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Performance of hurricane shutters under impact by roof tiles

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ABSTRACT

This paper presents an experimental investigation of the performance of shutter systems designed to protect windows from windborne debris. Observations from post hurricane damage investigations have found that a wide variety of windborne debris types cause damage to buildings, including roof tiles in residential neighborhoods. This investigation subjected steel and aluminum storm panel shutters to impact from concrete roof tiles commonly used in hurricane prone regions. 4.1 kg (9 lb) tiles were launched at 15.25 m/s (50 fps) using a custom apparatus, duplicating the 2 × 4 (in.) lumber impact product certification test in both missile weight and impact speed. The tests were then repeated using 2 × 4 lumber, providing a comparison of performance as a function of debris type. The test matrix included steel panels of three different thicknesses and aluminum panels of two different thicknesses. Three manufacturers of each of the five storm panel types were tested, each using two common installation methods. Tests were conducted with tiles impacting on their edge and impacting flat. Results demonstrate a significant difference in both total and plastic shutter deflection for tile impacts vs. 2 × 4 lumber. With regard to the vulnerability of the glass being protected, the results suggest that the current standards may not be conservative under circumstances likely to occur in tile roof residential neighborhoods.

1. Introduction

Windborne debris can cause significant damage to building envelopes in high wind events. Post storm investigation studies have noted a high degree of roof cover loss, indicating that roof cover is a primary source of potentially damaging windborne debris in residential areas (e.g. [1–8]). Building codes along much of the world's hurricane prone coastline have evolved to address debris impact on the building envelope, requiring the testing of window protection systems, fenestration, wall and roof claddings in order to certify a minimum impact resistance standard. Although it was recognized by the developers that roof cover material is a primary debris source, US and Australian standards (e.g. [9–13]) specify testing with 2 × 4 (in.) lumber and/or steel balls as the debris for the purpose of maintaining a repeatable procedure with controlled representative impact momentum [14]. Due to the limited relationship between the debris used in certification tests and that most commonly observed after hurricane events, the actual level of protection being evaluated by the existing certification methods is not well defined.

The design-level event Hurricane Charley (2004) produced statistical evidence that the use of window protection systems is an effective mitigation, reducing the probability of window damage by at least a factor of 2.5 relative to unprotected windows [1]. However, evidence collected during this same study demonstrated that some code approved opening protection systems experienced failures due to debris impact from roofing tiles. Tile is a commonly used roof cover in many hurricane prone regions in the US, Australia and elsewhere. For example, the proportion of residential roofs with tile exceeds 20% in some Florida counties [15].

Methods to model probable losses and to determine the cost effectiveness of various mitigation measures can benefit from specific information about the frequency and severity of damage to the building envelope, with the latter being the focus of this study. For example, risk models that project losses from hurricane winds address the vulnerability of both protected and unprotected glazed openings to windborne debris [16,17]. Recent advances in debris flight and impact probability modeling (e.g. [18–29]) can be enhanced with test data quantifying the vulnerability of the building envelope to debris typical of the hurricane environment.

The body of knowledge concerning the vulnerability of fenestration to impact includes numerous studies on the impact resistance of annealed, tempered, and laminated glass [30–43], including a recent study presenting the momentum threshold required to damage unprotected annealed residential window glazing when impacted by asphalt roof shingles and wooden dowels [44]. The current study continues this focus on physical testing of the building envelope with realistic debris by documenting the performance of metal shutter systems impacted by concrete roof tiles. The study also provides results from impact testing using 2 × 4 lumber as a

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benchmark representing current certification methods. This original contribution to the body of knowledge presents a clear contrast between building envelope protection performance as evaluated via (a) current test standards, and (b) experiments that better represent field conditions with regard to debris type.

All tests were conducted at a speed of 15.25 m/s to provide a direct comparison to the speed currently used in certification standards. At an elevation of 10 m, a 33.1 m/s sustained (one minute average) marine exposure wind speed defines the lower bound of a Saffir–Simpson Hurricane Wind Scale Category 1 event [45,46]. In overland open exposure conditions the expected three second gust is approximately ten percent higher than the sustained marine winds [47], or 36.4 m/s. The speed of 15.25 m/s, used for certification standards and for all tests in this study, is 42% of the 36.4 m/s three second gust of a minimal category 1 hurricane, and less than 33% of the gusts associated with a minimal category 2 hurricane. Recent studies (e.g. [26–29]) suggest that 0.33 is less than the median for the ratio of debris to gust wind speed, and post storm damage studies did not commonly find roof tile debris in regions that experienced less than category 2 winds. Therefore, winds strong enough to generate roof tile debris are likely to impart a speed to that debris that is higher than the 15.25 m/s used for the current standard and duplicated in this study. The 15.25 m/s test speed represents a lower bound of speeds likely to occur in real conditions.

2. Description of impact test methods and test matrix

This investigation subjected steel and aluminum panel shutters to impact from concrete roof tiles. 4.1 kg (9 lb) tiles were launched at 15.25 m/s (50 fps) using a custom apparatus, duplicating the 2×4 lumber impact test used for product certification in both missile weight and impact speed.

