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GRAVITY LOAD EFFECTS ON INELASTIC SIMULATION OF BUILDINGS SUBJECTED TO WIND LOADS

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Summary. Reduced-order (single-degree-of-freedom) models of buildings subjected to wind loads were analyzed to determine the effect of gravity loads on inelastic behavior. The lateral wind loads were based on data from atmospheric boundary layer wind tunnel tests to capture the temporal and spatial variation of wind pressure on a building envelope. The lateral load resisting system of the building was idealized using a bilinear relationship, and gravity load effects were introduced using a stability coefficient. Nonlinear response history analyses were solved using direct implicit integration of the equation of motion, and an energy balance was used to assess the quality of the numerical solution. The resulting response histories were used to interrogate the relationship between inelastic displacement, ductility, period of vibration, and gravity loads. The results indicate that inelastic displacements were approximately equal to the elastic displacements even in the presence of gravity loads for cross wind excitation. For along wind excitation, the inelastic displacements were approximately equal to the elastic displacements regardless of gravity loads. The findings suggest that the equal displacement concept may have application to the wind design of high-rise buildings where cross-wind loads control the design of the lateral system.

1 INTRODUCTION

A central concept in modern earthquake engineering is that the ductility of the lateral system can be more important than the strength of the lateral system. This surprising notion was first proposed by Veletsos and Newmark [1] who used response history analysis of inelastic single degree-of-freedom (SDOF) systems subjected to earthquake ground motion records to show that the peak inelastic displacement is approximately equal to the peak displacement of an equivalent elastic system and, thus, independent of the lateral strength. This concept is commonly known as the "equal displacement" concept. The concept has been shown to generally hold true as long as the strength and stiffness of the system does not degrade, fatigue is not an issue, and gravity load effects are minimized [2].

The equal displacement concept has important implications for the structural design of buildings. In earthquake engineering, a building can be designed for a reduced force if the lateral system can deform proportional to that reduction. This reduction in seismic design force is incorporated into many building codes. For example, the reduction in force is represented by the R value in ASCE 7-22 [3] used in the United States, the R_d value in the National Building Code of Canada [4], and the q' value in Eurocode 8 [5].

Although the equal displacement concept has traditionally been applied to only earthquake engineering, extension of the equal displacement concept to windstorm engineering is also important. In particular, wind events can generate elastic lateral demands that effectively limit the reduction in seismic design force. By limiting the reduction in design force, the elastic wind design approach can lead to structural designs that inhibit the formation of ductile mechanisms for seismic resistance. For example, in coupled shear wall systems, elastic wind demands can make it difficult to proportion “strong” shear walls and “weak” coupling beams.

Wind loading differs from earthquake loading in significant ways. Wind loads depend on the shape of the building, while earthquake loads do not. Seismic loads depend on the mass of the building. The magnitude of the wind loads can be long-term stationary events (e.g. during a synoptic wind event) or short-term non-stationary events (e.g. during a thunderstorm), whereas seismic loads are short-term non-stationary events. The frequency content of wind loads is higher compared to earthquake loads [6]. Additionally, wind loads can be either asymmetric or symmetric excitations with respected to the direction of loading. Wind loads acting on the building in the direction of the wind flow (along-wind) generate asymmetric excitations. Wind loads acting on the building in the direction perpendicular to the wind flow (cross wind) are nearly symmetric, depending on vortex shedding and harmonic effects.

The symmetry of wind loads has important implications for the application of the equal displacement concept to windstorm engineering. Analyses of reduced-order elastoplastic SDOF models of buildings with a fundamental period of vibration was equal to 1.0 s that were subjected to symmetric and asymmetric waveforms [7] indicate that the peak inelastic displacement is equal to the peak elastic displacement only if the excitation is completely symmetric. For asymmetric excitations, the analyses indicate that equal displacement concept does not hold. However, there were several important limitations to the study: (1) a single period of vibration was examined, (2) only one type of waveform was tested, and (3) the effect of gravity loads on the equal displacement concept was not examined. Applicability of the results across a broad spectrum of periods of vibration and for other types of excitations have not been established. Furthermore, an understanding of both the effect of period of vibration and gravity loads is needed to determine if the equal displacement rule may have application to windstorm engineering. The work described in this paper builds on the previous study by examining wind load excitations, a range of periods, and by including gravity loads effects.

