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Tornado-borne debris impact performance of an innovative storm safe room system protected by a carbon fiber reinforced hybrid polymeric-matrix composite

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ABSTRACT

A new tornado safe room design is proposed using a recently developed Carbon-fiber reinforced Hybrid Matrix Composite (CHMC), or "CarbonFlex," to withstand tornado-borne debris impacts. Test results reveal that the new CarbonFlex wall panel has superior impact resistance in comparison to conventional residential construction and some alternative residential tornado-resistant wall panel constructions observed in the literature and identified in the current work. Two CarbonFlex design groups successfully passed the high-debris impact tests at a missile speed of 44.7 m/s (100 mph), corresponding to a ground wind speed tornado of 111.7 m/s (250 mph) while the two other CarbonFlex wall panel designs passed tests at missile speeds of 40.2 m/s (90 mph), corresponding to ground wind speed tornados of 89.4 m/s (200 mph). Additionally, a control group wall panel design that was manufactured using a conventional carbon fiber reinforced polymer (CFRP), or more precisely a carbon fiber reinforced epoxy, indisputably failed two debris missile high-impact tests. The material processing parameters of CarbonFlex, i.e., the matrix thickness, h_p, and an intermittent curing time, t_c, show to be evidently influential on the impact resistance capability of the CarbonFlex panels where the resistance generally increases with smaller values of t_c and with greater values of h_p. The merits of using CarbonFlex over conventional building envelop components are quantified via vulnerability assessments of both conventional and the newly developed composite wall panel system under tornado transported debris impacts.

1. Introduction

The construction of tornado-resistant shelters and the development of building envelopes that are used to design residential wood-framed constructions against high-impact windborne debris are relatively new. Tornado-generated missiles are defined as objects and debris that are picked up and transported by violently rotating wind, and include smaller objects such as roof tiles [1] and larger objects such as railroad cars [2]. Several field studies of the damage paths of tornados through residential and light commercial regions reveal that the most common types of missiles are medium-sized timber planks from damaged or destroyed residential structures [2]. The ensuing windborne debris can lead to significant damage of the building envelopes [1,3]; however, between the 1940s and early 1970s, design protocols for building structures against the risk of windborne debris had received minimal attention. In the 1970s, Minor et al. [4,5] quantified the impact of various windborne debris to the performance of buildings during severe storms, including tornadoes, hurricanes, and thunderstorms; a later study by Minor [3] examined the effects of windborne debris impacts against building envelope in order to assess damage. In that same study, Minor [3] further concluded that the most common type of windborne debris in residential areas was flying timber from wood framed structures, where the debris was observed to cause penetrations of the walls and roofs of the impaled houses. These observations finally led to the acceptance of a representative 'object' for tornado transported large missiles [3], namely the 6.8 kg (15 lb), 3.66 m (12 foot), 2 × 4 timber. Since that time, attention to the development of accurate building envelopes that are used to design and protect buildings against damage arising from windborne debris has increased, including some recent experimental and computational studies [6–9] on the flying pattern and trajectory of windborne debris. An analytical study by Wills et al. [10] established a mathematical model for calculating the damage potential of flying debris in strong winds, where debris speed is a function of wind speed, projectile geometry, and material density, etc.

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Although several building codes in the United States have evolved in order to address the issue of windborne debris impacts on buildings [11–13], the number of studies that address the performance of building envelopes against tornado/hurricane transported debris impact has been relatively limited. An earlier study conducted by McDonald [2] investigated the tornado impact resistances of nine conventional ply-wood residential wall constructions (1219×2438 mm in dimension) and eleven concrete masonry unit (CMU) wall constructions having different grouting areas. The study was used to assess the behavior of the wall systems against missiles impacts having various shapes and materials, such as wood and PVC, and projected at various angels. The following conclusions and recommendations were drawn from MacDonald's work: (1) conventional residential wall constructions are unable to withstand the impact of tornado transported debris; (2) in order to prevent penetration and perforation of the wall, the CMU walls should be reinforced and grouted in each cell; (3) the shape of the missile end was not significant in assessment of the impact test results; and (4) missile that were fired at a 45° angle with respect to the impact face tended to bounce off the wall without causing evident damage. A later investigation by Herbin and Barbato [14] focused on a probabilistic point of view and developed fragility curves in order to study the effects on the building envelope components following windborne debris impacts. In this study, a Monte Carlo simulation was used in conjunction with a finite element (FE) method to account for the uncertainty of the modeling parameters. Other studies have been conducted on the impact performances of particular building components, such as window glass [15], and other projectile types, such as roof tile; additionally, wood planks have been investigated by Fernandez et al. [1].

