August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Assessment of Wind-induced Nonlinear Response of Tall Buildings Using Real-time Aeroelastic Hybrid Simulation

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SUMMARY:
This study presents the preliminary attempts to carry out nonlinear aeroelastic wind tunnel testing using real-time aeroelastic hybrid simulation. This method was recently developed and validated by the National Science Foundation (NSF) designated Natural Hazard Engineering Research Infrastructure (NHERI) Lehigh Experimental Facility and the NSF-NHERI Wall of Wind (WOW) Experimental Facility at Florida International University. The study investigates the aeroelastic effect on the nonlinear response of tall buildings. The results show that aeroelasticity can significantly alter the nonlinear response of a tall building, particularly in the across wind direction where underestimation of the peak and residual deformations was observed.

Keywords: Aeroelastic, Real-time Aeroelastic Hybrid Simulation, Tall Buildings, wind testing.

1. INTRODUCTION

The current design philosophy of tall buildings under wind loads limits their response at or below the first significant yield point. That is, the yielding point is the ultimate limit state for tall buildings which make them sometimes overdesigned and uneconomical systems. To overcome these limitations, several researchers suggested to adopt performance-based design (PBD) to wind engineering by allowing some performance objectives to exceed the linear limit. Yet, there is a lack of understanding of the true wind-induced response of tall buildings after exceeding the yielding point. The lack of understanding the combined effects of phenomena such as the softening of the structural stiffness in the nonlinear range (which reduces the natural frequency of the structure), the wind structure interaction, and potential aeroelastic instability limits progress towards the adoption of PBD in wind engineering. Furthermore, tall buildings are usually tested in wind tunnels as either rigid models or aeroelastic models with linear stiffness. Designing springs or mechanical devices to consider the change in the stiffness and damping with the increasing level of nonlinearity is very complex. Therefore, there is a necessity to develop techniques that enable considering both aeroelastic and nonlinearity effects in wind-tunnel testing. The objective of this study is to provide readers with preliminary results of wind tunnel tests of a scaled forty-story tall building with both nonlinear response and aeroelastic effects that are considered by adopting the Real-Time Aeroelastic Hybrid Simulation (RTAHS) technique.

2. METHODOLOGY

In this study, RTAHS is used to carry out the nonlinear aeroelastic wind tunnel test. Within this context, the structure is divided into numerical and experimental substructures [shown conceptually in Figure 1]. The experimental substructure consists of a physical 1:150 scaled model which was tested at the NSF-NHERI Wall of Wind (WOW) Experimental Facility at Florida International University (FIU) to measure the real-time wind pressures. For that purpose, 336 pressure taps were distributed over the surfaces of the model. This enables the estimation of the wind forces without the contribution of the inertial forces due to the model's mass. The numerical substructure consists of a two degree of freedom system based on the properties of a scaled 3D model of the 40-story prototype building. Both the analytical substructure and simulation coordinator are modelled and reside at the NHERI Lehigh Experimental Facility. Unlike conventional aeroelastic wind tunnel testing where the stiffness is represented using physical springs, the stiffness was considered by the numerical substructure which facilitates the consideration of the nonlinear response of the model. Thus, the need for physical springs with nonlinear stiffness is avoided by adopting the RTAHS technique.

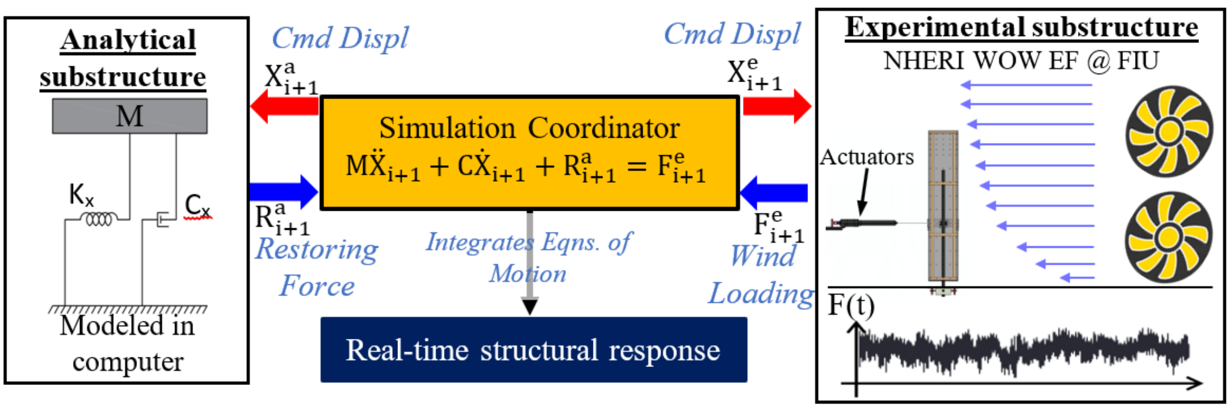

Figure 1. Overall concept of the proposed RTAHS technique.

