

Appendix K:
Guidance for Selection of Impact Resistant Constructed Wall and Roof Assemblies

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K.0 STRUCTURAL MISSILE IMPACT CRITERIA

The public shelter design criteria, which are also known as the EHPA criteria, require that exterior walls and roofs prevent perforation or penetration by windborne debris. Laboratory testing is the primary means of determining if a specific assembly (i.e., exterior and interior surface cladding, structural components and configurations, material properties, connections, etc.) is capable of satisfying the applicable performance criteria. Certain types of commonly used non-proprietary materials and constructed assemblies have been demonstrated through laboratory testing to satisfy the required debris impact performance criteria. Constructed assemblies that are approved for use without further testing by the authority having jurisdiction are commonly referred to as “deemed to comply.” The deemed to comply method is recognized in section 1626.4, FBC—Building. Appendix K has been prepared to assist designers with selection of constructed wall and roof assemblies that have been tested and satisfy applicable large missile impact criteria.

K.1 METHODOLOGY

To begin the assembly selection process, it is critical to determine the design wind velocity of the EHPA. Higher windfield velocities impart higher velocities to entrained debris. Higher wind velocities can also lift and accelerate larger and heavier debris objects, as well as extend the distance downwind that an object can travel. As a planning guide, unanchored or inadequately or poorly constructed large debris can be generated from sources within a distance of about 300 feet of proposed or constructed EHPA(s). Smaller debris down to the size of gravel can be generated from sources out to a range of possibly 1,500 feet. Current research being considered by the ICC storm shelter standard committee indicates that objects lifted by wind forces undergo rapid acceleration and achieve velocities of between 40 and 80 percent of the entraining windfield’s velocity. Thus the lower bound for representative missiles require test velocities of at least 40 percent of the proposed design wind speed.

The industry-recognized straight wind (which include hurricane) large missile that is used for impact testing is a nine pound sawn lumber 2x4 (9 lb 2x4). The industry-recognized 9 lb 2x4 large missile is also the missile required to satisfy the EHPA code provisions. For those school districts that are interested in incorporating tornado protection into an EHPA construction project, national guidance currently recommends that the large missile be increased to a fifteen pound sawn lumber 2x4 (15 lb 2x4). For those proposed EHPA’s that may be subjected to an unusual barrage of heavy debris (e.g., building materials and mechanical equipment) the Division recommends increasing the large missile requirement to a 15 lb 2x4.

Debris impact testing of wall and roof assemblies has generally been conducted using a limited number of specified conditions (e.g., 9 and 15 lb 2x4s propelled at 34, 50,

75 and 100 miles per hour). Many of the more robust materials and assemblies, such as reinforced concrete and solid-grouted masonry, have satisfied test requirements that are significantly more demanding than the EHPA code-required SSTD 12. Another factor considered by the Division is that current research indicates that an object's impact momentum, and not energy, provides the best correlation of test performance of a specified assembly when comparing missiles of different weights and velocities. Calculating the momentum associated with a published sample's impact test conditions permits the data to be converted to the industry standard straight wind 9 lb 2x4 missile. Impact momentum is calculated as follows: missile weight (lb) / acceleration of gravity (32.2 ft/sec²) x missile velocity (ft/sec) = momentum (lb-sec). It should be noted that Tables K-1 and K-2 provide impact energy equivalent values as well as momentum values to assist with conversion when the impact energy of a test is known, but momentum is not calculated.

The following reference data sources were used to compile the list of assemblies given in Table K-3. Windborne Debris Impact Resistant Wall Assemblies, and Table K-4. Windborne Debris Impact Resistant Roof Assemblies:

1. *Large Wind Missile Impact Performance of Public and Commercial Building Assemblies*, Florida Agricultural and Mechanical University-Florida State University (FAMU-FSU) in cooperation with the University of Florida (UF), 2004
2. *Summary Report on Debris Impact Testing at Texas Tech University*, Texas Tech University (TTU), 2003
3. *Design and Construction Guidance for Community Shelters* (FEMA 361), Federal Emergency Management Agency, 2000

These reference sources can provide additional guidance on selection of suitable wall and roof assemblies for both hurricane and tornado shelters.