2 METHODOLOGY

This study examined a low-rise (3-story) building that is 24.4-m wide by 38.1-m long by 12.2-m tall. This building was selected because a small-scale physical model of the building was tested in an aerodynamic boundary layer wind tunnel [8] and the recorded data is publicly available at the United States National Institute of Standards and Technology (NIST) website (https://www.nist.gov/). For this study, the effective force on the building was based on the wind tunnel data for the 270-degree wind and the along wind and cross wind directions.

Inelastic reduced-order elastoplastic SDOF models of the building were created for periods of vibrations of 0.2 s to 2.0 s. Nonlinear response history analyses of the building models subjected to the along wind and cross wind excitations were solved using direct implicit integration of the equation of motion. An energy balance approach was used to assess the quality of the numerical solution. The resulting response histories were used to determine the relationship between inelastic displacement, ductility, period of vibration, and the effect of gravity loads.

2.1 Excitation

The effective force on the building was developed using a data-driven approach, based on the recorded wind tunnel data for the "im1" model in the NIST database. For this study, the data was selected for the wind oriented in the transverse direction (270 degrees in the wind tunnel). In the wind tunnel tests, the model was instrumented with an array of pressure taps and the corresponding external pressure coefficient, C_p history was recorded at each pressure tap.

Since the external pressure coefficient, C_p recorded in the wind tunnel tests was referenced to the upper level of the wind tunnel, and since it was based on a mean-hourly wind speed of 14.3 m/s, for this study the values of C_p and corresponding time step, dt were converted to equivalent full-scale values that are compatible with ASCE 7-22, which references a 10-m height and uses a 3-second gust wind speed. Moreover, for this study, a 98.4 m/s wind speed was used. This wind speed was used because it is approximately the wind speed that may be of interest for inelastic wind design.

The original wind record was repeated and modified so that it linearly ramped up to the target wind intensity and linearly ramped down. The story forces for each principle direction of the building were computed based on tributary area of each pressure tap and the tributary area of the story.

The excitation (effective force, F_{eff}) history was computed for both the along wind (transverse) direction and the cross wind (longitudinal) direction, as shown in Figure 1. The duration of the excitation was about 25 min. For reference, the corresponding elastic design force, F_{asce} is shown in Figure 1, based on ASCE 7-22 and typical wind load parameters.