Permanent (plastic) and total (plastic and elastic) deflections were recorded using a high speed camera. These tests were then repeated using 2×4 lumber, providing a comparison of performance as a function of debris type. The test matrix included steel panels of three different thicknesses and aluminum panels of two different thicknesses. Products from three manufacturers of each of the five shutter types were tested, each using two common installation methods. Tests were conducted with tiles impacting on edge and impacting flat. Each tile impact test was conducted twice. A total of 180 tile impact and 60 2×4 impact tests were conducted. New specimens were used for every test.

Apparatuses were constructed to launch roof tile debris with controlled accuracy, flight mode and speed, and to launch 4.1 kg 2×4 lumber in a manner consistent with current debris impact certification standards. Both apparatuses are based upon the same air cannon platform. All testing was performed at the Powell Family Structures and Materials Laboratory located on the Eastside Campus of the University of Florida.

2.1. Launching apparatus

The tile launching apparatus is comprised of four major components; the pneumatic ram that propels the tile projectile along a guided track toward the target, the air reservoir tank and barrel that supply the propulsion force to the ram, the electronic butterfly valve that releases the pressure from the tank to the barrel, and the integrated electronic system which monitors projectile speed and maintains the desired tank pressure. Fig. 1 presents an illustration of the launching apparatus.

The air reservoir is coupled to a 10.16 cm diameter schedule 40 steel pipe connected to a 120 V AC electronic valve with a 7.62 cm diameter inlet and outlet. The ram fits within the barrel and harnesses the released pressure. The far end of the ram is located at the exit end of the barrel, and bears against the tile projectile. A launch deck (guided track) supported by extruded T-slot aluminum rails extends from the exit of the barrel towards the target. The tile projectile sits upon this deck and is propelled toward the target via the ram. The deck is lined with a polyoxymethylene sheet to reduce sliding friction. The ram forward motion is arrested as the tile and ram approach the end of the deck, putting the tile in free flight towards the target.

The electronic system includes feedback control for filling, purging, monitoring and maintaining air reservoir pressure, control of the electronic valve for projectile launch, and measurement of the projectile speed using two infrared beams. This system is controlled from a custom National Instruments LabVIEW application.

A wood frame bolted to the strong floor supports the storm panels (impact targets) during testing. The frame is constructed of 4×4 (in.) timber and is 1.70 m high and 1.52 m wide. The frame is sheathed with 1.9 cm thick plywood to act as both a diaphragm for stability and a barrier to stop any debris that penetrates the storm panels. All joints of the frame were reinforced by metal brackets. The inner dimensions of the frame opening are 160.02 cm (63 in.) wide by 156.84 cm (61.75 in.) tall. The span of the shutter system varied due to different keyhole spacing and the sheet metal stamping process; however the number of panels and the number of studs used to fasten all systems remained constant.

The 2×4 lumber testing was conducted after the tile testing was completed. The same apparatus described above was modified to accommodate 2×4 lumber. The launch deck and pneumatic ram were removed, resulting in a traditional air cannon lumber launch configuration, with the lumber missile taking the place of the push ram within the barrel.

2.2. Tile projectile

A nominal 4.1 kg (9 lb) common concrete S-shape roofing tile was used as the projectile (Fig. 2). Each test used a new undamaged tile. Every test was conducted at a launch speed of 15.25 m/s (50 fps). Thus, every tile test has a nominally equivalent momentum to a standard 2×4 impact test. The speed of the tile launch was controlled via air reservoir pressure and a series of calibrations using infrared sensors and a high speed camera to document launch speed.

2.3. Impact orientation of tile projectile

The flight mode of the tile, and therefore its orientation upon target impact, can be controlled by a combination of launch deck length and free flight distance to the target. The two impact orientations considered were edge impact and flat impact. For edge impact, the plane of the tile is perpendicular to the plane of the target, the normal to the tile plane is vertical, and the short edge of the tile impacts the target. For flat impact the tile and target are in parallel planes upon impact, with the long edge of the tile vertical. These repeatable flight modes are imparted by controlling the length of the launch deck. When the pneumatic ram motion is arrested prior to the tile exiting the deck, the tile travels toward the target normal to the tile plane vertical (edge impact). When the launch deck is shortened such that the front end of the tile exits the launch deck prior to arresting the push ram motion, a forward rotation is imparted to the tile. A calibration of the free flight distance to the target allows this rotation to result in a flat impact of the tile with the target. The free flight distance for the tile was 3.92 m for edge impact and 4.39 m for flat impact.

2.4. Impact location of tile and 2×4 projectiles

The shutter systems were impacted in one of two locations, in the center of the shutter assembly (opening mid-span) and in the

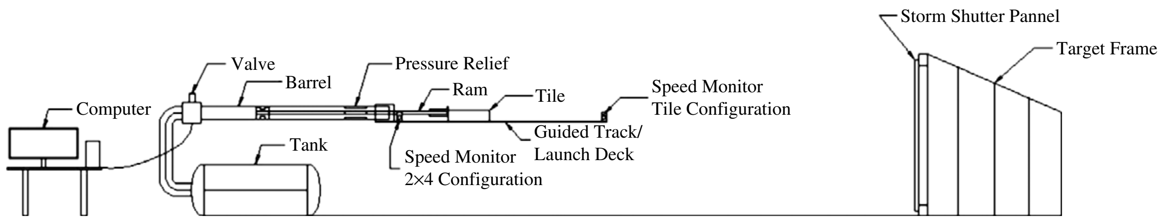

Fig. 1. Testing apparatus illustration.