In each time step, the wind forces acting on the model were measured by knowing the tributary area of each pressure tap and imposing the current displaced position and velocity of the model. The wind forces and restoring forces from the analytical substructure are fed back to the simulation coordinator to complete the integration of the equation of motion. For that purpose, the explicit unconditionally stable MKR-α method, which was developed by researchers at NHERI Lehigh, was used (Kolay and Ricles, 2019). The command displacements for both the analytical and experimental substructures are calculated, and the targeted displacements associated with the experimental substructure are achieved using two orthogonal actuators as shown in Figure 2.

To investigate the aeroelastic effect on the nonlinear response of tall buildings, two types of testing were carried out. The first test is an aerodynamic test where the scaled physical model in the wind tunnel was rigid and did not interact with the wind. The aim of this test was to record the wind pressure time histories that are then used to determine the nonlinear dynamic response of the numerical model (i.e., aeroelastic effect is ignored). This is the method that is usually used in the literature to evaluate the nonlinear response of tall buildings. In the second test, the RTAHS technique was used to determine the nonlinear response of the model while considering the wind-structure interaction by measuring the wind forces in real-time while the model is vibrating. For each test, two case studies were considered: the first case (named as Case 1) is selected to represent a tall building that is expected to exceed the linear limit only in the along wind direction. The second case (named as Case 2 thereafter) has lower yielding limit in the across wind direction to represent a tall building that exceeds the linear limit in both along and across wind directions.

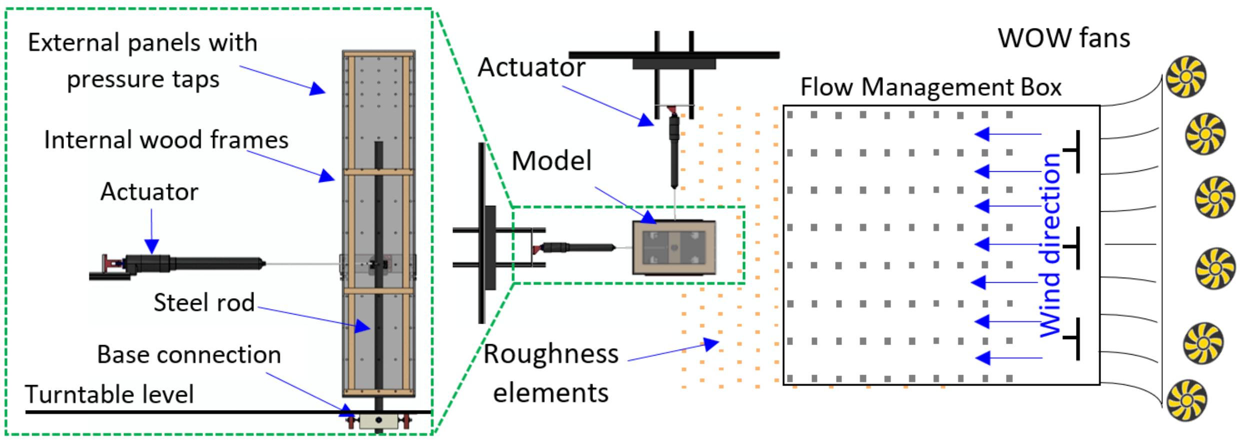

Figure 2. Schematic of the proposed RTAHS testing at the Wall of Wind facility.

3. RESULTS

Figure 3 shows the ductility time history in the along wind response of the two test cases. The aerodynamic curves represent cases with pre-recorded wind forces while the aeroelastic curves represents cases tested using the RTAHS technique. The ductility was calculated as the ratio between the roof displacement and the yielding displacement. Figure 4 shows the ductility time history in the across wind direction. It should be noted here that for this level of ductility, the ratio between the mean along wind force to the yield force is 0.45 and 0.49 for Case 1 and 2, respectively.

As can be seen in Figure 3(a), there is a difference in the along wind response of the two cases. Case 1 showed higher peak displacement and residual deformations when pre-recorded aerodynamic wind forces are used. Precisely, the difference in the peak along wind response is 31.5% and 16.2% for Case 1 and 2, respectively. With respect to the residual deformations, using the wind forces obtained from the aerodynamic test resulted in higher residual deformations by 56% and 27% compared to the aeroelastic model for Case 1 and Case 2, respectively. That is, using pre-recorded data from rigid models overestimates the residual deformations of tall buildings in the along wind direction. Interestingly, reducing the yielding limit of the across wind direction increased both the peak and residual deformation in the along wind direction as can be seen from the aeroelastic curves of Case 1 and 2. Such effect could not be captured using the pre-recorded wind pressures.

