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Tornado Debris Impact Tests of a New Composite Storm Shelter Room System

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Abstract

A tornado shelter design that is protected by a newly developed CarbonFlex composite is proposed and its capability to withstand the tornado-borne debris impact is evaluated via a series of missile impact tests. The test results revealed that the new CarbonFlex shelter wall panel design has much more superior impact resistance than the conventional wood constructions. Two of the four CarbonFlex design groups have successfully passed the impact tests with 47.4m/s (100 mph) missile speed, which corresponds to an 111.7 m/s (250 mph) ground wind speed; and another two designs passed the tests having missile speed of 40.2 m/s (90 mph), corresponding to ground wind speed of 89.4 m/s (200 mph). While a control group that was made from carbon fiber reinforced polymer (CFRP) failed the tests at both missile speeds. The material processing parameters of CarbonFlex, the matrix thickness h_p and intermittent curing time t_c, have evident influence on its impact resistance. Generally, the impact resistance of the panel increases with smaller t_c and greater h_p.

Keywords: Debris impact; Tornado; Shelter design; CarbonFlex composite.
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Introduction

The objects and debris that are picked up and transported by the violently rotating wind are call tornado generated missiles. The objects transported by tornadoes range from roof tiles [1] to large objects like railroad cars [2]. Filed studies of tornado damage paths through and residential and light commercial areas had revealed that the most common missiles are medium size timber pranks from damaged or destroyed residential structures [2]. The tornado generated missiles can lead to significant damage to building structures in the events of high wind [1]. Although several building codes in the United States have evolved to address the issue of windborne debris impacts on buildings [3-5]. The number of studies that cover the tornado debris impact resistance has been relatively limited.

The early study conducted by McDonald [2] investigated the tornado impact resistances of nine conventional ply-wood residential wall (4 feet by 8 feet in dimension) construction and totally eleven content masonry unit (CMU) wall constructions with different grouting area, and impacted by missiles with different shapes and materials, such as wood and PVC, at several different angels. The following conclusions were drawn from MacDonald's work: (1) conventional residential wall constructions could not withstand the impact of tornado transported debris; (2) in order to stop and missile, the CMU walls must have been reinforced and grouted in each of the cells; (3) the shape of the missile end was not significant for the impact results; and (4) missile shot at 45 degree with respect to the impact face tended to bounce off without causing evident damage. A later research carried out by Herbin and Barbato [6] studied the vulnerability of building envelope components subject to windborne debris impacts from probabilistic point of view, or more specifically, fragility curves. In this study the Monte Carlo simulation is used in conjunction of finite element (FE) method, such that the uncertainty of the modeling parameters could be taken into account. Other studies have been conducted on the impact performances of particular building components, such as window glass [7], and other projectile types, such as roof tile; additionally, wood pranks have been investigated by Fernandez et al. [1].

Due to the relatively poor performances exhibited by conventional residential components in previous studies, a new wall panel system that is protected by a recently developed CarbonFlex composite is proposed in the current study; the project is funded by the Department of Homeland Security (DHS). The tornado debris impact performance of this newly proposed system is investigated through a series of debris impact tests. The results are compared against those obtained for the same design, per general code provisions by the ICC 500 (International Code Council) and FEMA 320 and 361 (Federal Emergency Management Agency), except that conventional carbon fiber reinforced polymers (or CFRPs) are used for the protective layer in lieu of CarbonFlex (and in lieu of expensive, heavy and awkward, and less effective steel plates per design code provisions). Lastly, the influences of two key material processing parameters are discussed.