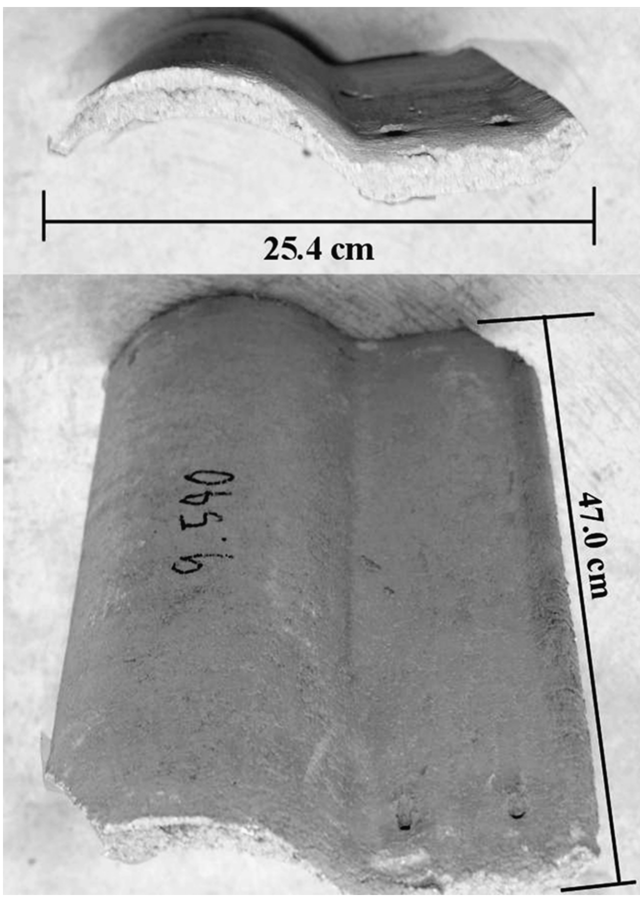

Fig. 2. Concrete tile used as windborne debris.

upper corner within 15.24 cm (6 in.) of either edge. Both flat and edge tile orientations were used for center impacts. Only edge tile orientation was used for corner impacts to avoid striking the frame. 2 × 4 testing was conducted at both center and corner locations. Each shutter sample was only impacted once.

2.5. Data recorded from impact tests

Multiple variables were recorded for each impact test, including shutter and mounting type. The speed of the projectile was recorded. Photographs of the test specimen before and after impact were taken. The post-impact condition of the installation was recorded (tearing, pulling out of track, etc.). Missile impact location and orientation (for tile) was recorded. The maximum permanent (plastic) deflection of the panel was measured and recorded. A high speed camera was used to view the backside plane of the shutter, and recorded the total deflection (elastic plus plastic). Thus, the potential damage to glass behind the shutter was determined for every impact test.

2.6. Velocity sensor

The velocity sensor system consists of photoelectric diodes and a National Instruments USB data acquisition unit. The photoelectric diodes have a response time that exceeds the 0.15 m/s required by ASTM E 1886-05 [9]. The diodes are mounted at the end of the guided track for the tile launch configuration, and near the barrel for the 2 × 4 launch configuration. In both cases, the system is triggered after the pressure cap on the pneumatic ram or 2 × 4 has passed the pressure relief ports at the end of the cannon barrel (see Fig. 1). This ensures that the speed is measured after the ram or 2×4 has stopped accelerating and has reached its peak velocity. For both configurations the sensor system was calibrated using both a high speed camera and radar gun monitoring the launch speed of the projectile. Thus, the impact speeds were carefully controlled and independently validated.

2.7. Shutter type and mounting

Steel shutters of three thicknesses (20, 22, and 24 gauge) and aluminum shutters of two thicknesses (0.050 and 0.060 in., or 0.127 and 0.152 cm) were tested. For each of these five shutter types, products from three different manufacturers were tested. Shutters were purchased from seven different manufacturers, and all products are approved for use in Florida. Panels measured between 33.02 and 37.78 cm wide and each was 167.64 cm (66 in.) tall. Four overlapping panels were installed in a vertical orientation, bearing against the frame at the top and bottom with no bearing along the vertical edges.

Each of the five shutter types were tested using both direct mount and track mount installation methods. In the direct mount configurations, the wood frame has threaded studs installed at a spacing of 15.24 cm (6 in.) on center or 15.87 cm (6.25 in.) on center across the top and bottom horizontal framing boarders. The studs pass through the panels and the panel is fastened by a 1/4-20 washered wing nut on each stud (Fig. 3). For track mounting a 5.1 cm (2 in.) wide *h*-header track guide is installed along the top border of the frame. The panels are slid into position with the track along the top restraining motion and studs and wing nuts along the bottom similar to the direct mount (Fig. 4). All installation hardware was purchased from an independent third party vendor, including the "*h*" headers and studded angles for the top and bottom installations of the track mount.

3. Results and discussion

3.1. Results presentation

All impact data are presented in a series of six graphs (Figs. 6–11). Each graph presents either edge tile impact and 2 × 4 impact, or edge tile impact and flat tile impact, represented by wide and thin bars, respectively. Each graph presents the results for each of the three manufacturers for every product tested (three steel thicknesses, two aluminum thicknesses). All tile and 2 × 4 impacts were performed using a nominal 4.1 kg (9 lb) object traveling at

Fig. 3. Direct mount installation.

