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Inelastic response analysis of tall buildings to wind using reduced-order model with degradation effect

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SUMMARY

Performance-based wind design of tall buildings requires improved understanding of inelastic building performance. This study describes the development of a two-degree-of-freedom (2DOFs) hysteretic reduced-order building model via static modal pushover analysis of a nonlinear finite element (FE) model for evaluating inelastic response of wind-excited tall buildings. The accuracy of the reduced-order model is verified through comparison of predicted alongwind and crosswind responses with those from the FE model of a 60-story high-rise steel building. The inelastic building responses under uniaxial and biaxial wind loads at different wind speeds are characterized. A comprehensive parametric study concerning the influence of biaxial interaction on inelastic responses is performed. This study also investigates the influence of the degradation of stiffness and strength of steel material on the degradation of generalized building stiffness and strength in both alongwind and crosswind directions. A biaxial hysteretic restoring force model with degradation effect is used to examine the influence of degradation on inelastic building response.

Keywords: Inelastic building response, Reduced-order model, Biaxial and degradation effects

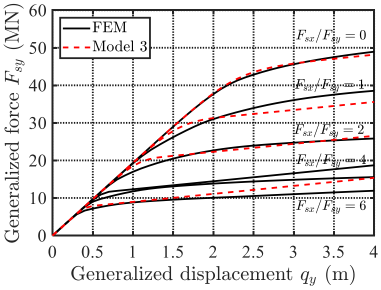
1. INTRODUCTION

Limited inelasticity is permitted in performance-based wind design (ASCE/SEI, 2019), which can potentially lead to safer and more economic building design solutions. Inelastic building design requires improved understanding of building performance beyond linear elastic limit. Inelastic response analysis of a wind-excited tall building using a finite element (FE) model can shed more insights on the building performance but is computationally expensive (e.g., Huang and Chen, 2022). This study describes the development of a reduced-order model established from static modal pushover analysis (MPA) of the FE model and verifies its accuracy and efficiency. Furthermore, this study examines the biaxial interaction of alongwind and crosswind responses through a comprehensive parametric study. This study also investigates the influence of strength and stiffness degradation of material on building inelastic response.

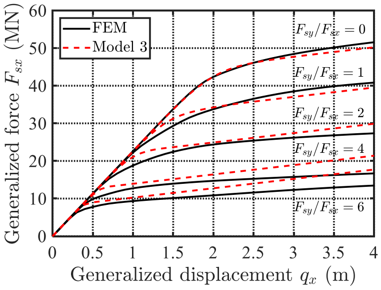
2. REDUCED-ORDER BUILDING MODELING

The inelastic building responses in both alongwind and crosswind directions are modeled in fundamental modal responses. A two degrees of freedom nonlinear reduced-order building model in terms of generalized modal displacements can be developed. The hysteretic relationships between the generalized restoring forces and displacements are quantified via static MPA procedure using the nonlinear FE building model. The modal inertial forces in two directions are applied to the building model simultaneously. The relations of the generalized forces and building top displacements are determined, which are further described by a biaxial hysteretic Bouc-Wen model. A 60-story high-rise steel building with 182.88 m height, 45.72 m width, and 30.48 m depth is considered. The fundamental frequencies in two directions are $f_x = 0.173$ Hz and $f_y = 0.164$ Hz. The heightwise alongwind static wind force was described as a power law. The alongwind and crosswind fluctuating story forces are simulated from the cross power spectral density model using spectral representation method. The alongwind and crosswind loads are mutually independent. Figure 1 shows the hysteretic relationships of the generalized restoring forces and displacements, which are further fitted into a biaxial hysteretic Bouc-Wen model (Huang and Chen, 2023a and 2023b).

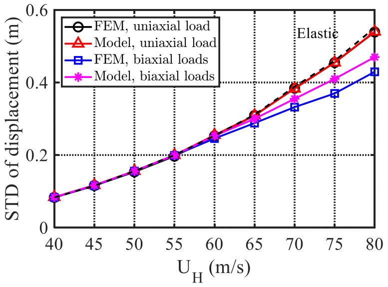
Figures 2 and 3 portray the standard deviations (STDs) of building top displacements and time-varying mean alongwind displacement under uniaxial and biaxial wind loads. The response STD, peak factor and kurtosis of the fluctuating response can be accurately estimated by the reduced-order model as compared to the FE model. The time-varying mean alongwind displacement is overestimated by the reduced-order model. Biaxial interaction leads to reduction of the response STD due to the additional hysteretic damping introduced from yielding. The time-varying mean displacement is increased under biaxial loads as more drift is introduced due to the reduction of the yield displacement, but its steady-state value is not affected, which is determined by the mean wind load and post-yielding stiffness. The biaxial effect is more significant when the yielding level of crosswind response is high and both responses are more distinct. The correlation of alongwind and crosswind fluctuating displacements only slightly affects the biaxial interaction. The biaxial effect results in more correlation between alongwind and crosswind responses.