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

Storm shelter wall panel systems composed of a recently developed **C**arbon-fiber **H**ybrid-polymeric **M**atrix **C**omposite (CHMC) that has been recently developed by Zhou and Attard [8], Dhiradhamvit et al. [9] and Zhou et al. [10] are designed to resist tornado impact loads. The CHMC will be herein referred as to CarbonFlex. CarbonFlex (nonprovisional patent on file, M12-023, PCT/US11/63581, and International Publication Number WO 2012/078664 A1 on "High Strength and High Elasticity Composite Materials and Methods of Reinforcing Substrates with the Same") is a carbon fiber-based composite manufactured via a new patented hybrid-matrix system involving amino-based polymeric compounds that provides necessary damping and high strength sustainability of the carbon fibrous underlying component. An earlier study by Zhou and Attard [8] indicates the enormous potential benefits of CarbonFlex used as a structural retrofitting material, to sustain the strength of an otherwise brittle carbon fiber-based composite system and to subsequently preclude catastrophic failure of structures. In the current study, CarbonFlex is used as one of the constituent layers of the newly proposed tornado shelter wall panel system, such that high tornado debris impact performance is achieved in comparison to similar storm room designs per FEMA P-320/ P-361 [3;4]. Two material processing parameters for CarbonFlex manufacturing - the matrix thickness h_p and an intermittent curing t_c, which would prominently affect the damage tolerance and material internal damping - will be analyzed to assess their potential impact on the ability of the wall panels to pass tornado impact at various speeds correlated to FEMA-regulated tornado levels (1 – 5). In addition to the CarbonFlex shelter wall panel designs, a controlling specimen group was designed and constructed using conventional carbon fiber reinforced polymer (CFRP) using the same layout and carbon fiber content as the CarbonFlex designs, in order to compare the two systems in ascertaining a viable shelter design solution using composite materials as a constituent layering system to enhance debris impact resistance for the highest-rated expectant tornado impact, level-5 tornados (250 mph ground wind speed tornados).

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 proposed herein as an alternative substitute to the conventional plywood wall shelters. The proposed CarbonFlex wall panel were designed and constructed per FEMA320/ 361 and ICC500 [3-5] specifications. Based on ICC500 [5], the size of the wall section subjected to debris impact test shall be at least 4 feet in width by 4 feet in height. In order to accommodate the dimensions of the target frame and for the ease of transportation, the wall panel specimens used in this study were designed to have a dimension of 4 feet by 4 feet, or 1219×1219 mm in metric notation. The impact test results of five series of wall panel designs are reported in this paper. The panel frames are constructed using double 2×4

(38×89mm cross section) Douglas Fir studs spaced 16 inches (or 406.4mm) apart, see Figure 1a. The exterior layers of the wall panel are two plies of 3/4 inch plywood sheets and a CarbonFlex layer (2 plies of 0.167mm thick carbon fiber orientated at 0° and 90°) starting from the impact face. And 1/2 inch thick Oriented Strand Board (or OSB) sheathing was used as the interior of the wall panels. Four types of CarbonFlex with two varying material processing parameters, which are the matrix thickness h_p and intermittent curing time t_c, were used for the wall panel construction. The detailed layout of the composite wall panels are presented in Figure 1b and 1c, and specimen numbers together with the corresponded material information, such as h_p and t_c, are listed in Table 1. The wall panel specimens were simply supported at the top and bottom to the target frame, as shown in Figure 2.

Table 1. *Material used for the wall panel specimens*

Wall number	Material on impact face	Expecting strength level (1 is highest)	Mater. Para.	
			h_p(mm)	t_c(hr)
1	CarbonFlex + 2plies of ¾" Plywood	1	5	2.5
2	CarbonFlex + 2plies of ¾" Plywood	2	5	3.5
3	CarbonFlex + 2plies of ¾" Plywood	3	3	2.5
4	CarbonFlex + 2plies of ¾" Plywood	4	3	3.5
5	CFRP + 2plies of ¾" Plywood	5	N.A.	N.A.