To match the existing data sources test conditions with a practical range of corresponding design wind speeds, the Division consolidated the data into categories defined as "Levels of Protection." The test performance required to satisfy each level of protection category is bounded by the respective category's highest hurricane design wind speed. As an example, Enhanced-B's design wind speed range is 165 to 200 miles per hour (mph), therefore the assembly must satisfy a laboratory missile test equal to a 9 lb 2x4 propelled at 80 mph ($200 \times 0.40 = 80$).

The lowest level of protection, which is referred to by the Division as "Basic-D," is equal to the large missile test requirements of SSTD 12 and ASTM E 1996 Missile Level D (i.e., 9 lb 2x4 propelled at 34 mph). Basic-D is the minimum code requirement for EHPA walls and roofs. ASTM E 1996 also establishes an "Enhanced Protection" requirement for essential facilities, which includes designated hurricane shelters. ASTM E 1996's enhanced missile is defined as Missile Level E and increases the test velocity of the 9 lb 2x4 to 50 mph. For the purposes of this appendix, ASTM E 1996's Missile Level

E is referred to as “Basic-E.” The reference sources used by the Division for preparation of this appendix do not provide test data specific to ASTM E 1996’s Missile Level E.

The Division’s Enhanced-A level of protection corresponds to design wind speeds of 130 to 160 mph (3-second gust), which is consistent with the EHPA criteria’s recommended addition of the 40 mph for EHPA’s proposed to be located in ASTM E-1996’s Wind Zones 1 and 2 (i.e., basic wind speeds < 130 mph). ASTM E 1996’s Wind Zones 1 and 2 do not normally require “Missile Level E” (as defined by ASTM E 1996), so the 130 to 160 mph range serves as a convenient wind speed range for the Division’s lowest level of protection category (i.e., “Enhanced-A”). The Enhanced-B level of protection corresponds to design wind speeds of 165 to 200 mph, which is consistent with the EHPA criteria’s recommended addition of the 40 mph for EHPA’s proposed to be located in ASTM E-1996’s Wind Zones 3 and 4 (i.e., basic wind speeds \geq 130 mph). The Enhanced-B missile requirement is equal to a 9 lb 2x4 propelled at 80 mph. Conveniently, the 9 lb 2x4 propelled at 80 mph test missile has approximately the same impact momentum as the Department of Energy’s recommended straight wind missile criteria, which is a 15 lb 2x4 propelled at 50 mph (15 lb 2x4 @ 50 mph). The 15 lb 2x4 @ 50 mph is a commonly used test so there are several wall and roof assemblies that have been demonstrated to satisfy its performance requirements.

The Enhanced-C level of protection exceeds the EHPA’s design wind speed range, but is consistent with hurricane design wind speeds of 205 to 250 mph. Design wind speeds in this range are consistent with a Saffir-Simpson Scale hurricane Category 5 and are provided for comparison purposes only. Enhanced-D and Enhanced-E levels of protection are consistent with tornado missile test criteria established in FEMA 361 and other national guidance publications for F2 and F3 tornadoes respectively.

It should be noted that Tables K-1 and K-3 provide criteria for exterior envelope vertical surfaces, such as walls. Exterior envelope surfaces that are inclined less than 30 degrees from horizontal are considered horizontal surfaces, and Tables K-2 and K-4 apply. For the purposes of this appendix, the missile velocity requirement for horizontal surfaces is assumed to be 67 percent of that required for the respective vertical surface. This is consistent with tornado missile test criteria found in FEMA 361 and other national guidance publications. This is conservative since hurricane missile requirements for horizontal surfaces may only be 25 percent of that required for vertical surfaces, but negligible data is available for such low impact criteria. Also, weak to moderate tornadoes and other isolated wind disturbances can be embedded in hurricanes, which can cause severe local impacts. Therefore, the use of the tornado missile requirement for horizontal surfaces of hurricane shelters is not exceptionally conservative.

