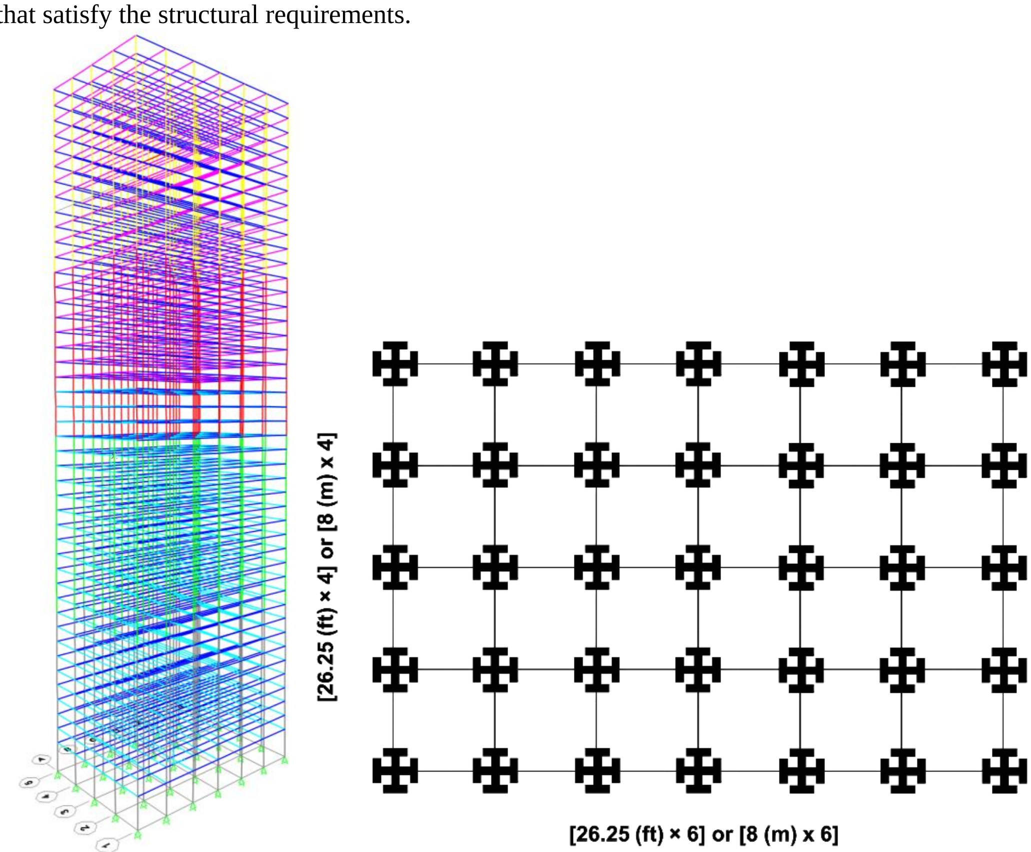
fluctuate about a mean wind speed corresponding to the height at which it acts. The wind models based on straight-line conditions cannot predict the structural response beyond the fundamental mode of vibration. The design wind speed specific to Miami-Dade County (130 mph) given by ASCE -07 was taken as the mean wind speed and a normal wind speed distribution was developed to identify the range of wind speeds in which the performance of building was to be analyzed. In this study, these parameters that are required for generating the wind-load time histories for various locations of the building along its height are extracted from wind tunnel experiments. For this purpose, the aerodynamic properties of the section model of example tall building that is subject to a two-dimensional smooth flow were extracted and applied to predict the wind loads on the tall building in time domain, where the variations of wind velocities (mean and fluctuating) in a typical atmospheric boundary-layer wind along its height were considered. A section model (1:400 scale) of the CAARC Standard tall building with a rectangular cross section was tested in the aerodynamic test section of the wind tunnel in uniform and smooth flow to obtain the static mean load coefficients. The wind acting on a tall building excites it under the action of a mean wind speed $U(z)$ at elevation z from the ground and time varying or turbulence components, $u(z,t)$ and $v(z,t)$ in the along- wind and across- wind directions about the mean wind speed, $U(z)$. The turbulent time histories are generated based on the algorithm proposed by Deodatis 1996.

A 44-story steel moment frame building under the wind load actions is designed for this study. The building is 528 ft. (161 m) tall and has a plan aspect ratio (B/D) of 1.5:1. The steel frames are composed of beams made from wide flanged I-sections and columns of cross rectangular sections built-up with wide flanged I sections. The steel beams in the frame have a span of 26.25 ft. (8 m) with 6 spans along the longer direction and 4 spans in the perpendicular direction. The 3-D and plan views of the model is shown in Figure 1. The building was designed under static loads based on the provisions of AISC 360 and ASCE 7-16 for a design wind speed of 130 mph (58 m/s) for Miami Dade County in Florida. The static analysis, and design was conducted in SAP2000 and frame sections were chosen that satisfy the structural requirements.



(a) (b)

Figure 1: 44-story steel frame building (a) 3D view of the SAP model and (b) Plan view with column sections along beam lines

To understand the structural response under long duration wind loads, the building was subjected to randomly varying

wind loads for a duration of 30 minutes. Different time history analyses were performed with wind speeds varying between 100 and 180 mph. The building responses recorded include acceleration and displacement time histories at every floor level. The member forces were recorded to identify the locations of plastic hinges and also to interpret any unusual variations in the recorded accelerations and displacements in the building. Multiple iterations of analyses for each set of wind speeds were used to develop fragility curves for different structural/non-structural components in the building. The fragility curves maybe used in the loss analysis of the structure. This study provides an effective method to understand the non-linear behaviour of tall buildings under high velocity long duration wind loads. The fragility curves also offer an attractive methodology to optimize the design of non-structural components of wind-sensitive high-rise buildings.

Keywords: Performance-based wind design, tall buildings, nonlinear response, performance objectives