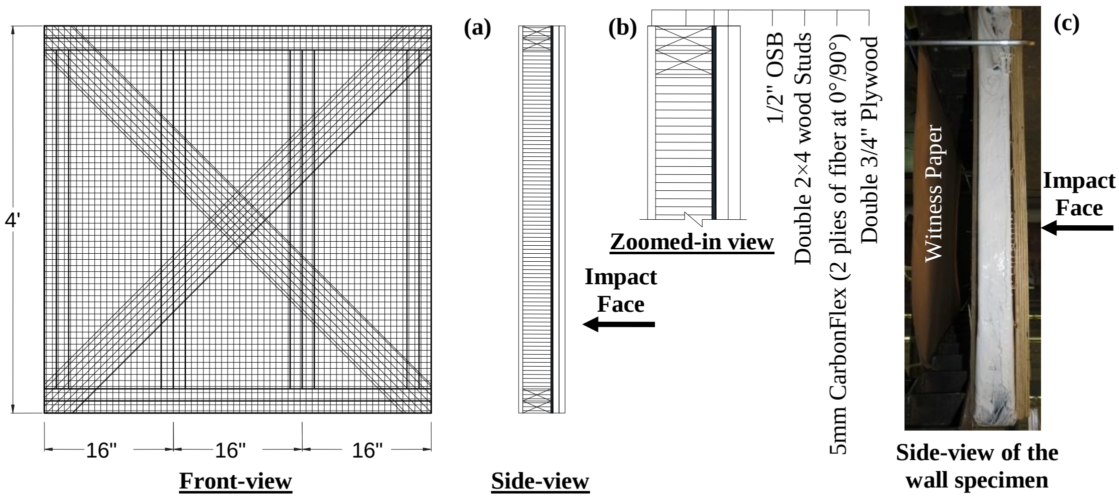


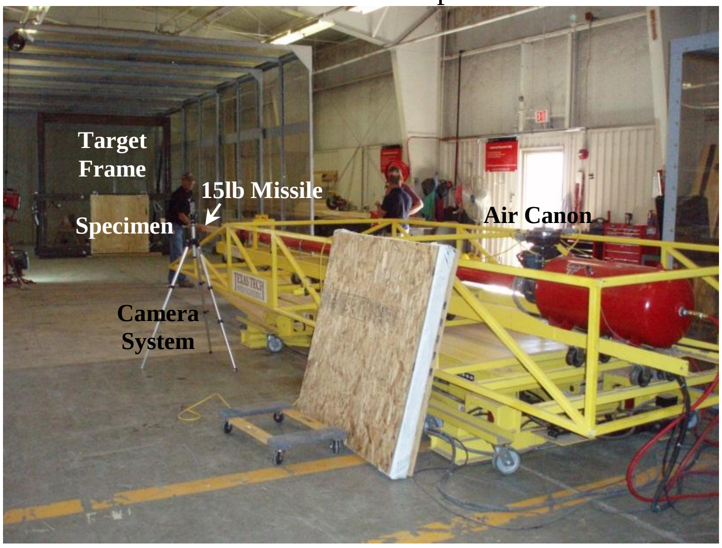
Figure 1. *The dimension and detailed layout of the wall panel impact specimens*

3.2 Experimental setup and test procedures

3.2.1. *The missile launching apparatus*

The missile impact tests were conducted at the Wind Science and Engineering Research Center (WiSE) at Texas Tech University. The missile lunching apparatus is comprised of an air-actuated cannon that is capable of propelling a medium weight missile to a speed of 67.1 m/s (150 mph). The specimens were mounted on a target frame that was placed 5.5 m (18 feet) from the end of the barrel of the cannon. Four high-speed digital cameras were used to record the impacts. The experimental setups are shown in Figure 2.

Figure 2. Experimental instrumentations and setup



3.2.2. *Properties of the projectile*

All tests were conducted according to ICC/NSSA Standard [5]. ICC500 provides thorough procedures for conducting debris impact testing, permitting most common types of softwood types of lumber having a No. 2 grade stamp or better for use as missiles. The missile must be free of splits, checks, wane, or other significant defects. The cross-section of the missile is to be that of a typical 2 by 4 lumber, i.e. 38×89mm in dimension. The wood density, including moisture content, should be such that the weight of the missile is 15 ± 0.25 pounds having a length of 13.5 feet ± 6 inches. The exact weight of the each missile was measured prior to each impact test; it was later used to calculate the kinematic energy of the missile prior to impact.

According to ICC500 [5], in order to represent flying debris during a tornado having a ground wind speed of 130 mph to 250 mph, the speed of the missile must range between 80 mph to 100 mph. The actual velocity (m/s) of each missile was measured by a laser speed device installed at the muzzle of the air cannon, see Figure 2. The correlations of tornado wind speeds and missile speeds are presented in Table 2.

