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Finite Element Analysis of Carbon Fiber Composite Sandwich Panels Subjected to Wind Debris Impacts

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Abstract: Hurricanes and tornadoes are the most destructive natural disasters in some central and southern states. Thus, storm shelters, which can provide emergency protections for low-rise building residents, are becoming popular nowadays. Both FEMA and ICC have published a series of manuals on storm shelter design. However, the authors found that the materials for related products in the market are heavyweight and hard to deliver and install; renovations are necessary. The authors' previous studies found that lightweight and high-performance composite materials can withstand extreme wind pressure, but some building codes are designated in wind-borne debris areas. In these areas, wind debris can reach greater than 100 mph speed. In addition, the impact damage on the composite materials is an increasing safety issue in many engineering fields; some can cause catastrophic results. Therefore, studying composite structures subjected to wind debris impact is essential. The finite element models are set up using the software Abaqus 2.0 to conduct the simulations to observe the impact resistance behavior of the carbon fiber composite sandwich panels. The selected wood debris models meet the FEMA requirements. The outcome of this study is then employed in future lab tests and compared with other material models.

Key words: Wind debris, Storm shelter, Finite element analysis, Carbon Fiber, Composite sandwich panel

1. INTRODUCTION

Extreme storms such as hurricanes and tornadoes frequently occur in the central and southern regions of the United States. It is estimated that the average annual loss caused by wind disasters is more than 6 billion US dollars, accounting for more than 50% of the total weather-related losses and more than 40% of the total losses related to natural disasters [1]. Due to awareness of evacuation issues during a strong wind event, Federal Emergency Management Agency (FEMA) has long supported updating the design criteria of storm shelter building codes. However, through the retrospect of storm shelter products for the past ten years, the authors found that most products used steel, CMU, or concrete and lacked innovations compared with other building materials. Therefore, the authors begin the research for upgrading product materials for aboveground residential hurricane shelters. The material resistance capacity to wind debris impact is one of the required properties in the related specifications.

1.1. Wind-borne Debris

Wind-borne debris (WBD) is one of the crucial damages to storm shelters. Therefore, it is essential to assess WBD components for damage risks for the residential shelters. The debris fight trajectory problems need to evaluate its component size, generation, flight, and impact behavior, involving flying aerodynamics and mechanics [2]. The studies of simulating WBD dynamics in wind fields can be categorized into analysis approaches, experimental approaches, and statistical approaches. To quantify the uncertainties of the debris impacting load is complicated [3]. Given the complicated and unequaled background of wind debris behavior, none of the building codes addressed this problem before the 1992 Hurricane Andrew. After Hurricane Andrew, Florida Building Code, ASCE 7, ASTME1996, and IBC were developed and updated their WBD provisions depending on the reliability analysis of different building components [4].

The bear capacity of impact test requirements for storm shelters is much higher than wind tunnel test requirements. The newest FEMA design criteria for the debris hazards are based on the ICC 500 for a residential safety room, which must meet the 250 mph design criteria [5]. The missile speed needs to be classified as the followings:

