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Review article

A review of wood-frame low-rise building performance study under hurricane winds

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ABSTRACT

The unsatisfying performance of light-frame low-rise buildings under hurricane winds is a long-standing issue. Most past research effort has been made in creating a wind pressure database using advanced testing facilities, studying "cutout" subassemblies (i.e., roof subassemblies/sheathed shear walls) without considering the imparted influences of the whole system, analyzing load transfer mechanisms within full building models in the linear range, and quantifying building performance for the purpose of estimating economic losses. What still remains unclear is the contribution of some key factors, such as the simplified spatial-temporal varying wind loads, the resolution of numerical models, and the building component capacities, with large uncertainties, to the ultimate building performance. This paper aims to review the state-of-the-art research of four related disciplines that may contribute to a rational building performance assessment from an engineering perspective. Hurricane hazards, public wind pressure databases, and design wind loads are reviewed to indicate the importance of parameters other than wind speed to the building performance. The evolution of the low-rise building FE modeling is summarized with an emphasis on the connection modeling as well as their comparisons with experimental measurements. The quantification of the building performance is discussed by using stochastic finite element modeling techniques. At last, areas requiring future studies are identified to fill knowledge gaps.

Contents

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1. Introduction

Low-rise residential buildings have performed unsatisfactorily during past hurricane events. Seven out of the ten most costly catastrophes in terms of insured U.S. properties through 2014 were hurricane-induced, as summarized in Table 1 in the descending order of loss [1], which excludes flood damage covered by the federally administered National Flood Insurance Program. In general, low-rise residential buildings have not received rigorous engineering design like tall buildings have. In ASCE 7 [2], low-rise residential buildings are defined as having a mean roof height, h, less than or equal to 18 m (60 ft.) and a height not exceeding the least horizontal dimension. Traditional dwelling construction practices generally deliver reliable building performance under gravity loads. However, the inadequate considerations on the structural performance under non-gravity loads, such as wind/wave uplifts and horizontal earthquake shaking forces, result in large differences in structural integrity. These defects put the ever-growing building stock along the hurricane-prone coastlines vulnerable to abrupt climate changes. In 2013, a total of 61,678,940 countrywide homeowner package policies were written to cover residential building damage and contents loss according to NAIC [1]. With this large number in mind, it is not surprising to see in Table 1 that the insured property loss caused by Hurricane Katrina in 2005 was twice as much as that caused by 911 terrorist attacks on World Trade Center in 2001.

The studies performed in the past on low-rise building performance under hurricanes fall into four major categories: (1) hurricane catastrophe models using little or empirical structural analysis for economic loss prediction purposes [3–10]; (2) deterministic finite element analysis of different modeling scopes, including the component level, the subassembly level [11–14], and the whole building level [15–19]; (3) probabilistic building performance assessment at the component level, i.e., a piece of roof sheathing [19,20]; and (4) direct building tests under natural wind [18,21,22] and under wind pressures replicated from wind tunnel measurements [23,24]. Until now, no study has been done on the probabilistic building performance assessment at the system level to account for both uncertainties in wind loads and structural resistances, which would provide the most comprehensive information on how to improve building performance. Fortunately, this goal could be achieved by combining the strengths of each involved discipline, as briefed in the following sections.

Modern hurricane catastrophe models contribute to integrate the structural damage assessment into a probabilistic framework by using vulnerability curves to quantify the extent of structural damage as illustrated in Fig. 1. After Hurricane Andrew in 1992, the structural performance assessment was included to help lay down a foundation for the loss estimation over the high wind speed range where the loss rate escalates, but the claim data is usually not sufficient for reliable regressions without large errors. In catastrophe models, the structural performance under hurricane winds is measured by the damage ratio, i.e., the replacement cost divided by the property cost, over a wind speed range. The vulnerability curve is generated using the mean percent damage value from the damage distribution at each wind speed [25] as illustrated in Fig. 1. Without the subjective segregation of the damage level as used in the qualitative damage matrix, i.e., "no damage," "moderate damage," and "severe damage" [8], vulnerability curves provide sufficient resolution to quantify damage or to evaluate structural degradation and beneficial structural upgrades. However, the structural representations of low-rise buildings by catastrophe models are focused on reflecting the structural damages as sufficiently as possible for the economy loss estimation rather than investigating the root causes of structural failures. For example, the building system is empirically simplified into several 2D super elements, i.e., a piece of shear wall with predefined constant load sharing in the Hazus®-MH and the Florida Public Hurricane Loss Model (FPHLM) [26,27]. This approach reflects failure modes consistent with post-disaster investigations, but it is limited because it cannot reveal the weakest load path nor the damage propagation.

Available deterministic static analysis of a truss assembly by Cramer et al. [13] found that a system does impart influence into a single representative 2D truss, which indicates that the aforementioned assumed fixed load sharing might not be appropriate even under static loads. Alternatively, the load transfer mechanisms within low-rise residential buildings could be captured rigorously by finite element modeling techniques based on mechanical principles. The building structure will be represented at a selected resolution varying in complexity and accuracy, especially for the inter-component connections that govern the ultimate building performance in a nonlinear manner. Finite element models yield verifiable structural responses, such as the peak global responses, which were compared with experiments set up in a controlled manner in the past [18,28,29]. Also, the influence of the uncertainties inherent in hurricane-induced loads and structure

Table 1
Ten most costly insured property U.S. catastrophes through 2014.

Rank	Date	Peril	Dollars when occurred (millions)	In 2014 dollars (millions)
1	Aug. 2005	Hurricane Katrina	41,100	48,383
2	Sep. 2001	Terrorist Attacks on World Trade Center and Pentagon	18,779	24,279
3	Aug. 1992	Hurricane Andrew	15,500	23,785
4	Oct. 2012	Hurricane Sandy	18,750	19,307
5	Jan. 1994	Earthquake in Northridge, CA	12,500	18,345
6	Sep. 2008	Hurricane Ike	12,500	13,639
7	Oct. 2005	Hurricane Wilma	10,300	12,125
8	Aug. 2004	Hurricane Charley	7475	9,083
9	Sep. 2004	Hurricane Ivan	7110	8,639
10	Apr. 2011	Tornado in Tuscaloosa, AL	7300	7,652