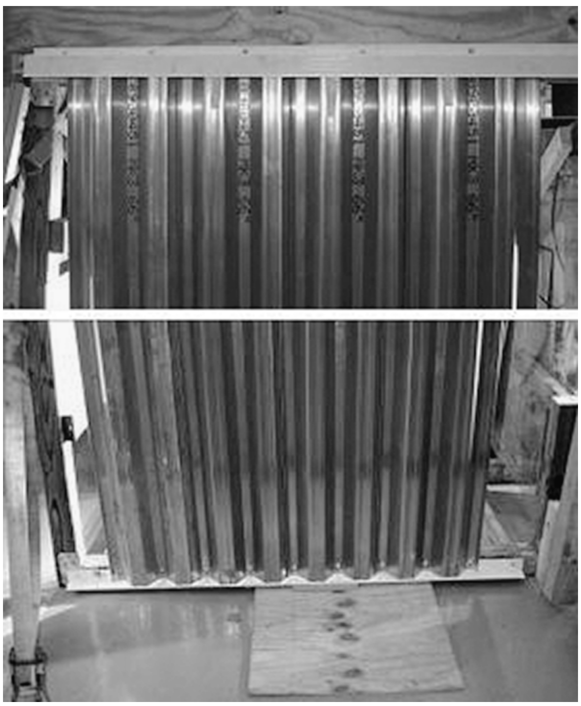

Fig. 4. Track mount installation using *h*-header along the top and stud mount along the bottom.

15.25 m/s (50 fps). Every tile test was conducted twice for every condition, and each graph presents the results of both tests. Every 2 × 4 test was conducted once. In the four graphs that present 2 × 4 impact tests (Figs. 8–11), the 2 × 4 results are repeated for direct comparison to both tile tests. The horizontal axis in each graph indicates the anonymous manufacturer designator (A-G), product type, and test number using the key provided in Fig. 5. Fig. 5 also illustrates the proper interpretation of the plastic (permanent), elastic (recovered) and total (plastic plus elastic) deflections presented in Figs. 6–11.

In many tests, damage occurred at the installation (the interface between the panel and frame). For direct mount installation, damage is defined as the stud tearing through the panel at one stud or more. For track mount installation, damage is defined as either a pull-out or push-through of the panel from the track, such that the top edge of the panel is partially or fully separated from the track. Examples of tearing for direct mount and pull-out and push-through for track mount installation are shown in Fig. 12. Installation interface damage occurred for a small number of 2 × 4 tests, and a larger portion of the tile tests. In most cases, damage at the interface is associated with a more severe panel deflection. Each of the individual tests that resulted in installation damage is indicated in the six graphs (Figs. 6–11) with an icon above the deflection results for a given test. These icons are defined in Fig. 5.

3.2. Discussion: tile edge vs. tile flat impact (Figs. 6 and 7)

Fig. 6 provides the results of the flat tile and edge tile impacting the center of the direct mounted panel system, and Fig. 7 presents the results of the flat tile and edge tile impacting the center of the track mounted panel system. Flat tile impacts were not conducted for corner shots. These two figures contrast the deflection caused by a tile impacting on edge (wide bars) and flat (thin bars). In Fig. 6 the missing thin bar for the second 24 gauge steel product indicates that the high speed camera did not function for that test. Notable observations from Figs. 6 and 7 are provided below. Refer to the accompanying figures for specific values that support these observations:

- For any given product, the two repeated tests yield very similar results in most cases, while results among different manufacturers of the same product type vary widely. For example, the 20 gauge steel product (first 6 columns in Fig. 6) shows strong repeatability of results for a given manufacturer, while the results among manufacturers varied.
- The total deflection from edge tile impact is larger than that from flat tile impact in most cases.
- In every case, the edge tile impact total deflection exceeded 7.62 cm (3 in.). This is significant, as the tested products required a minimum distance of 7.62 cm between product and window glass for installation based on the results of the certification testing.

The remaining four results' figures each compare deflection from 2 × 4 and edge tile impacts. Figs. 6 and 7 provide a means to compare 2 × 4 with flat tile impact results.

3.3. Discussion: direct mount impact with edge tile and 2 × 4 *(Figs. 8 and 9)*

Fig. 8 presents the results of the 2 × 4 (thin bars) and edge tile (wide bars) impacting the corner of the direct mounted panel system, and Fig. 9 presents the results of the 2 × 4 and edge tile impacting the center of the direct mounted panel system. Notable observations are provided below. Refer to the accompanying figures for specific values that support these observations:

- Deflections are larger in almost all cases for the center shots compared to corner shots.
- As was the case for Figs. 6 and 7, the two repeated tile tests yield very similar results in most cases, with exceptions for the 22 gauge steel corner impacts (attributable to pull-out of the shutter from its track in the second test).
- In most cases the edge tile impact yielded considerably larger deflection than the 2 × 4 impact.
- Plastic deflection from the 2 × 4 tests did not exceed the critical setback value of 7.62 cm for any test in Figs. 8 and 9, and in only a few cases the total deflection from 2 × 4 impact exceeded that value. This seems to conform to the setback recommendations based on plastic deflection from certification tests.