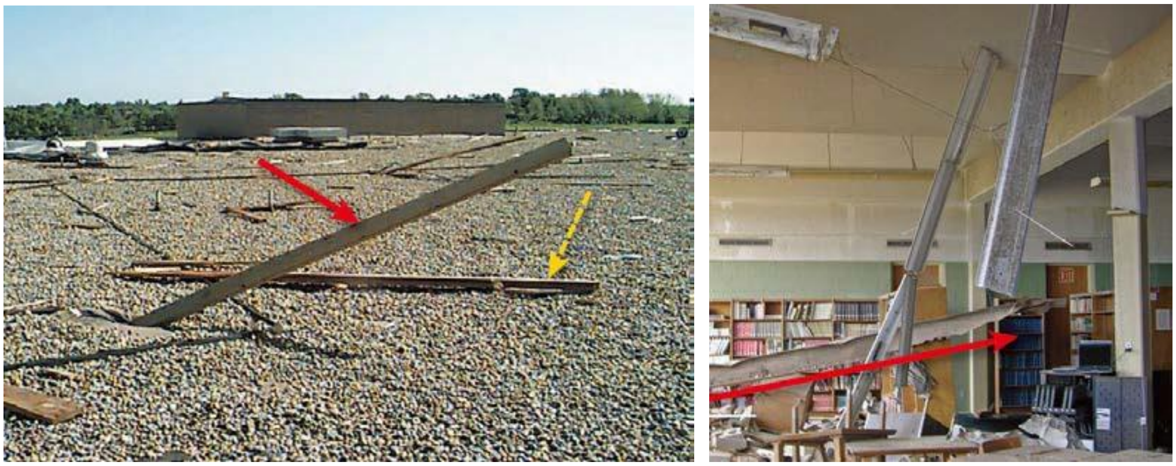

Figure 1. Medium and large debris [4]

According to FEMA 361 (2021) table B3-3, B-4, B-5, this study chooses 9-lb 2x4 inches vertical board members as missiles, and the test wind speed showing in table 1.

Table 1. Test Missile Speed

Design Wind Speed (mph)	**Missile (Vertical)**	**Missile Size (lb.)**	**Missile Speed (mph)**
160	2x4 inches	9	64 (0.4 wind speed)
250	2x4 inches	9	100

1.2. Research Review

Many universities, including Texas Tech University, University of Florida, Louisiana State University, and University of Western Ontario, have already taken the wind-borne debris impact tests for different building assemblies. The traditional test assemblies using the materials include but are not limited to CMU walls, metal, hollow core slabs, plywood, stud walls, wood, steel, glass fiber reinforced concrete wall, prestressed concrete, reinforced masonry unit, stull walls with polystyrene infill [6]. These traditional building materials have detailed requirements in the FEMA and ASCE 7 building codes. In the past 10 years, many scholars have constantly been researching and developing new materials to resist the wind debris impact. The most popular is high-performance concrete or precast concrete sandwich panel (PCSP). Concrete has excellent performances in related impact tests because of its high impact resistance and energy absorption capacity. For example, the Clemson University lab test by Behnam Naji shows that a solid reinforced concrete panel could pass the missile test, but the hollow core and sandwich panels need to gain more thickness [7]. Research on another material is also popular: a composite material that evolves from a wooden structure. For example, the Tianjin University and Curtin University joint research center has done oriented strand board (OSB) skin insulated panels (SIP) experimental studies; the outcome shows that these SIP panels could withstand at a velocity of 59 mph [8].

The materials mentioned above, the concrete panels perform well, but due to its overweight, not conducive to the portability of small storm shelters. The latter can meet some regional requirements as a general building structure material, but it is not standard for storm shelters. Nowadays, FRP materials are used in various construction projects due to their high strength and easy fabrication. Moreover, due to the development of modular building technology, FRP materials dominate the market with their lightweight and cost-effective properties [9]. Although there are few impact resistance studies for FRP sheets used in storm shelters, more data studies of impact, crash, or penetration of FRP materials used in aircraft areas could be referenced. The impact damage on the FRP composite materials is an increasing safety issue in many engineering fields; some can cause catastrophic results [10].

2. MATERIALS

Composite sandwich panels are widely known for their lightweight and high performance. The design concept of sandwich panels is to separate relatively complex, strong, and thin panels through light and thick flexible core. The authors' previous studies found that lightweight and high-performance composite materials can withstand extreme wind pressure and provide enough stiffness, high strength, and bulking resistance. But FEMA codes are also designated in some wind-borne debris areas; the storm shelters caused damage by the impact of wind debris is more stringent than wind loads. Therefore, studying composite sandwich panels subjected to wind debris impact is also essential.

Although many scholars have studied the problems of low-velocity impact on composite panels, the composite materials' damage capabilities are still needed to observe case by case. This is because there are multiple uncertainties in composite materials, such as material properties, structural interface properties, and failure criteria. Currently, the most widely used fibers are carbon fiber, glass fiber, and aramid fiber. This research chooses carbon fiber to set up the model. At present, carbon fiber of T300 and T700 is the most common products in the market. The tensile modulus of both is around 230GPa, but the tensile strength of T300 is 3400MPa, and the tensile strength of T700 is 4800MPa. In the case of tensile fracture, T700 has a much higher density than T300, and the overall performance has a 30% improvement [11]. This study used T700 carbon fiber laminate for the faced sheets of the sandwich panel.

