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Tornado fragility and risk assessment of an archetype masonry school building

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ABSTRACT

Tornadoes are a low-occurrence high-consequence hazard and not only threaten the life safety of building occupants but have recently resulted in billions of dollars in direct and indirect damages for single events. Design codes do not consider tornado loads for building and other structures (with the exception of nuclear facilities) because the occurrence rate has historically been considered too low. The advent of performance-based seismic design has revolutionized the engineering thought process and as a result building owners can consider performance objectives that enable a building to perform better in an extreme hazard than observed with current design code. In this paper, the performance of a masonry school building subjected to tornado wind loads is investigated using a fragility methodology. The tornado fragility assessment methodology is described along with proposed damage states for consideration in loss estimation. An array of masonry material types are considered based on the Masonry Standards Joint Committee (MSJC) code to enable applicability of the fragilities developed herein for a range of designs throughout the United States.

1. Introduction

1.1. Tornado risk assessment

Tornadoes are a low-occurrence high-consequence hazard and have resulted in billions of dollars in direct and indirect damages for single events and continue to threaten life safety in many regions of the United States [1]. While a number of studies have been conducted focusing on tornado dynamics (e.g., [2]), tornado wind pressure distributions (e.g., [3,4]), design of structures for tornadoes (e.g., [5,6]), and damage prediction for buildings in tornadoes (e.g., [7]); there still remains a substantial dearth of tornado-risk-assessment in the general open literature. Moreover, there is an extensive body of literature on seismic fragility analysis [8] and vulnerability assessments in the case of strong straight-line winds (i.e. Hurricanes) [9,10]. However, there are only several tornado risk assessment studies, which have focused on risk for nuclear power plants [11] and other critical infrastructure but not typical buildings within communities. Thus, in order to perform a community risk analysis for tornado hazard, a significant body of research is needed to fill this dearth.

The low probability of occurrence of tornadoes has prevented consideration of tornado loads in modern building codes, but this is changing as a result of deadly and damaging tornadoes over the last five years (Tuscaloosa, 2011; Joplin, 2011; Moore, 2013). Although a number of studies had been done on tornado-induced loads on buildings [12,13], the data deficiency motivated researchers to investigate tornado-induced forces on buildings [14,15]. In this regard, tornado-like vortices have been simulated and investigated in laboratories, including the VorTECH simulator at Texas Tech University [16], the Iowa State University (ISU) simulator [14], and the Wind Engineering, Energy and Environment (WindEEE) Dome at Western University [17]. At ISU, Haan et al. [14] studied tornado-induced wind loads for a laboratory-simulated tornado and compared them with the provisions of building codes. Their study revealed that tornadoes can generate load coefficients greater than those prescribed by ASCE 7-05 [18] for straight-line wind over open terrain. Based on the discussion by Kopp and Morrison [19] on the study done by Haan et al. [14], it is clear that further studies are needed to investigate spatial correlation of tornado loads on the building envelope, translation speed of the vortex, duration effects, and changes to the internal pressure during a tornado, which were the main disagreements among the researchers. Kikitsu et al. [20] strengthened the formula proposed by Simiu et al. [21], for calculation of tornado-induced pressure, to consider the effect of both opening and leakage on internal pressure. In fact,

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this proposed approach provided a better model for tornado loading; however, additional studies would provide statistics for the parameters related to leakage and opening in different types of buildings as well as other coefficients.

Based on the work completed by van de Lindt et al. [6], tornado-induced loads can be calculated by applying tornado coefficients to pressure coefficients using the common approach in ASCE 7-10 [18]. Tornado coefficients used in this study are based on the study done by Haan et al. [14]. Note that Haan et al. [14] used ASCE 7-05, but using ASCE 7-10 does not alter the values since they are the same for both editions. Using this procedure, van de Lindt et al. [6] proposed a dual-objective design philosophy to reduce damage for tornadoes in the EF0 to EF2 (Enhanced Fujita scale [22]) range, and focus on life safety in tornadoes of higher intensity, i.e. EF3 to EF5. Moreover, this method has been used in tornado risk analysis of wood-frame buildings [23,24] and performance assessment of earthen masonry dwelling buildings [25].

