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Finite-element modeling framework for predicting realistic responses of light-frame low-rise buildings under wind loads

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ABSTRACT

Low-rise wood frame buildings are one of the most vulnerable structures that are often damaged in windstorms. On the other hand, numerically modeling the structural behavior of wood frame buildings poses significant challenges. This paper presents a computational modeling methodology that can help determine the realistic load paths and load sharing for light-frame low-rise buildings under wind loadings throughout the linear to the nonlinear range. A three-dimensional finite-element (FE) model is developed to capture the behavior of a building under wind loading, a large-scale model of which was tested at the Wall of Wind (WOW) Experimental Facility (EF) at Florida International University to provide experimental results for the validation of the FE modeling. This comprehensive numerical model can accommodate various materials and structural connections with mechanics-based load-deformation characteristics such as sheathing nails and framing-to-framing connections, so as to be capable of predicting the performance of the components and connections that are difficult to model in general but are the most vulnerable parts of a low-rise structure as witnessed during past hurricanes. The predicted structural responses of the computational framework showed reasonable agreement when compared to the experimental measurements in terms of the deflection at roof sheathings and roof-to-wall connections (RTWCs). This validated framework is then used to analyze different modeling effects. Different ways to represent the RTWCs and foundation fasteners are compared, which determines the boundary conditions of the roof assembly and full building simulations, respectively. The modeling of wall stud connections is discussed to fill in the corresponding gaps in the past research. A controversial issue that whether the effect of the rotational capacities of sheathing nails can be ignored or not is also discussed.

1. Introduction

In the United States, light-frame wood buildings account for over 95% of all residential structures, and the majority of these buildings are designed as low-rise buildings [12]. These wood structures are not rigorously constructed, which follows the prescriptive requirements of the local building code rather than being fully analyzed and engineered [18]. As a result, poor performance of these non-engineered buildings has been witnessed during the past hurricane events (e.g. [9–11,37]). Low-rise buildings thus represent one of the most vulnerable structures under extreme wind events and are the largest source of the damage and fatality directly and indirectly inflicted by extreme weather events such as hurricanes, tornadoes, and storm surges [21,33]. As reported by the National Association of Insurance Commissioners, hurricane-induced catastrophes account for seven out of the top ten costly insured property catastrophes in the U.S. [26]. Compared to wind analysis and wind design of high-rise buildings, which are often informed by extensive wind tunnel studies, the work dedicated towards the low-rise building performance under winds, in stark contrast, falls behind. Meanwhile, the wind performance analysis of light-frame low buildings lags far behind the seismic analysis for such structures that employs finite-element (FE) modeling technique. This is partly due to the complexity of modeling the flow around low-rise buildings and the effect of oncoming turbulence due to the terrain roughness. Without detailed wind tunnel testing, which is mostly done for tall buildings (due to economic reasons), it is challenging to predict the realistic wind-induced effects on low-rise buildings which have large variation in geometries, including different shapes, roof types, and roof slopes that influence flow separation, reattachment, and vortex formations. Fluctuations in surface pressures and dynamic load transfer within the

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structural system are also important factors that can produce dynamic effect in terms of load attenuation for low-rise buildings, as confirmed by Zisis and Stathopoulos [41]. Overall, the estimation of realistic wind-induced effects (e.g., pressures, forces) and responses (e.g., deflections, strains) for low-rise buildings poses significant challenges due to the complex flow-structure interaction and strong temporal and spatial variations of wind loading. Thus, evaluation of realistic wind performance of and risks to low-rise buildings deserves more attention in light of the urgent need to reduce significant losses to these non-engineered structures during wind events, as will be discussed next.

The prediction of hurricane losses is of compelling interest to insurance companies besides the federal, state and local government who are responsible for enacting policies for reducing the vulnerability of infrastructures, e.g., DMA2K—Law 106–390 [31]. The insurance industry demands the assessment of structural performance under hurricanes in a quantitative way that is measured by damage ratio (repair/replacement costs) over a wind speed range, which involves a series of nonlinear deformations and progressive failures greatly influenced by building configurations. As such, some full-scale wind engineering laboratories are constructed, e.g., the Insurance Institute for Business & Home Safety (IBHS) Research Center, to provide more realistic predictions of the structure performance with realistic building configurations under high winds [25].

Direct experimental studies on low-rise wood buildings under winds are considered as one of the most reliable ways to analyze the structural behavior for more effective designs. However, due to the high cost, these full-scale wind tests are performed for limited number of structures only, and their main objective is supposed to serve as the validation of numerical models, as indicated by the committee of National Research Council (US) [27] after reviewing the need for the large-scale test facility. Furthermore, even the wind tunnel tests on scaled building models for specific designs are rare and only possible for big projects due to cost issues.