K.2 SELECTION OF WALL OR ROOF ASSEMBLIES

With the type of wind event (straight or tornado wind) and design wind speed established, the designer or specifying authority can select an appropriate windborne debris impact level of protection that best suits performance expectations. The levels of protection categories simplify the selection of appropriate wall and roof assemblies to

match the EHPA's design wind speed. As an example, for an EHPA with a hurricane design wind speed of 140 mph the representative missile's lower bound velocity is equal to 40 percent of the design wind speed, or 56 mph ($140 \times 0.40 = 56$). Instead of searching for test results specific to a 9 lb 2x4 propelled at 56 mph (9 lb 2x4 @ 56 mph), the designer or specifying authority can select the level of protection applicable to 140 mph from Table K-1 (for vertical surfaces), which is an "Enhanced-A" level of protection; i.e., design wind speed between 130 and 160 mph. The Enhanced-A determination will also concurrently apply to the building's horizontal surfaces, such as roofs.

There is insufficient data available to establish a stand-alone Basic-E level of protection category. Therefore, in the absence of specific tests performed to satisfy Basic-E, the Division recommends use of the Enhanced-A level of protection category for design wind speeds that are less than 130 mph.

With the level of protection determined for both vertical and horizontal surfaces, the designer or specifying authority then selects a wall and roof assembly from Tables K-3 and K-4, respectively, that satisfies the minimum required impact momentum resistance criteria. Tables K-3 and K-4 provide the following information:

Column 1 (left-most column) – A wall/roof number for reference purposes

Column 2 – Assembly Type, such as wood, metal, CMU/masonry, reinforced concrete, etc; light wood and metal stud framing is included under wood assembly type, and brick masonry over sheathing material and light wood or metal framing is also included under wood assembly type

Column 3 – Assembly description, which includes inside and outside sheathing materials (if any) and nominal dimensions, reinforcement and connections as applicable

Column 4 – Data source, which can be used as reference for additional information; the data sources are:

1. *Large Wind Missile Impact Performance of Public and Commercial Building Assemblies*, Florida Agricultural and Mechanical University-Florida State University (FAMU-FSU) in cooperation with the University of Florida (UF), 2004
2. *Summary Report on Debris Impact Testing at Texas Tech University*, Texas Tech University (TTU), 2003
3. *Design and Construction Guidance for Community Shelters* (FEMA 361), Federal Emergency Management Agency, 2000

Column 5 – Level of Protection, which is subdivided into Basic-D (9 lb 2x4 @ 34 mph) and Enhanced-A (9 lb 2x4 @ 65 mph) through Enhanced-D/Tornado F2 (15 lb 2x4 @ 85 mph); Column 5 also lists the respective impact momentum associated with each level of protection

Under the listed levels of protection in Column 5, the specified test performance results are given as “Satisfied the Test Criteria” (S); “Failed the Test Criteria” (F); or “No Data/Not Determined” (ND). For assemblies that fail at a given level of protection, the higher performance requirements are listed as “---.”

All dimensions are subject to conventional industry tolerances unless noted otherwise. The order of materials given in each assembly description is listed from the outside/outer most surface material (opposite the occupied shelter space), then inwards toward the inside finish surface material (if any). The missile impact is assumed to be on the outside surface. The order of installation is important, since some of the assemblies rely on flexure to absorb the impact forces (e.g., for wall #7, the 14 ga. expanded steel sheeting must be located between the double 2x4 wood stud supports on the inside of the assembly, and the two layers of 3/4 inch plywood must be located at the outer most surface).

Tables K-3 and K-4 provide nominal reinforcement and connection information. The building designer of record is responsible for determining all design loads and specifying all structural elements and connections in accordance with applicable material design standards, codes, rules, regulations and manufacturer’s instructions. The Division strongly recommends that design wind pressures for components and cladding be calculated with directionality factor (K_d) = 1.0 and wind exposure category = C.