This model's sandwich composite foam core chooses a rigid, closed-cell, polyurethane foam, called the Last-A-Form® Fr-3700 series. It exhibits a high strength-to-weight ratio due to its cellular structure and cross-linked resin [12]. Referring to the requirement of storm shelter, this model is preliminarily selected FR-3710 foam core [12][13]. The FR-3710 Structural Form Core properties are shown in Table 2.

Table 2. FR-3710 Structural Form Core [12]

Orthotropic Elasticity Properties (75°F)	Value (English Units)	Value (Metric Units)
Poisson Ratio	0.3	0.3
Compressive Modulus	9,600 psi	66.2 MPa
Compressive Strength	300 psi	2.05 MPa
Flexural Modulus	12,900 psi	88.9 MPa
Flexural Strength	450 psi	3.0 MPa
Shear Modulus	11,500 psi	79.3 MPa
Shear Strength	225 psi	1.6 MPa

The connecting material between layers is epoxy resin (hot/wet). The stacking sequence and thickness of carbon fiber in each layer shows in table 3.

Table 3. Stacking Sequence of the Sandwich Composite Panel

Ply No.	Layer	Orientation	Thickness (in)	Thickness (mm)
1	T700	-45°	0.03	0.762
2	T700	45°	0.03	0.762
3	T700	90°	0.03	0.762
4	T700	-45°	0.03	0.762
5	T700	45°	0.03	0.762
6	FR-3710	0°	0.4	10.0
7	T700	90°	0.03	0.762
8	T700	90°	0.03	0.762
9	T700	90°	0.03	0.762

3. MODEL ANALYSIS

3.1. Finite Element Model

We normally recommend the use of single line spacing. However, when typing complicated mathematical text, it is important to increase the space between text lines to prevent sub- and superscript fonts overlapping one another and making your printed matter illegible. The evolution of impact theory mainly contains four aspects: classical mechanics, elastic stress wave propagation, contact mechanics, and plastic deformation. Different impact theories apply different impact characteristics (speed and material properties), assumptions, and conclusions. The literature reviews indicate that the finite element method was used to study the contact/impact problem earlier, and it is based on the finite element principle of non-linear mechanics [14].

The FEA model is based on the software program ABAQUS/Explicit to establish an impact simulation model for the composite sandwich panels. This study analyzes its destructive damage and deformation mechanism under wind debris impact. At the same time, a comparison model using steel plates is established, which is now the most widely used material in the market. In most dynamic reactions, metal produces highly non-linear deformation rebound. Therefore, it is difficult to predict all possible interactions between a solid and a surface during an impact. However, the general contact algorithm available in Abaqus/Explicit is very powerful. To use it, we only need to define the contact domain that contains all the components that may be contacted. Then, during the simulation, the algorithm automatically detects which surfaces and edges are in contact. The key features and advantages of ABAQUS/Explicit are as the followings. The sample finite element model shows in figure 2.

- The progressive failure and ductile metal failure.
- The impact and fragmentation increase with the depth of the model definition.
- The material has independent functions to achieve complex damage, and failure.

3.2. Steel Plate Model

The size of the steel plate is 24x24 inches; the thickness is 0.6 inches. The debris missile is the 9-pound red oak, and the density is 46.2-pound per square foot. Therefore, the length of the missile is 84 inches. The steel plate impact may produce a rebound phenomenon compared with the composite panels. Moreover, the impact process may produce elastic deformation, plastic deformation, or damage. See the figures below for details.