Table 2. *Projectile speed for debris impact testing for tornado shelter*

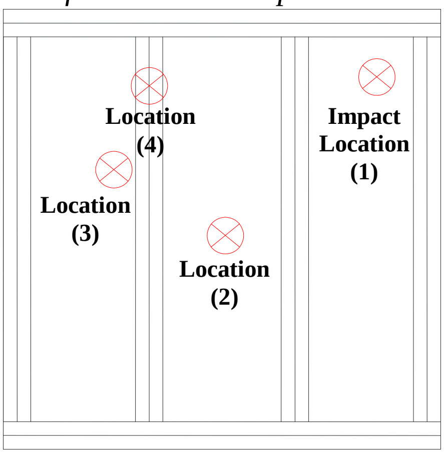
Tornado wind speed (mph*)	Corresponding missile speed (mph)
130	80
160	84
200	90
250	100

*mph = miles per hour

3.2.3. *Impact locations and failure criteria*

Four impact locations were used during testing, provided that the specimen construction includes interior studs or supports [5] as follows: (1) at the corner of the specimen within 6 inches from each edge, (2) at the center of the panel, (3) within 3 inches adjacent to the stud, and (4) directly on the stud. In this study, the 'corner' and 'adjacent to the stud' locations were considered as "shear zones", i.e., locations (1) and (3), whereas the 'center' location, i.e., location (2), were considered "bending zones," dominated by member bending.

Figure 3. *Impact locations for the debris impact test*



According to ICC500 [5], a specimen will have 'passed' its impact test per specified speed if each of the following three criteria are met:
(1) The specimen is not perforated by the missile;
(2) The interior surface of the specimen has permanent deformation less than three inches;
(3) In addition, ICC500 requires that specimens and fasteners must not become disengaged or dislodged, and spall should not be released from the interior surface of the specimen [5]. To ensure this, a witness screen made from a #70 unbleached Kraft paper is placed 5 inches from the interior surface, see Figure 1c. If any damage occurs due to disengagement/ dislodgement of the fasteners or the spalls from the specimen on the witness screen, the specimen is considered to be failed.

In this study, a expected strength was assigned to each wall, see Table 1. The wall with the highest expected strength was tested first. The impact test started with the missile speed of 100 mph, however, if the specimen failed at higher speed, the missile speed might be reduced to a lower level based on Table 2.

4. Results and discussion

4.1. Experimental results of the tornado impact tests

A total of five design categories of wall specimen were tested, and the primary results are listed in Table 3. The specimen of the first design category, i.e. specimen number 1, was impacted at four locations as described in Figure 3: the first missile, which traveled at a speed of 45.15 m/s (101 mph), created a 38.1 mm deep indentation on the impact face, see Figure 4a, and was bounced back after impact; the second missile was shot in the "bending zone" at 45.6 m/s, creating a 123.825 mm deep indentation at the impact location; and both the third and the fourth missiles, which targeted at the locations 6 inches beside the stud and directly on the stud, had created indentations about 38.1 mm deep. The first series of impacts had also caused minor nail protrusion on the interior face of the wall panel, however, the witness paper was intact and the permanent deformation is less than three inches. Thus, the first design category was considered to have passed the impact test at 100 mph missile speed, corresponding to tornados with ground wind speed of 250 mph. The specimen series 2 was shot five times at two missile speed levels. The first two impacts took place with a missile speed of 44.7 m/s (100 mph), however the missiles had perforated the specimen in both impact, see Table 3. Consequently, a lower missile speed level (40.23 m/s, or 90 mph) was used for the remaining impacts. The three missiles, travelling approximately 40 m/s, were shot to lower right corner, center, and lower left corner of the specimen producing indentation depths of 38.1 mm, 44.45 mm, and 34.93 mm, respectively, see Table 3. After these three impacts, no major damage was observed on the interior surface of the specimen, and witness paper was intact. Therefore, the design category two was considered to have passed the test for the tornados with 89.4 m/s (200 mph.) ground wind speed, however, failed at the ground wind speed of 111 m/s (250 mph).

Specimen series 3, which was made of a thinner CarbonFlex (i.e., h_p = 3 mm), was shot at by three missiles traveling at 44.7 m/s (100 mph). The missiles impacted the left corner, middle, and top right corner of the wall creating indents of 38.1 mm, 38.1 mm, and 57.15 mm deep, respectively. The witness screen was not damaged even though minor fasteners protruded from the interior surface. The specimen series 4, which has a lower strength expectation than series 2, was impacted with missiles having speed of approximately 40 m/s (90 mph). The missiles, targeting at the location (1), (2), and (3) as described in Figure 3, created indents of 88.9 mm, 28.58 mm, and 30.16 mm deep, respectively. No major damage was observed on the interior OSB face of the specimen, thus, the specimen series 4 was considered had passed the test with 89.4 m/s (200 mph) ground wind speed.