In light of the above discussions, it is important to reduce future reliance on physical model testing by developing numerical modeling approaches to predict performance of light-frame wood houses subjected to wind loads. This numerical modeling should be validated to be capable of predicting all of the critical locations, structural behaviors, and load paths over the entire failure process and apply simplifications without significantly affecting the results so as to reduce computational effort. The wind loads, applied to the surface of a structure determined by the eddy-structure interactions with building geometries, tend to follow the load paths governed by structural configurations through the relative stiffness and locations of individual components [39]. Trautner and Ojdrovic [35] found that the critical structural actions and locations of one building may not be the same for other buildings even with a single difference in bracing schemes. In light of this, more emphasis should be put on the modeling accuracy of the building configuration that determines how structures behave or deform, which further leads to a different sequence of failure modes. Observations from wind damage reconnaissance events revealed that the main source of damage in residential houses was the lack of continuous uplift load path from the roof down to the foundation [37]. Along the load path, the roof-to-wall connection (RTWC) [32,37,7] and sheathing-to-truss connection (STTC) [9,33] are identified as the most critical weaknesses. Therefore, a higher resolution of numerical modeling on the building configuration that incorporates the behavior of inter-connections contributes to a more accurate prediction of structural responses and failure sequence along with the failure modes.

He et al. [14] reviewed and discussed the paucity of the available complete numerical low-rise building models under wind loads, and cited the research work by Zisis [40], Asiz et al. [4], Martin et al. [24], Zisis and Stathopoulos [41], Malone et al. [23], Pan et al. [29] and Pfretzschner et al. [30]. The building models of Martin et al. [24] and Pfretzschner et al. [30] were validated by comparing responses through three levels such as the deflections in 2D individual truss, load and deflection sharing in 3D truss assembly, the correlation of in-plane stiffness of the wall system and nail spacing in a 2D shear wall, and influence functions in 3D complete houses. In their models, sheathing gaps and sheathing nails were ignored by assuming the continuity of sheathing panels and incorporating the effects of sheathing nails into wall and roof by adjusting the shear modulus of the sheathing, respectively. Such modeling method was later adopted by Malone et al. [23]. However, the capability of their linear modeling methods that is sufficient for predicting lateral and vertical load paths is within the elastic range as concluded by Martin et al. [24], and the behavior of the critical location in the wind loading case on the inter-component connections such as sheathing nails cannot be captured.

Asiz et al. [4] and Pan et al. [29] both developed a 3D building model that is capable of capturing the sheathing nail behavior by adopting nonlinear elements simulating the translational deformation in three global directions. Asiz et al. [4] model considered all the inter-component connections including anchor bolts to the foundation, sheathing-to-frame nails, and framing-to-framing nails with special cares on the RTWCs by using nonlinear link elements. This numerical model was calibrated by a full-scale wind test on a simple box-type light-frame wood structure where only three sides, i.e., two front wall and the whole roof surfaces, were applied with corning wind loads by using pressure loading actuators (PLAs) with load traces derived from wind tunnel tests. Despite the nonlinear capability, their model was only well validated at low loading level within the linear range rather than at high loading level, attributed to the exclusion of material nonlinearities of frame and sheathing members, as well as neglecting geometric nonlinearity induced by the large deformations that were observed before failures [4]. Pan et al. [29] incorporated the geometric nonlinearity into their modeling analysis and made one of the earliest attempts to address the progressive failure issue by utilizing one piece of sheathing panel on the roof and identifying seven failure modes. The failure modes include three capacities of STTCs regarding the withdrawal, pull-through, and load-slip, and four sheathing capacities on axial stress, shear stress, bending stress, and displacement thresholds. Pan et al. [29] modeling method with the geometric nonlinearity will be followed and validated in the current study.

Zisis and Stathopoulos [41] addressed the dynamic effect of the light-frame construction subjected to wind loads on the complete building level benefited from the NSERC Collaborative Research and Development (CRD) Project entailing the field monitoring with heavily instrumented full-scale facilities and special costly laboratory accommodations (Zisis 2011). Taking advantage of the load cell mounted on the frame, roof, and foundation, the structural attenuation, a phenomenon incorporated in the National Building Code of Canada, was experimentally justified for the first time. To investigate the structural attenuation of the wind-induced internal force flow, a simple 3D linear elastic building model was created and applied with wind loading time series, of which the predicted forces were treated as a baseline and compared with the monitored values. The predicted uplift force at the RTWCs and foundation level in the form of correlation plots and reduction factors showed higher values. Based on that, they addressed that the estimation of building performance would tend to be conservative based on static analysis of structural systems inherent in the current wind design practices. This FE model was validated by comparing the distribution of uplift foundation forces under static analysis [14].

The current complete FE models subjected to wind loads remain validated within linear elastic range, and challenges exist with respect to the modeling technique and loading sources. The models involved significant simplification on the semi-rigid connection modeling with linear material property assumptions. Moreover, the spatiotemporally varying wind loading is usually simplified and applied in the form of static, slow increasing ramps or very basic cyclic loading. These issues have been greatly improved in the FE models at the roof structural level with advanced modeling techniques except specimen boundary