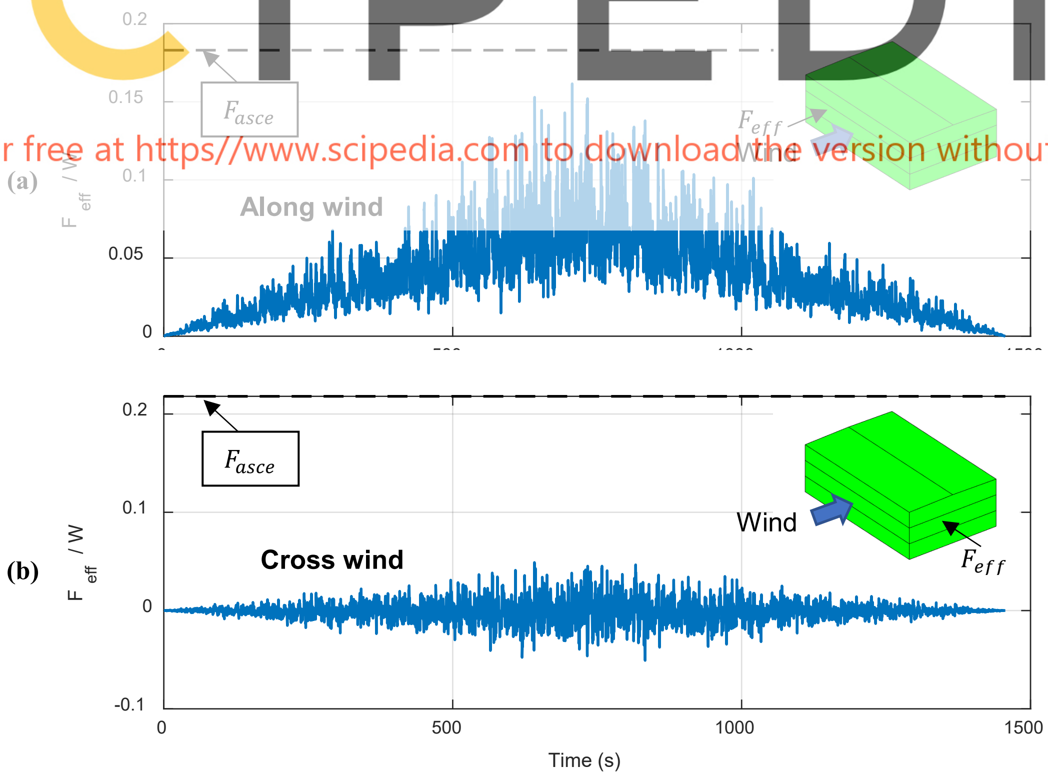

Figure 1: Excitation: (a) along wind, and (b) cross wind directions.

2.2 Reduced-order modelling

Reduced-order SDOF models of buildings were defined with an elastoplastic lateral system. The lateral system force versus deformation relationship is shown in Figure 2. This study examined buildings with a period of vibration, T from 0.2 s to 2.0 s. Based on vibration test data of actual buildings [9], this range of periods covers most types of lateral systems for this building height.

The initial stiffness of the lateral system, k was computed based on the period of vibration, two lateral resisting lines, and a tributary building weight equal to 5720 kN per line. Two ratios of gravity load to elastic buckling load, commonly referred to as the stability coefficient, θ_s, were examined: 0% (no gravity load effects) and 2.5% (gravity load effects).

The pseudo-static wind force, F_s was the mean wind force. The yield strength of the lateral system, F_y was equal to the peak elastic force, F_e divided by R, accounting for any reduction in strength due to stability, as shown in Figure 2. The peak elastic force, F_e was determined in linear response history analysis. This study examined values of R from 1 (elastic non-ductile lateral system) up to 2 (ductile inelastic lateral system).

The inelastic deformation, Δ was defined as the peak inelastic displacement, u minus the displacement corresponding to the mean wind force, u_s. The elastic deformation, Δ_e was defined as the peak elastic displacement, u_e minus u_s. If the equal displacement concept holds, $u = u_e$, as depicted in Figure 4. Note that without gravity load effects, $R = F_e/F_y$ whereas with gravity load effects $R \approx F_e/F_y$ due to the small reduction in the yield strength (F_y'). Thus, even for an elastic system, the ratio of u/u_e can be less than 1.0. Geometric nonlinearity was introduced using a linearized approach via the stability coefficient.

The nonlinear equation of motion was solved iteratively using implicit direct-time integration. Viscous damping (at strength-level wind loads), ζ was set at 5% of critical damping. Newmark's constant average acceleration method was used with Newton-Raphson iterations until the incremental force was less than 10^{-8}. Newmark's method was used because it is relatively efficient compared to explicit integration methods, unconditionally stable for linear analysis, and generally effective for bilinear and elastoplastic behavior.

The difference at each time step between external energy from the excitation and the internal energy (energy due to the inertial force, the damping force, and the force in the lateral system) was used to assess the quality of the numerical solution. An example of this energy balance is shown in Figure 3. As shown in the figure, the error estimated in the solution was small.