Specimen series 5 was deemed a control group, made of conventional carbon fiber reinforced polymer, or CFRP, and in contrast to the CarbonFlex designs, in order to investigate the benefits of CarbonFlex to resist impact loads over CFRP. The specimen was shot three times having missile speeds of 45.6 m/s, 44.7 m/s, and 40.68 m/s (102, 100, and 91 mph). The first and third impacts perforated the specimen; severe damages can be observed on the interior surface, and the witness paper had completely ripped. Since the CFRP wall panel had been perforated at both missile speeds, i.e. 44.7 m/s (100 mph) and 40.23 m/s (90 mph), it was considered to have failed the tests with both 111.6 m/s (250 mph) and 89.4 m/s (200 mph) ground wind speeds. Specimen series 5, after impacts, is presented in Figure 5, where severe damage is observed on the interior surface, see Figure 5a. The panel was perforated by the missile up to 152.4 mm measured from the interior OSB surface, as shown in Figure 5b.

Table 3. *Experimental results of the impact tests*

Panel #	Mater.	Impact No.	hp (mm)	tc (hrs.)	Projectile Speed (m/s)	Indentation (mm)	Impact Energy (*J*)
1	CarbonFlex	1	5	2.5	45.15	38.1	6935.22
	CarbonFlex	2	5	2.5	45.60	123.8	7073.23
	CarbonFlex	3	5	2.5	45.15	38.1	6935.22
	CarbonFlex	4	5	2.5	45.15	28.6	6935.22
2	CarbonFlex	5	5	3.5	44.70	152.4 mm perforation measure from the back	6798.57
	CarbonFlex	6	5	3.5	44.70	63.5 mm perforation measure from the back	6798.57
	CarbonFlex	7	5	3.5	40.23	38.1	5506.84
	CarbonFlex	8	5	3.5	40.68	44.5	5629.89
	CarbonFlex	9	5	3.5	41.13	34.9	5754.31
3	CarbonFlex	10	3	2.5	44.70	38.1	6798.57
	CarbonFlex	11	3	2.5	44.70	38.1	6798.57
	CarbonFlex	12	3	2.5	44.70	57.2	6798.57
4	CarbonFlex	18	3	3.5	39.79	88.9	5385.15
	CarbonFlex	19	3	3.5	40.23	28.6	5506.84
	CarbonFlex	20	3	3.5	41.13	30.2	5754.31
5	CFRP	21	No	No	45.60	396.9	7073.23
		22	No	No	44.70	54.0	6798.57
		23	No	No	40.68	714.4	5629.89

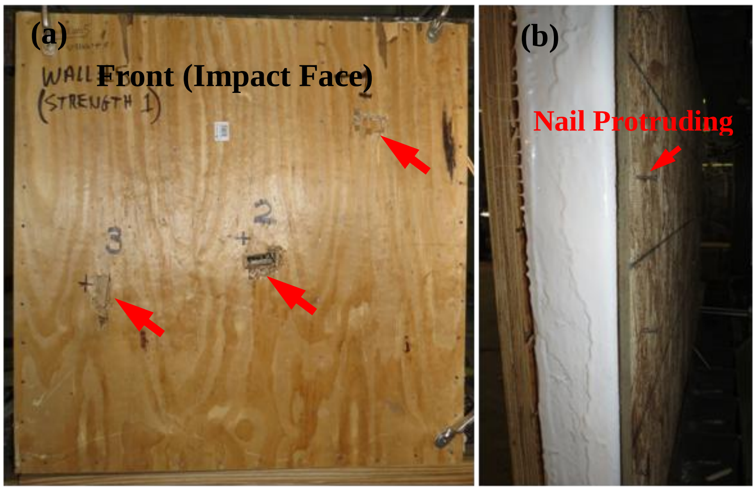


Figure 4. *The CarbonFlex wall panel #1 after test: (a) the indented impact face; (b) back of the specimen was largely intact except for minor nail protruding*