Table K-1. Windborne Debris Impact Criteria Comparisons for Vertical Surfaces

Level of Protection, Vertical Surface	Hurricane Design Wind Speed, mph (3-sec. gust)	Missile Weight, lbs	Missile Velocity, mph	Missile Velocity, ft/sec	Energy, ft-lb	Momentum, lb-sec
Basic-D	85 or less	9	34	50	349	14
Basic-E	90-125	9	50	74	765	21
Enhanced-A	130-160	9	55	80	894	22
Enhanced-A	130-160	9	60	88	1,082	25
Enhanced-A*	130-160	9	65	95	1,261	27
Enhanced-B	165-200	9	70	103	1,483	29
Enhanced-B	165-200	9	75	110	1,691	31
Enhanced-B*	165-200	9	80	117	1,913	33
Enhanced-C	205-250	9	85	125	2,184	35
Enhanced-C	205-250	9	90	132	2,435	37
Enhanced-C	205-250	9	95	139	2,700	39
Enhanced-C*	205-250	9	100	147	3,020	41
Enhanced-B	165-200	15	50	74	1,275	34
Enhanced-C	205-250	15	55	80	1,491	37
Enhanced-C	205-250	15	60	88	1,804	41
Enhanced-D*	F2 Tornado	15	85	125	3,639	58
Enhanced-E*	F3 Tornado	15	100	147	5,033	68

*-Denotes missile impact criteria (weight and velocity) selected to represent the specified protection type

Table K-2. Windborne Debris Impact Criteria Comparisons for Horizontal Surfaces

Level of Protection, Horizontal Surface**	Hurricane Design Wind Speed, mph (3-sec. gust)	Missile Weight, lbs	Missile Velocity, mph	Missile Velocity, ft/sec	Energy, ft-lb	Momentum, lb-sec
Basic-D***	85 or less	9	23	34	162	10
Basic-E***	90-125	9	33	48	322	13
Enhanced-A	130-160	9	37	54	408	15
Enhanced-A	130-160	9	40	57	454	16
Enhanced-A*	130-160	9	44	65	590	18
Enhanced-B	165-200	9	47	69	665	19
Enhanced-B	165-200	9	50	74	765	21
Enhanced-B*	165-200	9	54	79	872	22
Enhanced-C	205-250	9	57	84	986	23
Enhanced-C	205-250	9	60	88	1,082	25
Enhanced-C	205-250	9	64	94	1,235	26
Enhanced-C*	205-250	9	67	98	1,342	27
Enhanced-B	165-200	15	33	48	537	22
Enhanced-C	205-250	15	37	54	679	25
Enhanced-C	205-250	15	40	57	757	27
Enhanced-D*	F2 Tornado	15	57	84	1,643	39
Enhanced-E*	F3 Tornado	15	67	98	2,237	46

*-Denotes missile impact criteria (weight and velocity) selected to represent the specified protection type.

**-Horizontal surface impact loading velocity is based on tornado factor of 0.67 of vertical surface velocity.

***-SSTD 12, ASTM E 1996 and the structural requirements of Section 423.25.4, FBC do not permit a reduction in missile test velocity due to an assembly's horizontal surface condition.

Table K-3. Windborne Debris Impact Resistant Wall Assemblies

Wall No.	Assembly Type	Assembly Description	Data Source	Level of Protection					
				Basic D	Enhanced A	Enhanced B	Enhanced C	Enhanced D	
				Minimum Required Impact Momentum Resistance, lb-sec					
				14	27	33	41	58	
1	Wood	One layer 1/2 inch CD grade plywood on metal or 2"x4" wood studs	1	F	---	---	---	---	
2	Wood	Stucco veneer on one layer 1/2 inch CD grade plywood, OSB, GWB or rigid insulation on metal or 2"x4" wood studs	1	F	---	---	---	---	
3	Wood	One layer 3/4 inch CD grade plywood on double 2"x4" wood studs (4" x4")	2	S	F	---	---	---	
4	Wood	Two layers 3/4 inch CD grade plywood on double 2"x4" wood studs (4" x4")	2	S	S	F	---	---	
5	Wood	One layer 1/2 inch CD grade plywood with masonite siding on 2"x4" wood studs	2	ND	ND	F	---	---	
6	Wood	One layer 1/2 inch CD grade plywood with 5/16 inch hardboard siding, metal or 2"x4" wood studs	1	F	---	---	---	---	