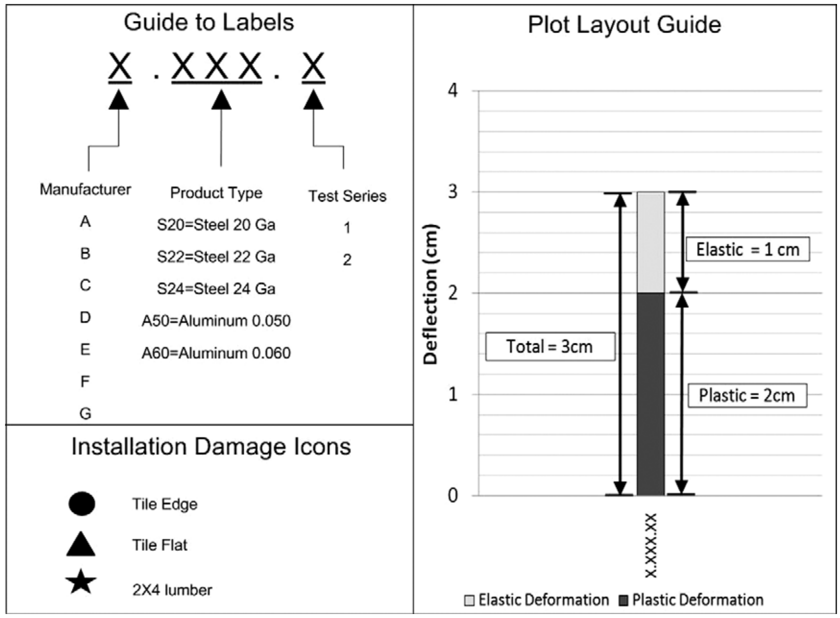

Fig. 5. Guide for Fig. 6 through 11: horizontal axis labels (top left), icons indicating installation damage (bottom left), and a guide to interpreting deflection results (right).

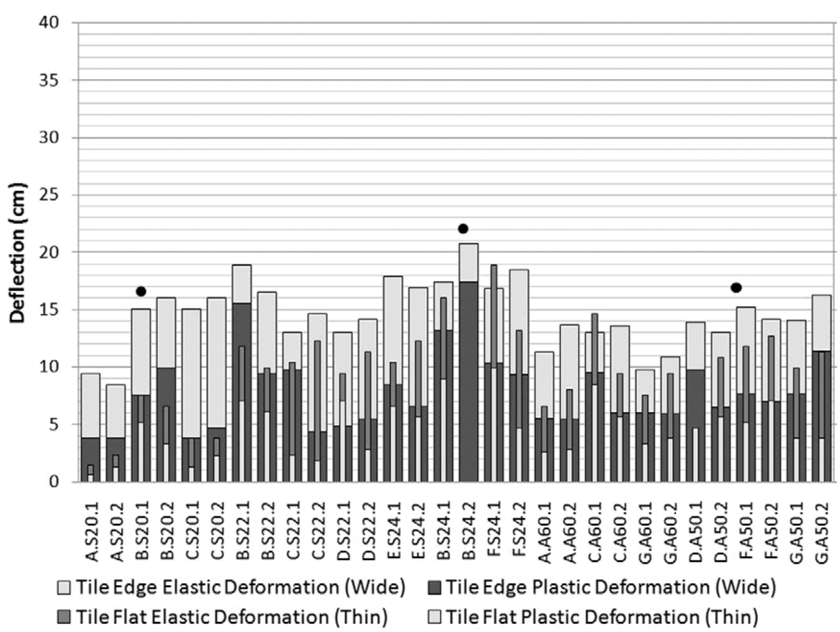

Fig. 6. Center impact, direct mount, tile edge and tile flat.

- In contrast, plastic deflection from edge tile impact in the corner (Fig. 8) exceeded 7.62 cm for the thinnest steel and aluminum products, while total deflection exceeded this value in more than half of the corner tests.
- Tile impacts at the center of the direct mount panels (Fig. 9) produced plastic deflections in excess of 7.62 cm for half of the tests, while total deflection exceeded this value in almost every test.

3.4. Discussion: track mount impact with edge tile and 2 × 4 (Figs. 10 and 11)

Fig. 10 presents the results for the 2×4 and edge tile impacting the corner of the track mounted panel system, and Fig. 11 presents the results for the 2×4 and edge tile impacting the center of the track mounted panel system. Tile impacts are the wide bars, and 2×4 impacts are the thin bars. For the track mounted system, it can be observed that many corner shots yielded more deflection than the center shots. This is attributable to the pull-out of the shutter from the upper track mount, which was more common for corner shots than center shots, and permitted more deflection. Other notable observations are provided below. Refer to the accompanying figures for specific values that support these observations:

- The two repeated tests typically yield similar results in most cases, with a few exceptions.
- In most cases the edge tile impact yielded considerably larger deflection than the 2×4 impact.
- Plastic and total deflection from the 2×4 tests exceeded 7.62 cm for a minority of tests.
- In contrast, plastic deflection from edge tile impact in the corner (Fig. 10) exceeded 7.62 cm for the thinnest steel and aluminum products, while total deflection exceeded this value in more than half of the corner tests.