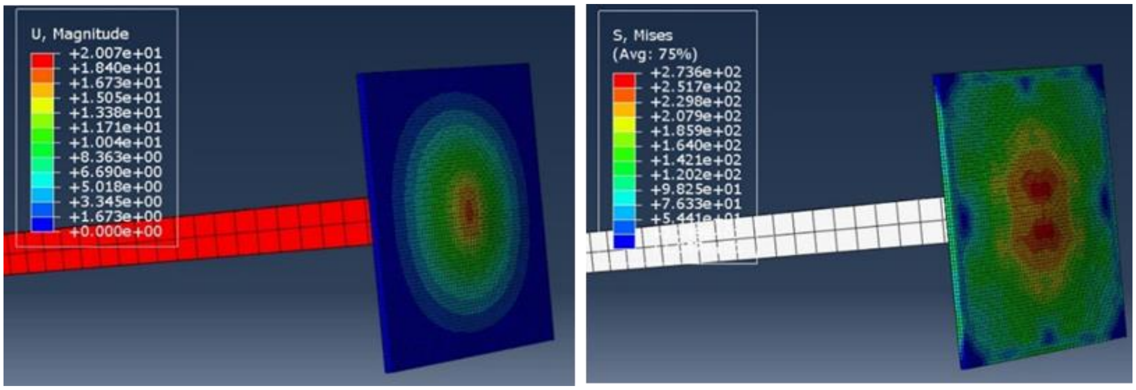

Figure 2. Maximum U, displacement, and S, stress contours of the steel plate before the rebound (Pass, Step 12 / Step 100, 64mph)

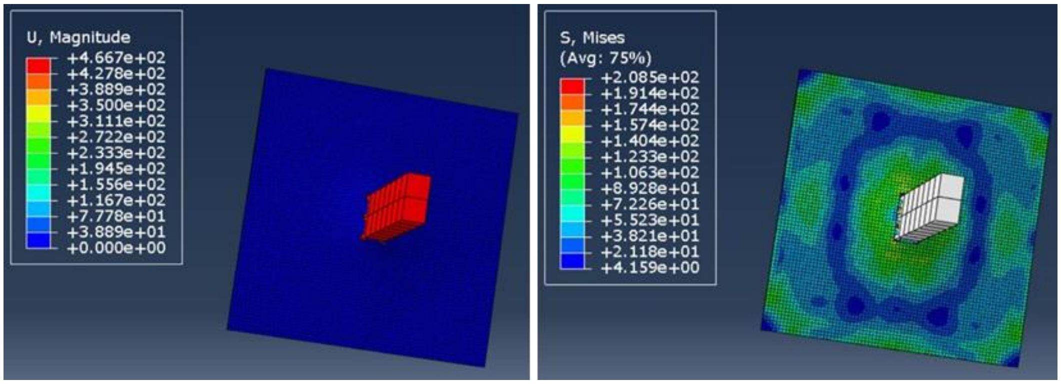

Figure 3. U, displacement, and S, stress contours of the steel plate (Fail, Step 100 / Step 100, 100mph)

3.3. CFRP Composite Sandwich Panel Model

The Area size of the composite sandwich panel is also 24x24 inches. For the brittleness of the composite panels, the FEA test results have proven its poor performance. Due to the increase in overall stiffness, the plastic deformation of the composite material is decreased, and the elastic performance is lower than the single-layer steel plate. The failure mode of the composite sandwich panel in the numerical analysis is shown in Figure 5 and Figure 6.

