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Performance and risk to light-framed wood residential buildings subjected to tornadoes

Timothy Maloney[a], Bruce Ellingwood[a], Hussam Mahmoud[a,*], Naiyu Wang[b], Yingjun Wang[b], Peihui Lin[b]

[a] Colorado State University, United States
[b] University of Oklahoma, United States

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ABSTRACT

Light-framed residential wood buildings constitute the majority of residential construction in the U.S. These buildings seldom are engineered for specific hazards. As a result, they may be inadequate to ensure life safety, let alone continued functionality during and after a severe natural hazard. The aims of this study are twofold: to assess the performance of light-frame wood residential buildings under tornado hazards, and to link performance of individual building components to building system performance so that the effect of implementing improved construction techniques can be quantified. These goals were realized through the development of detailed finite element models to capture individual building component behavior and building system performance under tornado wind pressure loading. Based on the data acquired from the finite element models, tornado wind fragilities (damage state probabilities) were developed for several building archetypes. First, typical construction quality was considered to establish a frame of reference; subsequently various improved construction techniques were considered in an effort to meet community resilience performance targets provided from concurrent research. The study shows that, while current construction practices fail to meet risk-informed building performance criteria needed to achieve community resilience goals, these goals can be achieved by modest improvements to existing construction techniques.

1. Introduction

A large portion of the investment in building construction in the United States is in light-framed wood residential homes. Such buildings are particularly susceptible to tornadoes, a hazard which threatens many communities throughout Mid-America. This susceptibility, coupled with the lack of engineering design standards for tornado effects, can result in substantial damage to residential buildings and social and economic losses. The Joplin, Missouri tornado in 2011, which took 161 lives and caused nearly $3 billion in damages [1] illustrates the level of devastation that a tornado can cause. Preventing tornado events from becoming disasters requires improved standards and construction practices to achieve resilient communities in tornado prone areas.

Most resilience research conducted to date has addressed actions and policies to achieve community resilience objectives [e.g., 2,3]. However, little work has been performed to explore the link between individual building performance and community resilience [4–6]. Without quantitative knowledge of this relationship, it is not possible to evaluate the community wide benefit of implementing individual building improvements or to assess which of these improvements may be economically and practically feasible in a given community. The current building regulatory process is focused on the performance of individual buildings for life safety; this focus presents a significant obstacle to the realistic realization of more resilient communities.

The study reported herein provides a framework for quantifying the link between individual building component performance and building system performance. This is achieved through the development of detailed finite element (FE) models for three representative light-framed residential wood building archetypes exposed to tornado wind pressures. The level of detail used in the FE models allows system behavior to be captured and facilitates the development of physics-based statistical models of building performance under tornado wind pressure loads. Previous models [e.g., 7–9] have utilized individual component performance and assumed failure sequences. This approach falls short of realistically modeling system behavior and performance because determining the

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* Corresponding author.

E-mail addresses: Timothy.Maloney@colostate.edu (T. Maloney), Bruce.Ellingwood@colostate.edu (B. Ellingwood), Hussam.Mahmoud@colostate.edu (H. Mahmoud), Naiyu.Wang@ou.edu (N. Wang), Yingjun.Wang-1@ou.edu (Y. Wang), Peihui.Lin-1@ou.edu (P. Lin).

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structural response of isolated subassemblies and inter-component connections is generally not sufficient to evaluate global structural response [10–12]. The physics-based statistical models, derived from the FE analysis, are used to develop fragilities that quantify the probabilities of progressively more severe damage states occurring for each archetype at increasing wind speeds. These fragilities are developed with and without the use of improved construction techniques and building components. By analyzing these fragilities, the effects of various individual components on total building performance are quantified, deficient components are identified, and improvements to current construction practices and criteria are proposed to meet community resilience performance goals identified in concurrent research [13].

2. Background

2.1. Tornado hazards

Wind pressures generated by tornadoes differ from those generated by straight-line winds stipulated in *ASCE Standard 7–16* [14]. Several studies of tornado effects on buildings, including those by Haan et al. [15] and Roueche et al. [16], have suggested modification factors to be applied to the *ASCE Standard 7* design wind pressures to account for these differences. Because of the uncertainties arising from such modeling assumptions, we have chosen to examine building performance using upper and lower bound estimates on tornado wind pressures on residential building archetypes: the upper bound is based on the procedure described in the Commentary to *ASCE Standard 7–16*, in which synoptic wind pressures are modified by tornado loading coefficients [15,16] (described subsequently), while the lower bound is determined from the unmodified *ASCE Standard 7–16* [14] wind pressures. The directional procedure (ASCE Standard 7, Chapter 27) is used to calculate the main wind force resisting system (MWFRS) pressures, while the pressures on components and cladding (C&C) are estimated using ASCE Standard 7, Chapter 30. The Enhanced Fujita (EF) tornado scale is used to relate wind speed into tornado intensity.