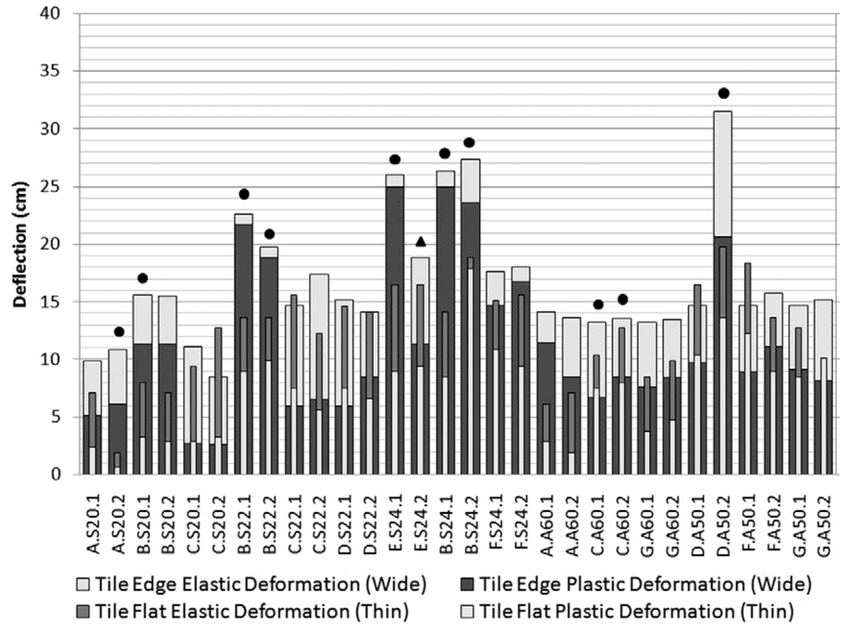

Fig. 7. Center impact, track mount, tile edge and tile flat.

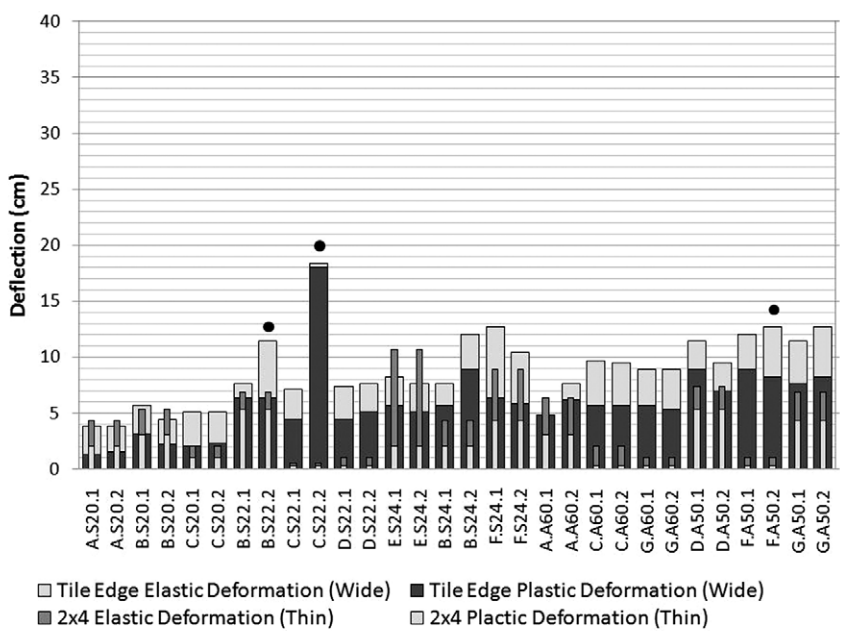

Fig. 8. Corner impact, direct mount, tile edge and 2×4.

- Tile impacts at the center of the track mount panels (Fig. 11) produced plastic deflections in excess of 7.62 cm for more than half of the tests, while total deflection exceeded this value in every test.

3.5. *Discussion: track and direct mount installations*

Typically the deflections in the track mount installation (Figs. 10 and 11) were greater than the deflection in the direct mount installation (Figs. 8 and 9). This difference is minor for 2×4 impacts, but much more pronounced for tile impacts. This is mainly attributable to the much higher rate of occurrence of installation damage for tile impacts. Installation damage is strongly associated with greater deflection, as observed by the icons above the individual tests. Ten percent of the tile tests produced installation damage to the direct mount systems for both corner and center impacts, while the tile tests damaged 73% and 33% of the track mount installations from corner and center impacts, respectively.

3.6. *Average statistics: ratio of tile to 2×4 deflection and total to plastic deflection*

The results in Figs. 8–11 were analyzed to provide some statistical quantification of shutter deflection. Table 1 presents the ratio of total deflection from edge tile impact to total deflection from 2×4 impact, stratified by product type, mounting, and impact location. The total deflection from each edge tile test is taken in ratio with that of the comparable 2×4 test, and these ratios are then averaged over the given stratification. Each value in the table is therefore an average from six tile tests (three manufacturers, two tests each). As an example to aid in interpretation, the direct mount corner impact ratio value of 11.32 for 22 ga steel in