Due to the relatively poor performances exhibited by conventional residential components in previous studies, a new tornado safe room system that is protected by a recently developed CarbonFlex composite is proposed. The tornado debris impact performance of the newly developed system is investigated using a series of debris impact tests. The influence of two key material processing parameters of the CarbonFlex composite on the impact resistance are also investigated and discussed. Lastly, the tornado transported missile impact performance of the newly proposed system is compared against that which had been obtained for traditional building envelope components (BECs) such as the plywood stud walls and concrete masonry unit (CMU) wall units through a vulnerability study.

2. An innovative carbon fiber based polymeric composite system for impact protection

In this study, an innovative storm safe room system is proposed in lieu of expensive, heavy and awkward steel plate-designed storm safe rooms. The suggested composite safe room system is composed of two plies of 19.1 mm (¾ in.) thick C–D grade plywood and a layer of a recently developed Carbon-fiber reinforced Hybrid-polymeric Matrix Composite (CHMC) protective insert layer. The CHMC, having been recently developed by Zhou and Attard [16] and Zhou et al. [17,18], will be herein interchangeably referred to as "CarbonFlex" – the technology for which exists a nonprovisional patent on file: Case M12-023P, PCT/US2011/063581 "High Strength and High Elasticity Composite Materials and Methods of Reinforcing Substrates with the Same" [19]. CarbonFlex is a carbon fiber-based composite manufactured via a new patented hybrid-polymer matrix system involving amino-based polymeric compounds to provide necessary damping and high strength sustainability of the carbon fibrous component under high impact loading. Earlier studies conducted by Zhou and Attard [16] and Zhou et al. [17,18] indicate the capability of CarbonFlex, as a structural retrofitting material, to sustain the strength of an otherwise brittle carbon fiber-based composite system and to subsequently prevent the catastrophic failure of structures. Due to the superior deformation and energy dissipation capabilities of the CHMC – as exhibited in previous research – the CHMC (or CarbonFlex) is used here as a constituent layer within a composite wall panel system for tornado safe rooms in order to sustain the potential tornado-borne debris impacts. The light-weight feature of the carbon-fiber based composite used in the system not only allows the safe room to be designed as a stand-alone space, but may also be easily altered/or retrofitted from existing rooms having traditional wood stud wall construction. In addition, the newly developed CHMC has been used as a protection layer of the corollary door assembly, in order to enhance its tornado debris impact resistance. The proposed tornado safe room – together with its wall panel and door assembly systems – are illustratively shown in Fig. 1a–c. The microstructure of the CarbonFlex composite obtained using a scanning electron microscopy (SEM) are presented in Fig. 1d. Previous studies by Zhou et al. [17,18] indicates that a significant portion of the internal damping of CarbonFlex is attributed to a porous polymeric phase-I having a thickness of h_p, see Fig. 1d; on the other hand, the cohesion between the two polymeric phases of the CHMC system occurs within the hybrid matrix system that controls how the constituent materials function together. More precisely, this inter-phase cohesion will depend on an intermittent curing time parameter, t_c, which is shown in Fig. 1d. Consequently, the damage tolerance and material damping of CarbonFlex is believed to be a function of both the matrix thickness h_p and the intermittent curing time t_c. Facture surface morphology and nanoindentation studies conducted by Zhou et al. [18] have validated the critical role that the interfacial region, following the chemical interaction between polymeric phases A and B, has in precluding certain damage modes to exist in the CHMC at the micro-scale level. Following this, the interfacial region's morphology is clearly a function of the two material processing parameters, h_p and t_c, and confirms their role in the design and manufacturing of CarbonFlex, and, in fact, where h_p and t_c have been shown to control the macro-mechanical properties and performances of the CHMC. While the polymeric phases A and B may each be designed variably (perhaps exhibiting different elastomeric behaviors or with the addition of fire-retardants), previous tests indicate no discernible differences in the CHMC in terms of impact resistance, damping, or energy dissipation [20,21]. In addition, the attainable strength of the CHMC depends on the fiber-type and its layout (orientation), see Fig. 2c. A quantitative study on how these two material processing parameters would affect the performances of the composite wall panel system to prevent missile penetration are analyzed later following the large missile impact test results.

In addition, due to the widespread applications of carbon fiber reinforced polymers (CFRPs) in civil infrastructure systems [22,23], a controlling specimen group with conventional CFRP in lieu of the CHMC (or CarbonFlex) using the same framing, fiber-layout, and carbon fiber content was designed and constructed, such that the potential benefits of CarbonFlex over conventional CFRP in impact-load resistance could be investigated. Additionally, three door assemblies that were specifically designed for tornado safe rooms were also tested under missile impacts; the doors are classified as Ceco Legion™ brand [24] and are 14 gauge (1.90 mm thickness), 16 gauge (1.52 mm thickness), and 18 gauge (1.21 mm thickness) steel door panels protected by the CHMC.

3. The tornado debris impact experimental setup and test matrix

3.1. Specimen configurations and test matrix

Several carbon fiber reinforced hybrid-polymeric matrix composite (CHMC), or CarbonFlex, storm shelter system designs are