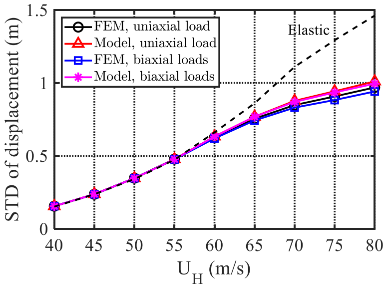
a) Alongwind (y)



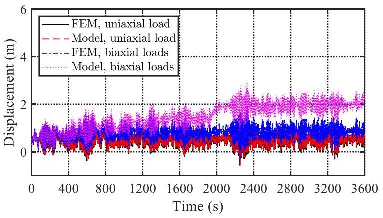
b) Crosswind (x)



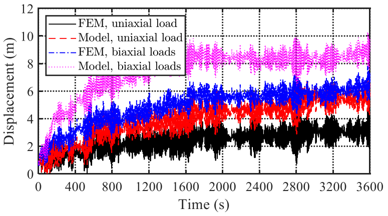
a) Alongwind displacement



b) Crosswind displacement



a) $U_H = 60$ m/s



b) $U_H = 80$ m/s

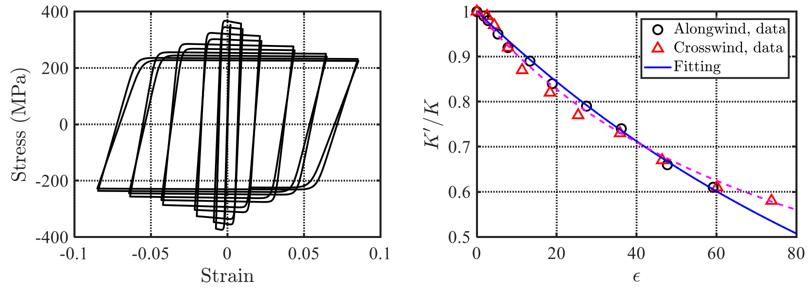
Figure 1. Generalized restoring force and deformation relations

Figure 2. STDs of alongwind and crosswind response

Figure 3. Comparison of alongwind building top displacement

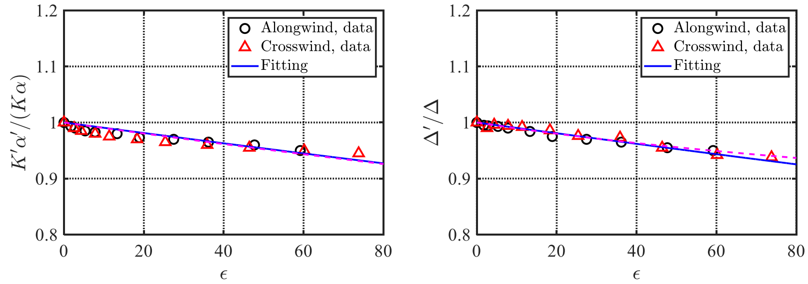
3. EFFECT OF DEGRADATION

The degradation of stiffness and strength of the steel material is considered, which leads to degradation of building initial stiffness, second stiffness and yield displacement in both directions as functions of the normalized accumulated hysteretic energy ϵ (Figure 4). A biaxial hysteretic restoring force model with consideration of degradation effect is introduced to fit the data determined from FE model. The effect of degradation on alongwind and crosswind response statistics are studied by using the reduced-order model. The accuracy of the reduced-order model was verified by comparing the results from FE model (Figure 5). The degradation leads to increase in inelastic alongwind and crosswind responses.



a) Stress-strain relation

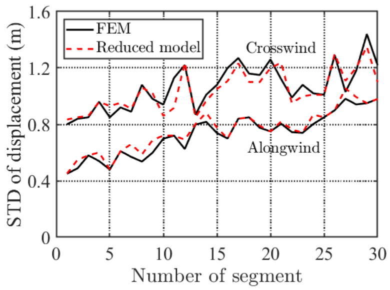
b) Normalized initial stiffness



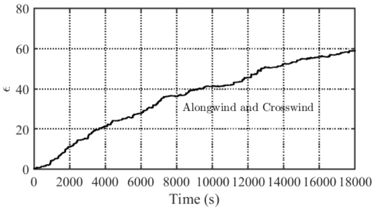
c) Normalized second stiffness

d) Normalized yield displacement

Figure 4. Effect of degradation on hysteretic force model parameters



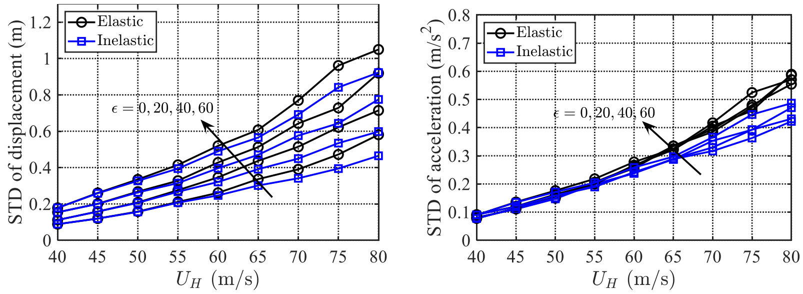
a) STDs of displacements



b) Normalized hysteretic energy

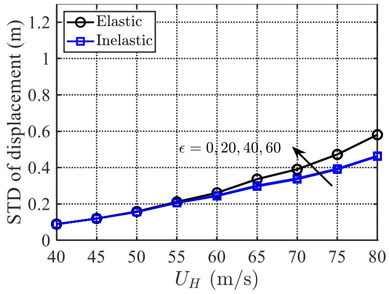
Figure 5. Displacements affected by degradation (Biaxial loads, U_H=80/s)