7	Wood	Two layers 3/4 inch CD grade plywood, 14 ga. sheet steel liner and double 2"x4" wood studs (4"x4")	2	S	S	S	S	S	S
8	Wood	4 inch brick veneer, 1/2 inch CD grade plywood sheathing and 2"x4" wood studs at 24 in oc	1	S	S	F	---	---	---
9	Wood	4 inch brick veneer, 7/16 inch OSB sheathing on 2"x4" wood studs at 24 in oc	1	S	S	F	---	---	---
10	Wood	24 ga. or 26 ga. galv. metal siding on 1/2 inch CD grade plywood and 2"x4" wood stud	1	S	F	---	---	---	---
11	Wood	24 ga. or 26 ga. galv. metal siding on 7/16 inch OSB and 2"x4" wood stud	1	S	F	---	---	---	---
12	Metal	24 ga. or 26 ga. (50 ksi) galv. metal panels on Z 8.25, 14 ga. girts @ 5 feet oc	1	S	ND	ND	ND	ND	ND
13	Metal	24 ga. (50 ksi) galv. metal panels on Z 8.0, 16 ga. girts @ 3 feet oc	1	S	S	S	S	ND	ND
14	Metal	24 ga. (80 ksi) galv. metal panels on Z 8.0, 16 ga. girts @ 3 feet oc	1	S	S	S	S	ND	ND
15	Metal	20 ga. or 22 ga. (50 ksi) metal panels on Z 8.25, 16 ga. girts @ 3 feet oc	1	S	S	S	S	ND	ND
16	CMU	8, 10 and 12 inch hollow cell CMU with #4 or larger rebar vertical reinforcement in grout filled cells as required for wind design; truss-type horizontal reinforcement in joints @ 16 inches oc	1,2	S	F	---	---	---	---

17	CMU	8 inch structural pea-gravel grout filled CMU reinforced with #4 or larger rebar as required for wind design; truss-type horizontal reinforcement in joints @ 16 inches oc	2	S	S	S	S	S	S	ND
18	CMU	4 inch brick veneer with 8, 10 or 12 inch hollow cell CMU back-up reinforced with #4 or larger rebar as required for wind design; truss-type horizontal reinforcement in joints @ 16 inches oc	1	S	S	ND	ND	ND	ND	ND
19	CMU	6 inch structural pea-gravel grout filled CMU reinforced with #4 or larger rebar in every cell; truss-type horizontal reinforcement in joints @ 16 inches oc	2,3	S	S	S	S	S	S	S
20	CMU	8, 10 or 12 inch structural pea-gravel grout filled CMU reinforced with #4 or larger rebar in every cell; truss-type horizontal reinforcement in joints @ 16 inches oc	2,3	S	S	S	S	S	S	S
21	RC	2 inch pea-gravel concrete with #4 rebar at 12 inches oc each way	2	S	F	---	---	---	---	---
22	RC	3 inch pea-gravel concrete with #4 rebar at 12 inches oc each way	2	S	S	S	S	S	S	S
23	RC	4 inch to 6 inch pea-gravel concrete reinforced with #4 rebar at 12 inches oc each way	2	S	S	S	S	S	S	S