The wind load (pressure) acting on the MWFRS or C&C of the residential building is [14]:

$$w = q_h(GC_p - GC_{pi}) \tag{1a}$$

in which the velocity-related (or stagnation) pressure at mean roof height h, q_h, is

$$q_h = 0.613\ K_d\ K_z\ V^2 \quad [\text{in Pa, with V in m/s}] \tag{1b}$$

and G = gust factor, C_p = external pressure coefficient, GC_{pi} = aerodynamic coefficient describing internal pressures, K_z = exposure factor, describing the increase in wind speed with height, K_d = wind directionality factor, and V = 3-s gust tornado wind speed. All buildings in this study were assumed to be located in Exposure C (open country) because the boundary layer and surface roughness effects for tornadoes are not well-understood. Since K_z and K_d were developed for synoptic winds rather than tornado vortices and the residential buildings of interest have mean roof heights less than 15 m, we assume that the boundary layer effect is negligible and K_z and K_d both equal 1.0. Wind pressure variability is accounted for using methods described in references [8,17,18,19] – see, e.g., Tables 1 and 4 of Ref. [18] for more details.

Commentary section 26.14 to *ASCE Standard 7–16* suggests two approaches to calculating tornado wind pressures on MWFRS and C&C. Method 1 uses Eqs (1a) and (1b) directly, with some modifications to G and to GC_{pi}. Method 2 simply multiplies Eq. (1a) by a tornado load factor (TLF) intended to account for the differences between tornado and synoptic winds. The TLF approach yielded comparable, if slightly conservative, results for the three residential building archetypes analyzed in this study. Table 1 presents a summary of wind parameters and their statistics applicable to all archetypes. Specific aerodynamic coefficients applicable to local areas of roofs and walls are found in refs [14,18–20].

While breach of the building envelope due to excessive wind pressure is considered, the impact of wind-borne debris, which may cause a breach of the building envelope and a corresponding internal pressure increase, is reflected in the value of GC_{pi} in Method 1 and in TLF in Method 2 above. Wind-borne debris effects can be mitigated by the use of storm shutters and/or tempered glass to prevent windows from being shattered prior to breach of the building envelope by other means, such as roof panel uplift or window/door pressure blowout.

2.2. Typical residential home construction in the Midwest of the US

Typical light-framed residential wood buildings are generally non-engineered and have not been constructed or retrofitted to mitigate tornado risk. Common wall and roof construction practices used for current typical construction quality levels (CQL) of each component examined in this study are summarized in Fig. 1. These practices are common in communities in the Midwest of the US, such as Norman, OK, which was selected to represent a typical, tornado-prone community. Typical building component construction practices that are not shown in Fig. 1 include: (1) Bottom Stud-Sill to Foundation Connection: 2.5 cm diameter steel anchor bolts @ 1.8 m C—C, (2) Windows/Doors: DP25 windows; 2.4 kPa rated doors [21] and (3) Roof Covering: 0.3 m × 0.15 m class D asphalt shingles.

2.3. Observed building failures under tornado action

Existing research and field observations provide information about commonly observed failures in light-framed residential wood buildings subjected to tornado winds [9,16,21]. This information was used to determine the failure and damage modes considered in this study. These modes include: (1) Roof Sheathing Panel Failure, (2) Roof-Wall Connection Failure, (3) Wall-Foundation Connection Failure, (4) Roof Covering Damage, (5) Wall Sheathing Damage, and (6) Window/Door Pressure Blowout.

2.4. Experimental connection strength values

Experimental test data was used to define load-displacement behavior of various individual fastener connections considered in this study. Load-displacement relationships for some connections were modified from experimental data in [20] to reflect differences in the experimental test conditions *vs* typical CQL conditions. Common reasons for these modifications include differences in embedment wood species [22] and nail size. Fig. 2 shows common load-displacement relationships for individual fastener types used in the FE models developed subsequently. Connections generally consist of multi-fastener configurations. To capture connection strength variability in the statistical analysis, statistical data for each connection type is used. This data is taken from various sources, including [8,9,23] (See Table 2.5 of [20]). Building dead load also contributes to resistance against tornado uplift pressure. Dead load statistics are taken from Tables 3.5 and 3.6 of [9] which summarize data from [8,17,18].

3. Building archetypes and FE modeling approach

We considered three building archetypes, which are representative of residential building practices in the central US. *Archetype*