Figure 4(b) indicates that neglecting the wind structure interaction by using aerodynamic wind forces underestimates the nonlinear across wind response. For example, the aeroelastic model experienced higher peak displacements by 24%. Interestingly, using the data from the aerodynamic model significantly underestimated the residual deformation in the across wind direction. The aeroelastic model showed 0.6% residual drift ratio compared to 0.1% for the rigid model. This difference the residual deformations can result in serious consequences. For example, it is reported that repairing buildings suffered residual deformations more than 0.5% following an earthquake is not economically feasible. Moreover, exceeding this inclination level causes occupants to have headache and dizziness during a wind storm which makes the habitability of the building after surviving an extreme wind event questionable (McCormick et al. 2008). Therefore, using pre-recorded wind pressures, as is the current standard, and neglecting the wind structure interaction in predicting the nonlinear response of a tall building may lead to an inappropriate design which in turn may affect the targeted performance and functionality objectives of the structure. Therefore, this study recommends carrying out nonlinear wind tunnel testing using RTAHS if there is interest in the tall buildings' response beyond the elastic limit.

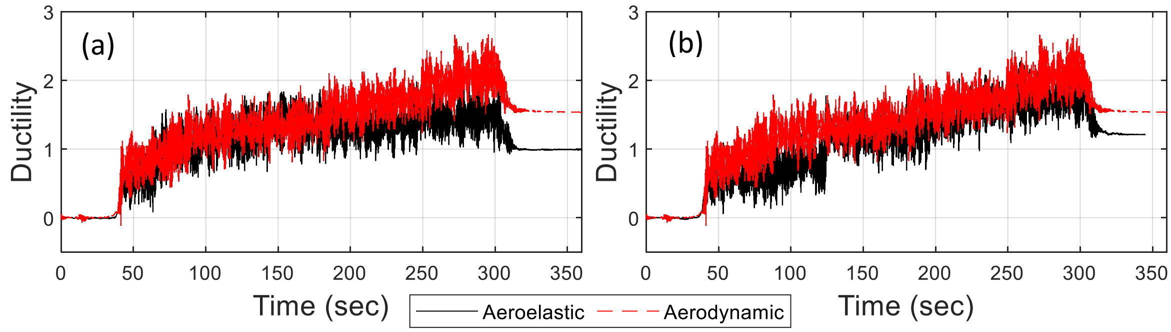

Figure 3. Ductility time history in the along wind response: (a) Case 1, and (b) Case 2

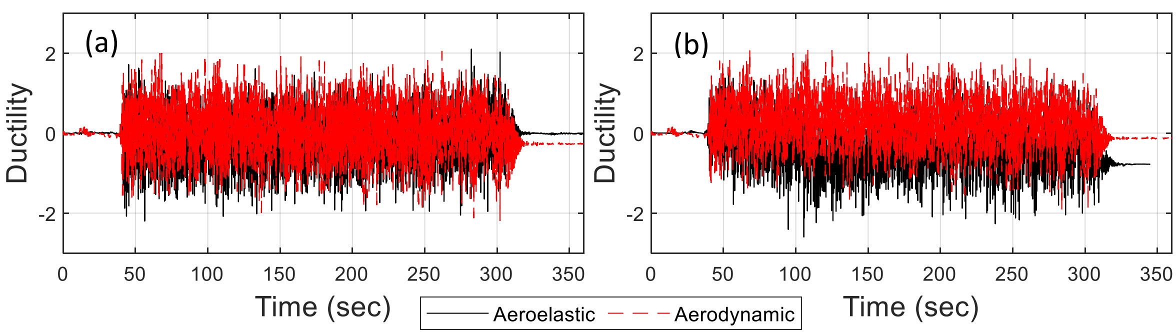

Figure 4. Ductility time history in the across wind response: (a) Case 1, and (b) Case 2

4. CONCLUSIONS

The objective of this paper is twofold. First, to promote the adoption of the RTAHS technique in carrying out nonlinear wind tunnel testing to assess wind induced response of tall buildings. Second, to quantitively assess the aeroelastic effect on the nonlinear response of tall buildings. Results indicated the suitability of using RTAHS in carrying out nonlinear wind tunnel testing. Furthermore, results show that aeroelastic effect can significantly alter the nonlinear response of tall buildings. Therefore, using nonlinear wind tunnel testing instead of using predefined wind forces is necessary for future research related to the nonlinear response of tall buildings.

ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the NHERI Wall of Wind Experimental Facility (NSF Award No. 1520853 and No. 2037899) and the NHERI Lehigh Real-Time Multi-Directional Experimental Facility (NSF Award No. 1520765 and No. 2037771) to conduct the tests.

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