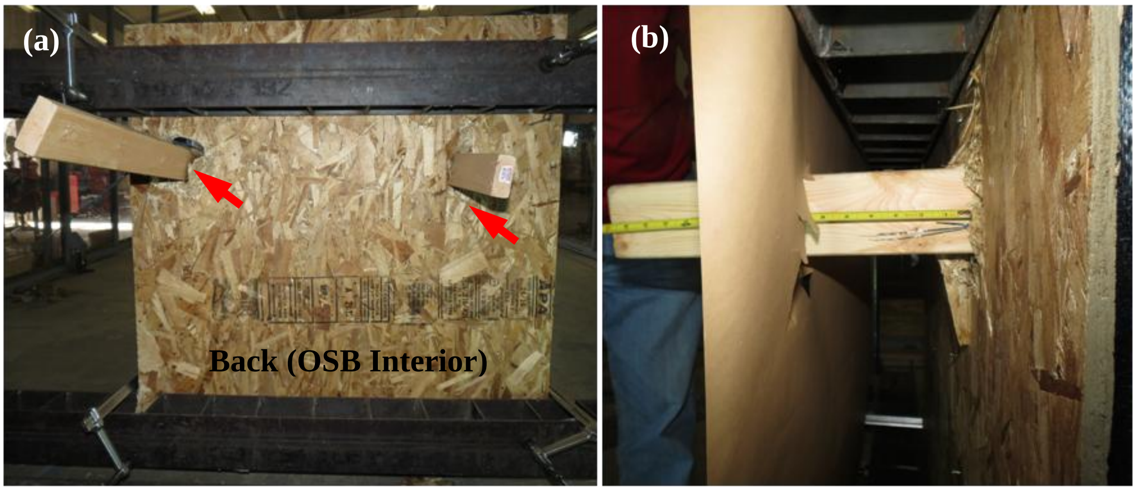
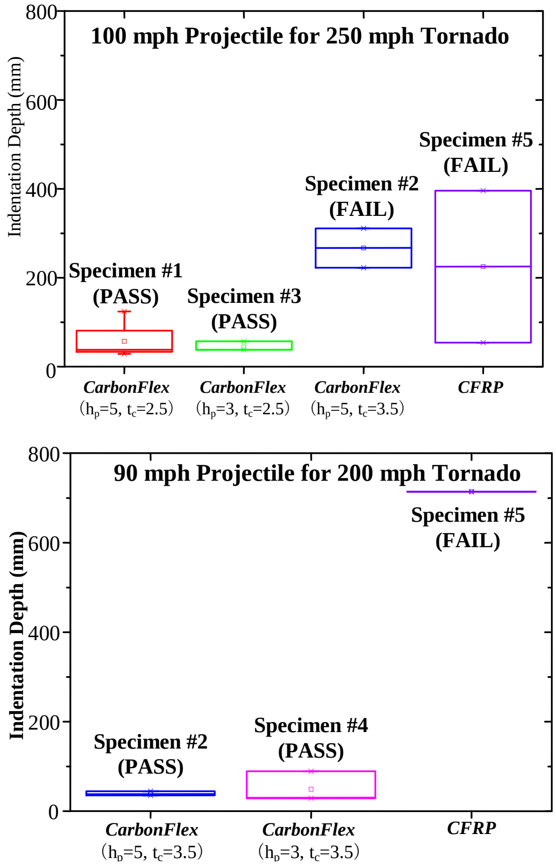


Figure 5. *The CFRP wall panel #5 after test: (a) the back face of the perforated wall specimen; (b) the perforated specimen with damaged witness screen (side view)*