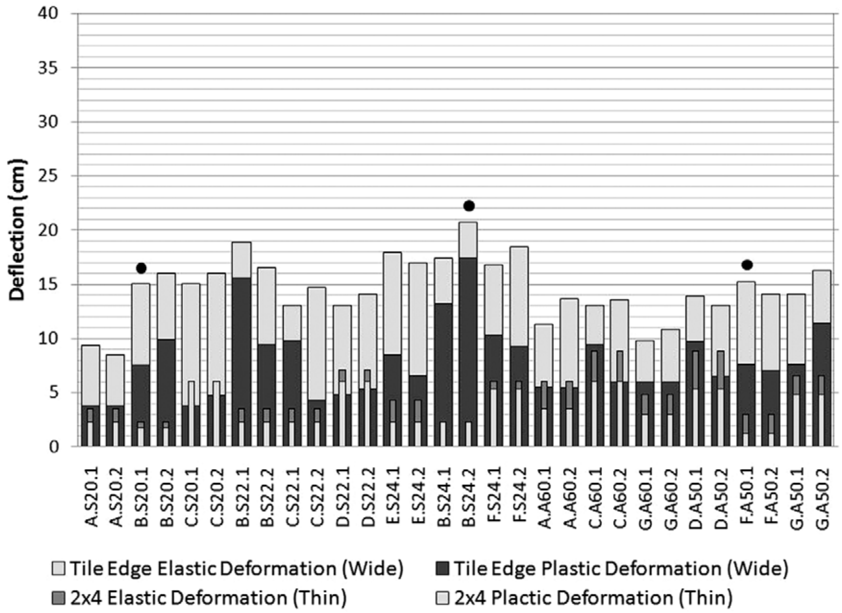

Fig. 9. Center impact, direct mount, tile edge and 2 × 4.

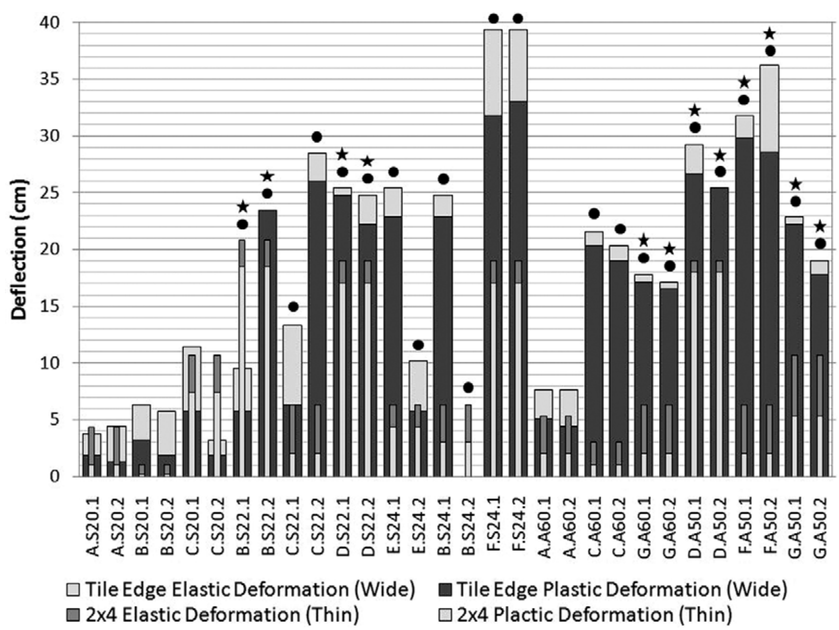

Fig. 10. Corner impact, track mount, tile edge and 2 × 4.

Table 1 can be seen graphically in Fig. 8, columns 7 through 12, by comparing the wide bars to the thin bars. In particular the product by manufacturers C & D (columns 9 through 12) shows a very large ratio due to small deflections from the 2 × 4 tests. In all cases in Table 1 the average ratio exceeds 1.0. The deflection from edge tile impact is more severe than deflection from a 2 × 4 of identical weight and speed, regardless of impact location, mounting type, or product material or thickness. Referring to Figs. 8–11, only 7.5% of the individual test cases produced a 2 × 4 induced deflection that exceeded the tile induced deflection.

Table 1
Average ratio of total deflection from edge tile to 2 × 4 impacts.

Mount	Location	20 ga steel	22 ga steel	24 ga steel	.06 alum	.05 alum
Direct	Corner	1.45	11.32	1.45	5.66	5.15
	Center	3.95	3.58	5.10	1.88	2.88
Track	Corner	2.53	1.80	2.74	3.68	3.22
	Center	3.75	4.18	5.98	2.53	1.72

The dark and light stacked bars in Figs. 6–11 visually demonstrate that for any given test the ratio of total to plastic deflection varies with test conditions and product. Interpretation of the ASTM test [10] is based upon measured plastic deflection and some assumptions about the total deflection (recording the total deflection is not required in the test standard). Table 2 presents the ratio of the total deflection to plastic deflection, stratified by debris type, product type, mounting, and impact location. The ratio of total to plastic deflection for each impact test is calculated, and these values are then averaged over the given stratification. Each value in the table is the average from either six or three tests for tile or 2 × 4 results, respectively. For the 2 × 4 tests the average ratio ranges from 1.28 to 5.22. The average of the 2 × 4 ratios for