24	RC	5 inch pea-gravel concrete tilt-up wall panel reinforced with #5 rebar at 12 inches oc longitudinal and #3 rebar at 12 inches oc temperature reinforcement	1	S	S	ND	ND	ND
25	RC	6 inch pea-gravel concrete panel reinforced with #4 rebar at 12 inches oc each way	2,3	S	S	S	S	S
26	RC	6 inch pea-gravel concrete panel reinforced with #4 rebar at 24 inches oc each way	2	S	S	S	S	S
27	RC	8 inch to 10 inch pea-gravel concrete reinforced with #4 rebar at 12 inches oc each way, placed 1-1/2 inches from each face	2	S	S	S	S	S
28	RC	11 inch brick cavity masonry wall with cavity filled with pea-gravel concrete and reinforced with #4 rebar at 12 inches oc each way	2	S	S	S	S	S
29	ICF	6 inch (or thicker) ICF wall panels with concrete at least 4 inches thick and reinforced with #4 rebar at 12 inches oc each way	1,2	S	S	S	S	ND
30	ICF	6 inch (or thicker) ICF waffle-grid wall section reinforced with #5 rebar every 12 inches vertically and #4 rebar every 16 inches horizontally	1,2	S	S	S	S	ND
31	AAC	8x8x24 Autoclaved Aerated Concrete wall panel	1	S	F	---	---	---

S = Satisfied the Test Criteria

F = Failed the Test Criteria

ND = No Data/Not Determined

Table K-4. Windborne Debris Impact Resistant Roof Assemblies

Roof No.	Assembly Type	Assembly Description	Data Source	Level of Protection				
				Basic D	Enhanced A	Enhanced B	Enhanced C	Enhanced D
				Minimum Required Impact Momentum Resistance, lb-sec				
				10	18	22	27	39
1	Wood	One layer 1/2 inch CD grade plywood or 7/16 inch OSB on metal or wood joist or truss with wood, clay or asphalt shingle roof cover	1	F	---	---	---	---
2	Wood	One layer 19/32 inch or thicker CD grade plywood on metal or wood joist or truss with wood, clay or asphalt shingle roof cover	1	S	F	---	---	---
3	Wood	24 ga. or 26 ga. galv. metal roof cover on 1/2 inch or thicker CD grade plywood on metal or wood joist or truss	1	S	ND	ND	ND	F
4	Metal	24 ga. or 26 ga. (50 ksi) galv. metal panels on 16 ga. purlins @ 2 feet oc	1	S	S	S	ND	ND
5	Metal	20 ga. or 22 ga. (50 ksi) metal panels on Z 8.25, 16 ga. purlins @ 2 feet oc	1	S	S	S	ND	ND
6	Metal	1-1/2 inch 20 ga. or 22 ga. Type B, Grade 33 structural metal deck over Z 8.25 girt supports @ 5 feet oc with 26 ga. galv. metal roof cover	1	S	S	S	S	S

7	Metal	1-1/2 inch 20 ga. or 22 ga. Type B, Grade 33 structural metal deck over supports @ 4 feet oc with 26 ga. galv. metal roof cover	1	S	S	S	S	S	S	S
8	Metal	3 inch 22 ga. structural metal deck	1	S	S	S	S	S	S	F
9	RC	CIP 2 inch pea-gravel concrete with #4 rebar at 12 inches oc each way	2	S	S	S	F	---	---	---
10	RC	CIP 3 inch pea-gravel concrete with #4 rebar at 12 inches oc each way	2	S	S	S	S	S	S	S
11	RC	CIP 4 inch to 6 inch pea-gravel concrete reinforced with #4 rebar at 12 inches oc each way	2	S	S	S	S	S	S	S
12	RC	CIP 8 inch to 10 inch pea-gravel concrete reinforced with #4 rebar at 12 inches oc each way, placed 1-1/2 inches from each face	2	S	S	S	S	S	S	S
13	RC	4 inch or thicker concrete panel reinforced with #4 rebar at 12 inches oc each way	1,2	S	S	S	ND	ND	ND	ND
14	RC	Precast 6 inch reinforced concrete hollow core slab	1	S	S	S	S	S	S	ND
15	RC	Precast 8, 10 or 12 inch reinforced concrete hollow core slab	1	S	S	S	S	S	S	S
<p>S = Satisfied the Test Criteria F = Failed the Test Criteria ND = No Data/Not Determined</p>										