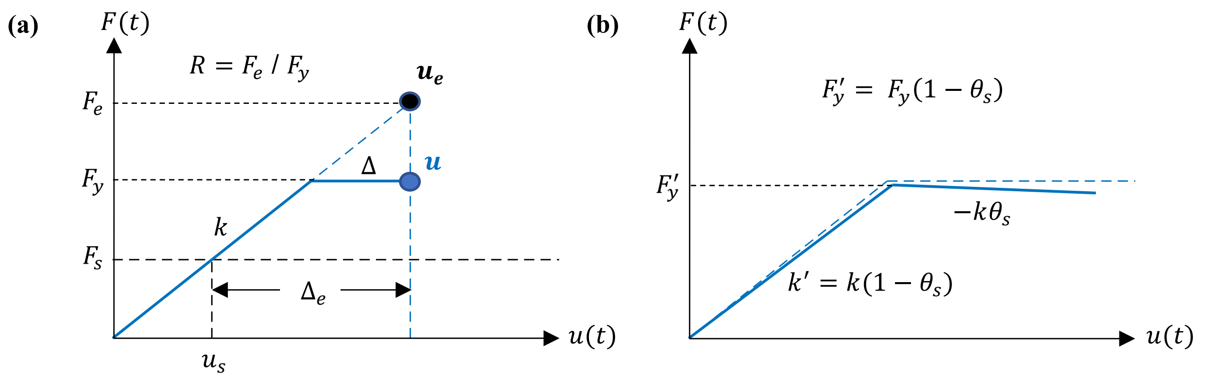

Figure 2: SDOF system force versus deformation relationship: (a) without and (b) with gravity load effects.

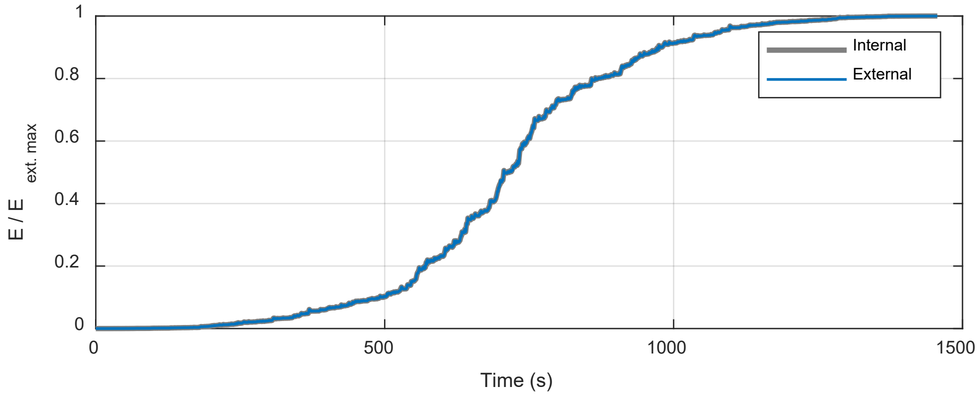

Figure 3: Comparison between the external energy and total internal energy in the system.

3 RESULTS

The resulting normalized peak inelastic displacement (u/u_e) versus R and T is shown in Figure 4. The three-dimensional surfaces demonstrate that for along wind excitation inelastic displacements were much greater than the elastic displacements for the range of periods examined, even when gravity load effects were not included. For cross wind excitation, inelastic displacements were approximately 1.0 to 2.0 times the elastic displacements, except for lower periods ($T < 1.0$) and lower yield strengths ($R > 1.5$).