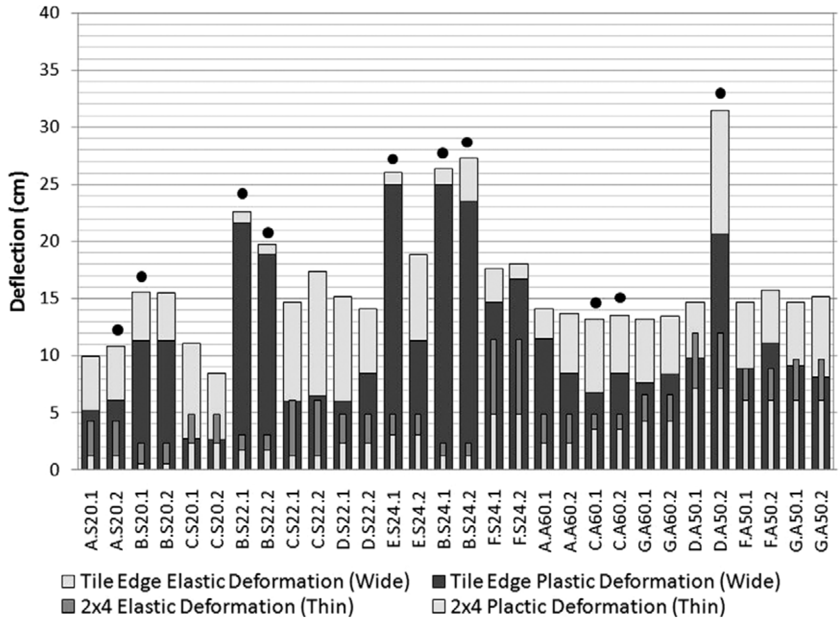

Fig. 11. Center impact, track mount, tile edge and 2 × 4.

Fig. 12. Examples of direct mount tear (left) and track mount pull-out (right).

Table 2
Average ratio of total to plastic deflection for edge tile and 2 × 4 impacts.

Mount	Location	20 ga steel		22 ga steel		24 ga steel		.06 alum		.05 alum	
		Tile	2 × 4	Tile	2 × 4	Tile	2 × 4	Tile	2 × 4	Tile	2×4
Direct	Corner	2.34	1.96	1.46	2.43	1.57	3.14	1.56	5.22	1.43	2.32
	Center	2.63	1.28	2.16	1.43	1.80	1.34	1.94	1.59	1.79	1.81
Track	Corner	2.36	3.23	1.33	1.79	1.28	1.56	1.24	2.09	1.11	2.06
	Center	2.29	3.34	1.90	2.88	1.20	1.92	1.63	1.67	1.60	1.57

direct mount is 2.25, and the average of the 2 × 4 ratios for track mount is 2.21. For the edge tile tests the average ratio ranges from 1.11 to 2.63. The average of the edge tile ratios for direct mount is 1.87, and the average of the edge tile ratios for track mount is 1.59.

The ratios reported in Table 2 are not consistently higher for one debris type, mounting, or impact location, but it is clear that the elastic portion of the deflection is significant. For the products tested, the total deflection can exceed the permanent deflection by a factor of more than two. With regard to the existing 2 × 4 standard, setback recommendations based on permanent deflection measurements should account for the elastic portion of the deflection to prevent glass breakage. The measurement of elastic deflection may be cost prohibitive for test certification labs. These results provide some guidance for the development of a multiplication factor for the permanent deflection.

3.7. Significance of results

The focus of this study is on the performance of certified window protection systems when impacted by roof tiles at a momentum value that corresponds to the current standards that use lumber as the debris. The results clearly demonstrate a statistically significant difference in deflection as a function of debris types with identical mass, speed and impact location. As a complement to these findings, recent studies (e.g. [26–29]) present evidence that roof cover debris speeds are very likely to exceed 15.25 m/s.

The results in this study indicate that the current 2 × 4 lumber based test standards do not offer a performance evaluation that is conservative with regard to the protection of windows from debris commonly observed in post hurricane damage studies. This is by no means a rejection of the value of using window protection. Studies clearly demonstrate the effectiveness of window protection [1], and even damaged shutters can continue to provide resistance to envelope failure. Much of the debris documented in post storm studies are lighter and more flexible than a 4.1 kg roof tile, such as roof shingles, and much less likely to cause severe deflections. However, the study presents evidence that questions the efficacy of applying the current debris impact test standard to evaluate shutter systems intended for use in neighborhoods where tile roof cover is dominant.

Field studies have documented that tile debris is often released from rooftops in fragments, which presents an additional mode of failure for window protection via puncture. Puncture failures were not observed in the current study using full tiles. A follow-up experimental study will quantify momentum thresholds for puncture of window protection from tile fragments.

4. Conclusions

This paper presents an experimental investigation of the performance of shutter systems designed to protect windows from windborne debris. Steel and aluminum storm panel shutters were subjected to impact from concrete roof tiles and 2 × 4 lumber. The results of this study indicate that there is a significant difference in the plastic and total deflection of the tested panels when impacted by roof tiles and 2 × 4 lumber of identical weight and speed. The major implication is that impact momentum alone is not a sufficient metric on which to base performance criteria. The deflection of the metal panel window protection system is highly sensitive to impact location (which is currently addressed in product approval testing), and also to debris type and impact orientation. In most tests, the deflection imparted by a tile impacting on its edge exceeded the specified setback from the glass, while only a few such cases were found for the 2 × 4 tests. Although the tested products did conform to the performance requirements for product certification, it is evident that the current product testing using a 2 × 4 missile does not provide an adequate evaluation of the expected performance of shutter systems subjected to tile debris. The tested window protection products are likely to allow glass breakage if impacted by roof tiles. This is by no means a rejection of the value of using window protection. Rather, the study presents evidence that questions the efficacy of applying the current debris impact test standard to evaluate shutter systems intended for use in neighborhoods where tile roof cover is dominant.

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