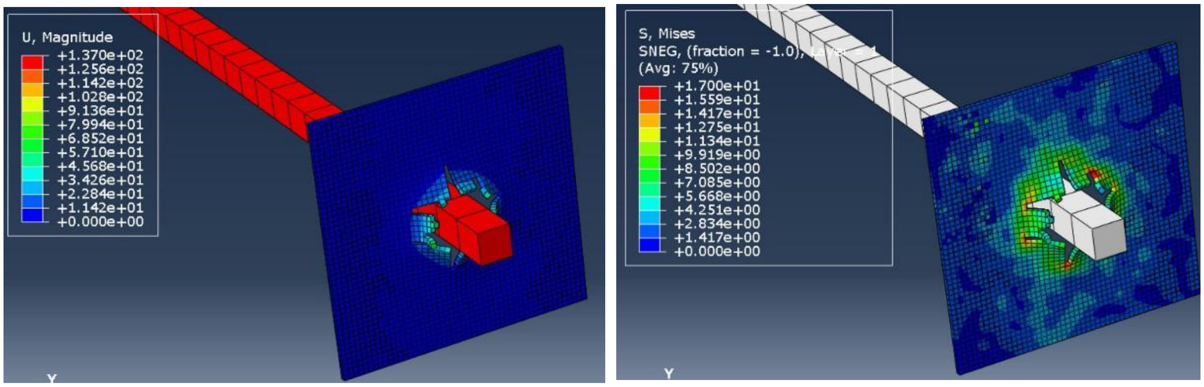

Figure 4. U, displacement, and S, stress contours of the composite sandwich panel (Fail, Step 100 / Step 100, 64mph)

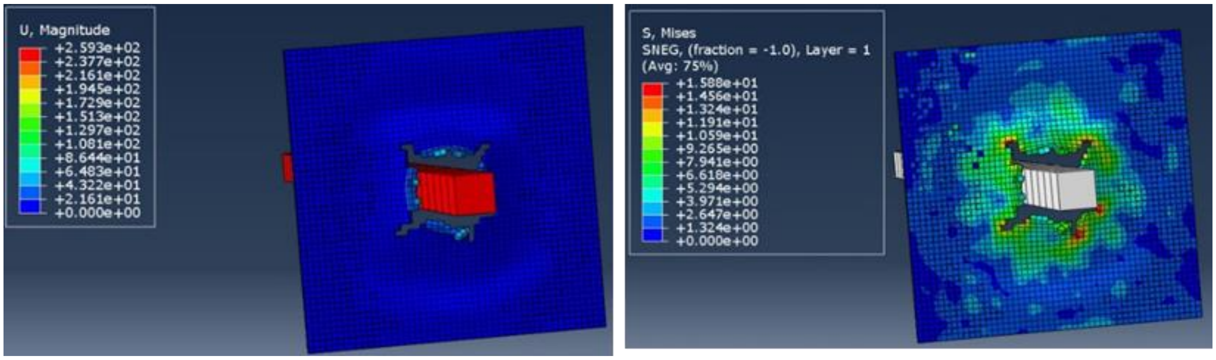

Figure 5. U, displacement, and S, stress contours of the composite sandwich panel (Fail, Step 100 / Step 100, 100mph)

4. CONCLUSION

This paper simulated finite element analysis of CFRP composite sandwich panel subjected to wind derbies impacts using Abaqus/Explicit. The FEA program Abaqus/Explicit has ideal modeling capabilities for highly dynamic non-linear applications. This study mainly observes the impact behavior of steel plates and composite sandwich panels.

The steel plate passes the impact test of the projectile at a speed of 64 mph and penetrates it at a speed of 100mph. In the former load condition, the plate reaches the maximum displacement of about 0.8 in (20mm) after step 12 (the total steps are 100) and rebounds the debris missiles. Observing the complete steps, the impact of debris causes permanent plastic deformation of the steel plate. In the latter condition, the test steel plate is failed. According to the CAE simulation, most of the contact face of the impact behavior is separated from the plate. The size of the opening is just the same as the penetration area.

The CFRP composite sandwich panel's destructive tests fully demonstrate its characteristics that are not resistant to high impacts. The bonding force of interlayers is fragile, and once delamination occurs; it causes severe damage to its overall performance. Thus, the composite panel proposed in the current test cannot support hurricane shelter or tornado shelter requirements. The strain transformation steps of the panel are also captured. According to the simulation, the missile impacted the composite panel at the center and made the panel crack from the contact surface. And the cracking areas expanded to the surrounding areas. The penetration area is larger than the steel plate.

However, more research needs to be done, and thicker panels may be needed to withstand the impact of wind debris. To avoid the penetration of composite materials under the high-energy impact, the authors in the subsequent experiments may also try other materials, metal composite material, polymer matrix composite, and other high-performance materials used in airspace, automobile, and other fields. The lab tests will be carried out in the next six months; the continuous optimization and simulation of the finite element model play a decisive role in selecting materials.

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