1.2. Schools in tornado-prone regions

Pressures caused by high wind speeds cause damage to buildings and other components making up community infrastructure. While all buildings are important, certain buildings capture the attention of communities because of their purpose. Some of these buildings are facilities such as emergency facilities, schools which host communities' children each day, and hospitals. According to the wind hazard map in ASCE 7-10 [18], the majority of the United States, including Tornado Alley and Dixie Alley, has a basic wind speed of 54 m/s (120 mph) for school buildings (risk category III and IV buildings). This wind speed is for straight-line winds from a Derecho or hurricane, but in theory possess the same wind speed of an EF2 tornado, although strong tornado wind speeds have never been explicitly measured with enough quality for use in analysis. Tornado wind speeds for significant tornadoes have been measured only through mobile Doppler radar but not at ground level. Approximately 97 percent of all recorded tornadoes are rated as EF2 or below [26]. Tornadic winds produce an intensified mean flow and enhanced turbulence at ground level [27], and include a large static pressure drop and a vertical wind velocity component, which together may result in a higher level of damage, especially roof damage, than their straight-line wind counterpart corresponding to the same horizontal velocity. However, this latter point is still a focus of on-going research around the world and lacks consensus.

Therefore, at issue is that damage caused by an EF2 tornado is not consistent to that of a 54 m/s (120 mph) straight-line wind underscoring the fact that no design codes or guidance address tornado-induced loads except those developed by the U.S. Nuclear Regulatory Commission (e.g. [11]) for reactor design. In fact, the wind pressures that tornadoes exert on a building were shown in one study to be more than twice [14] the minimum pressures derived from building codes, although as mentioned there has been disagreement among researchers to date on the approach used during the scale experiments [19]. In general, most buildings including schools will experience significant damage if they are in the path of a strong tornado because they have not been designed for this type of loading.

1.3. Observed damage to schools from tornadoes

Over the years tornadoes have destroyed or severely damaged a significant number of schools, resulting in injuries and fatalities. One well-known case was Xenia senior high school in Xenia, Ohio in the United States (Fig. 1) which was hit by an F5 tornado in 1974 [26]. The tornado passed directly over the school. The enclosure walls failed on the west and south sides; roofs collapsed over the three long spans—the auditorium, the boys' gym, and the girls' gym; and the lightweight roof was torn off by the extreme winds. St. Augustine elementary school in Kalamazoo Michigan was hit by an F3 tornado in 1980 [26]. The magnitude of the damage to the school was severe enough that demolition was eventually required. The loadbearing west wall collapsed inward, and the east wall fell outward. The roof fell into the building when the walls collapsed. Slender unreinforced masonry walls and the long-span roof structure were determined to be hazardous elements of this type of construction during post-event inspection. Kelly elementary school in Moore Oklahoma was hit by an F4 tornado in 1999 [26] to such an extent that the remaining structure was demolished and the school was reconstructed. Roof-to-wall connections were sufficient for gravity loads, but could not bear the high uplift loads caused by the wind. Unreinforced masonry walls failed when the roof system lifted off and was removed by tornado winds. Perhaps one of the most tragic school events occurred in the Enterprise, Alabama tornado in 2007 (EF4 tornado), when a school with unreinforced masonry walls and hollow-core concrete roof planks collapsed and eight student fatalities were reported [28]. On May 22, 2011, an EF5 tornado struck Joplin, Missouri. In the path of the tornado, Joplin High School, Franklin Technical Center, and Joplin East Middle School were extensively damaged while some other schools sustained moderate to intense damages. Although Joplin High School was built in 1968 and Joplin East Middle School was built in 2009, their performance from the tornadic winds was very similar [29,30]. On May 20, 2013, Moore, Oklahoma, was impacted by an intense EF5 tornado. The tornado struck Briarwood Elementary School, Plaza Towers Elementary School, and Highland East Junior High School. Briarwood and Plaza Towers Elementary Schools sustained enough damage to be considered a total loss, while for Highland East Junior High School the primary damage during the tornado was to the gymnasium, and only minimal damage occurred to the classroom building which was further away from tornado center. Moreover, seven fatalities occurred in the Plaza Towers Elementary School when a hallway being used as a place of refuge collapsed [31].

The study presented in this paper discusses performance of the building envelope, nonstructural, and structural building systems of an archetype unreinforced masonry school building using a tornado fragility analysis methodology and characterizes the resulting fragilities for components into damage state fragility curves for the school building based on proposed building damage states. The results can serve two major purposes: (1) they can be utilized to inform guidelines for better design practices related to new and existing schools in tornado-prone regions, e.g. using steel reinforcement with full grouting in all cells instead of unreinforced masonry construction, and (2) the fragility curves developed herein can be used to be representative of masonry school buildings in community risk and resilience assessment and improvement models.

2. Tornado fragility methodology

2.1. Fragility modeling

A fragility can be defined as a conditional probability of exceeding a specific amount of damage as a function of an intensity measure [32]:

$$Fr(x) = P[D(x) \geqslant R | IM = x] \quad (1)$$

where IM = random variable intensity measure describing the intensity of the demand on the system (e.g., 3-s gust wind speed; earthquake spectral acceleration at the fundamental period of the building, peak ground acceleration, etc.), $D(x)$ = demand on the sys-