Figure 6 shows the STDs of alongwind and crosswind building top displacements and accelerations affected by degradation under different levels of accumulated hysteretic energy ϵ, i.e., ϵ=0, 20, 40 and 60. Figure 7 displays the results affected by strength degradation only. The degradation of both stiffness and strength results in increase in response STD. The influence on displacement is greater than that on acceleration. For this building example, the degradation effect is primarily due to degradation of initial stiffness. The degradation in second stiffness leads to increase in steady-state mean alongwind displacement (Figure 8).

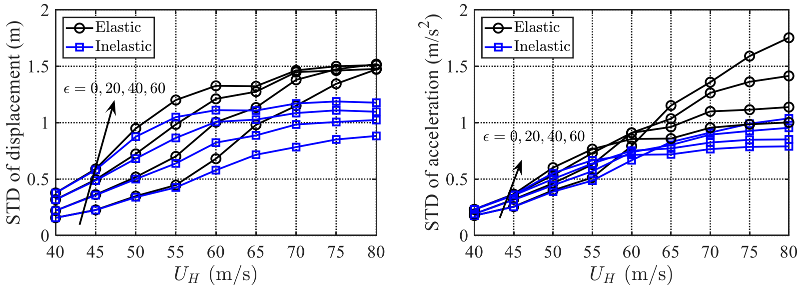


a) STD of alongwind displacement

b) STD of alongwind accleration

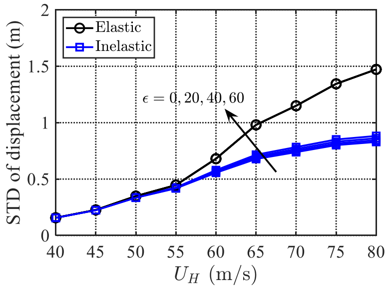


a) STD of alongwind displacement



c) STD of crosswind displacement

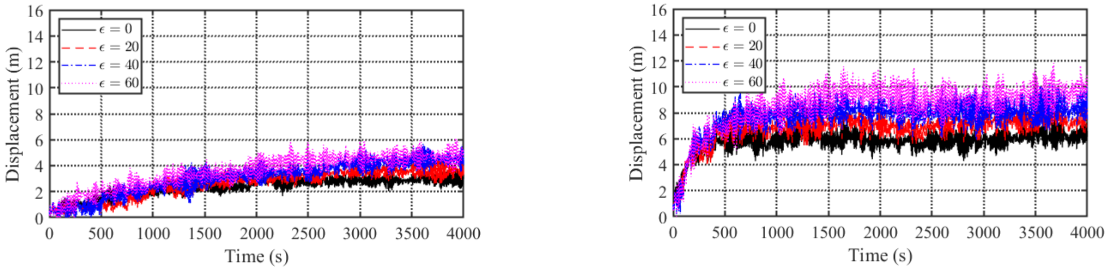
d) STD of crosswind accleration



b) STD of crosswind displaceent

Figure 6. Response STDs affected by degradation of both stiffness and strength under different wind speeds

Figure 7. Displacement STDs affected by strength degration only



a) $U_H = 60$ m/s

b) $U_H = 80$ m/s

Figure 8. Alongwind building top displacement affected by degdradation

4. CONCLUSIONS

The reduced-order modeling approach is very accurate and effective in estimating inelastic tall building response as compared to the FE model. The biaxial interaction results in an increase in the low-frequency component but decrease in the resonant component of alongwind fluctuating displacement. The biaxial effect is more significant when the yielding level of crosswind response is high and both responses are more distinct. The effect of degradation of strength and stiffness on the generalized restoring force and displacement relations, subsequently on building inelastic response were quantified. The degradation leads to increase in inelastic response.

ACKNOWLEDGEMENTS

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REFERENCES

ASCE/SEI, 2019. Prestandard for performance-based wind design. Reston, VA.

Huang, J., and Chen, X., 2022. Inelastic performance of high-rise buildings to simultaneous actions of alongwind and crosswind loads. Journal of Structural Engineering, 148(2), 04021258.

Huang, J., and Chen, X., 2023a. Inelastic response of high-rise buildings under strong winds: Accuracy of reduced-order building model and influence of biaxial response interaction. Journal of Structural Engineering, 149(1), 04022211.

Huang, J., and Chen, X., 2023b. Improved estimation of time-varying mean displacement and parametric study of biaxial effect on inelastic responses of high-rise buildings to wind. Journal of Wind Engineering and Industrial Aerodynamics, 232, 105279.