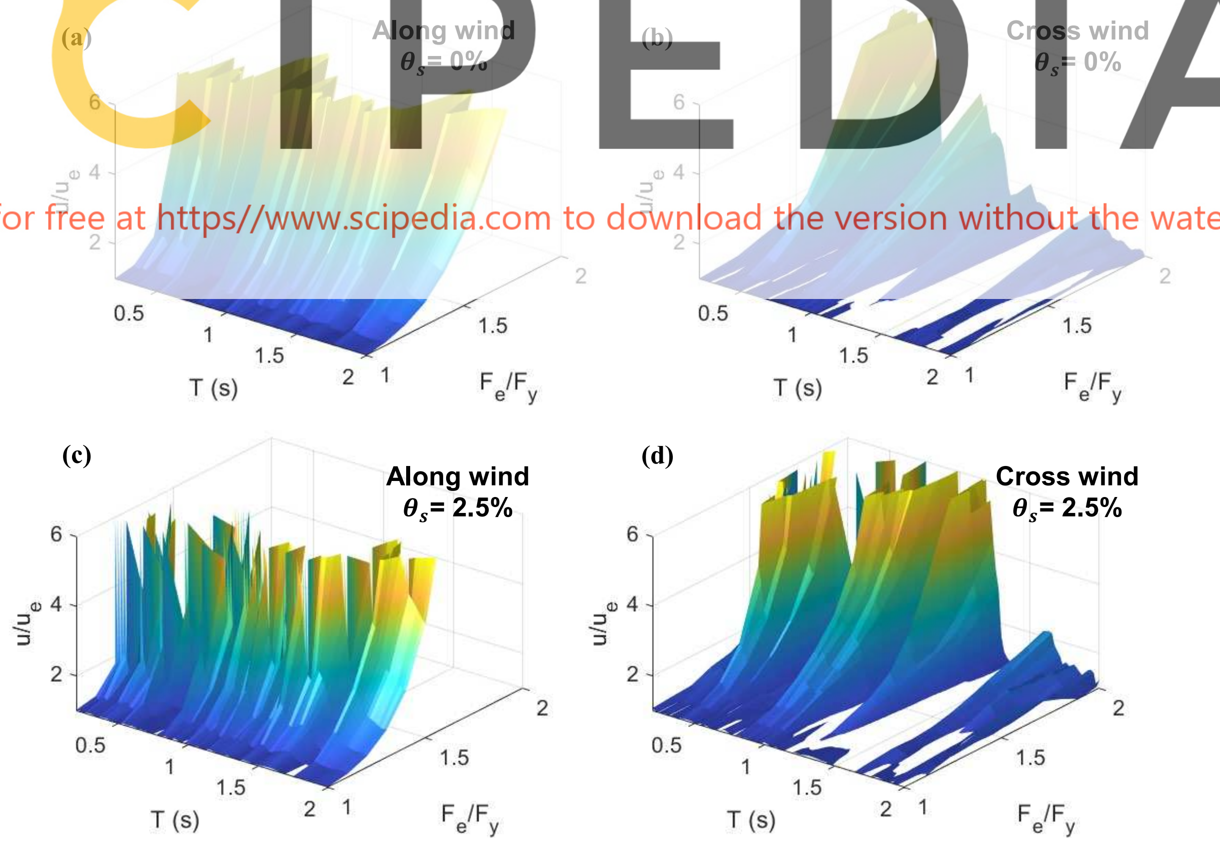

Figure 4: Normalized peak inelastic displacement versus strength reduction ratio and period of vibration: (a) along wind and (b) cross with without gravity load effects; (c) along wind and (d) cross wind with gravity load effects.

The large inelastic displacements for lower periods are expected for excitation that is in the acceleration-controlled range [2] and confirms the results from the prior study of the building with T = 1.0 s. The results show that the equal displacement concept did not hold for asymmetric loading, regardless of the period of vibration, for the full range of building periods, including acceleration-controlled, velocity-controlled, and displacement-controlled buildings.

However, the results indicate that the equal displacement concept generally did hold in the presence of moderate (θ_s=2.5%) gravity load effects as long as the excitation was symmetric. The physical explanation for this behavior is that as the building displaces, symmetric excitation brings the building back to the undeformed position. At the end of the excitation, the building has zero residual displacement. Thus, second-order ("P-Delta") effects do not come into play when the excitation is symmetric and the yield strength is relatively high (low values of R).

These results suggest that although the equal displacement concept will hold in an approximate fashion for stochastic excitation as long as it is generally symmetric, even a small degree of asymmetry tends to invalidate the equal displacement concept.

4 CONCLUSIONS

Reduced-order SDOF models of low-rise buildings were subjected to both asymmetric (along wind) and nearly symmetric (cross wind) excitations based on wind tunnel test data, and the peak inelastic displacements from the nonlinear response history analyses were normalized by the elastic displacements. The results showed that the equal displacement concept generally held for cross wind excitation, but not for along wind excitation.

The results indicate a reduced design force may be applicable in high-rise buildings where cross wind loads due to vortex shedding govern the design of the lateral system. In low-rise buildings where along wind loads dominate, a reduced design force based on ductility may not be justified in the same way that it is in earthquake engineering.

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