4.2. The influences of the material processing parameters h_p and t_c

The material processing parameters h_p and t_c contribute significantly to the internal damping and damage tolerance, which thus, prominently affect the ability of the shelter wall panels to withstand the debris impact. Figure 6 plots the indentation depths versus the material types used for the wall panel construction. It is evident from the comparison that CarbonFlex, in general, has superior impact resistance over conventional CFRP. Wall panels constructed with CFRP failed at both wind speed levels of 111.7 m/s (250 mph) and 89.4 m/s (200 mph) with average indentation depths of 225.5 mm and 714.4 mm, respectively. On the other hand, the wall panels constructed with Type I CarbonFlex (h_p=5 mm, t_c = 2.5 hr.) has an average indentation depth of 57.2 mm when subjected to speeds of 44.7 m/s (100 mph) and debris impact; interestingly, the panels made from Type III CarbonFlex (h_p=3 mm, t_c = 2.5 hr.) had an average indentation depth of 44.5 mm under the same missile speed, indicating that the energy dissipation ability of the CarbonFlex material is highly dependent on the chemical processing cure times of the various constituents used to manufacture the composite. As a result, panels constructed using Type II CarbonFlex (h_p=5 mm, t_c = 3.5 hr.) failed the 44.7 m/s (100 mph) debris impact test showing an average indentation depth of 266.8 mm; however, these panels did pass the 40.23 m/s (90 mph) tests showing an average indentation depth of 39.2 mm. The panel designed with Type IV CarbonFlex, which was expected to exhibit a lower impact resistance than the Type II system, resulted in an average indentation depth of 49.2 mm at a missile speed of 40.23 m/s (90 mph). The results generally match the strength expectations as listed in Table 1, which indicates a correlation between the impact resistance and the two material process parameters h_p and t_c. Generally, the impact resistance ability tends to increase in panels having lower values of t_c and greater values of h_p although the benefit of larger values of h_p appears to not be nearly as significant as that of having lower values of t_c.

Figure 6. *The indentation depth vs. material type used for the wall panel construction*



Moreover, the kinetic energy of the missile from each shot was calculated using equation 1; the results are summarized in Table 3:

$$E = 1/2mv^2 \qquad (1)$$

where, *E* is kinetic energy (J), *m* is a mass of the missile (kg), and *v* is the velocity (m/s). By comparing the results from specimen series 3 to those of specimen series 4, energy absorption of the wall was increased 26.2% by reducing t_c. The energy absorption capacity of the wall panels remains essentially identical even after increasing the value of the parameter h_p. This might serve as evidence to support the notion that t_c has a significantly greater influence to energy dissipation capability of the panel system than h_p.

5. Conclusions

Two of the newly proposed CarbonFlex tornado panel designs successfully passed the debris impact having a missile speed of 44.7 m/s (100 mph), corresponding to the ground wind speed of 111.7 m/s (250 mph), i.e., level-5 tornado, showing significant merit over conventionally designed plywood residential walls. A comparison between the wall panels constructed with CarbonFlex and CFRP indicates superior impact resistance of the CarbonFlex composite due to it high internal damping. In addition, the material processing parameters of CarbonFlex, h_p and t_c, have evident influences on the impact resistances of the panels after affecting and material damping and damage tolerance of the CarbonFlex composite.

Reference List

Fernandez G, Masters FJ, Gurley KR. Performance of hurricane shutters under impact by roof tiles. Eng Struct 2010;32(3384):3393.

McDonald JR. Impact resistance of common building materials to tornado missiles. J Wind Eng Ind Aerodyn 1990;36:717-24.

FEMA P-320. Taking shelter from the storm: building a safe room for your home or small business. Washington DC: **Federal Emergency Management Agency**; 2008.

FEMA P-361. Design and construction guidance for community safe rooms. Washington DC: Federal Emergency Management Agency; 2008.

ICC500. NSSA standard for the design and construction of storm shelters. International Code Concil, & National Storm Shelter Association; 2008.

Herbin AH, Barbato M. Fragility curves for building envelope components subject to windborne debris impact. J Wind Eng Ind Aerodyn 2012;107-108:285-98.

Masters FJ, Gurley KR, Shah N, Fernandez G. The vulnerability of residential window glass to lightweight windborne debris. Eng Struct 2010;32:911-21.

Zhou H, Attard TL. Rehabilitation and strength sustainability of fatigue damaged concrete-encased steel flexural members using a newly developed polymeric carbon-fiber composite. Comp Part B: Eng 2013;45:1091-103.

Dhiradhamvit K, Attard TL, Zhou H. Development of a new lightweight "Rubberized-Carbon" composite for wood home protection. 2011 Jun 20; Athens, Greece 2011.

Zhou H, Attard TL, Zhao B, Yu J, Lu W, Tong L. Experimental study of retrofitted reinforced concrete shear wall and concrete-encased steel girders using a new CarbonFlex composite for damage stabilization. Eng Fail Anal 2013.