4.5. Damage Analysis Results and Evaluation of Fragility Curves

In the damage analysis phase of the PBHE framework, the *EDP* values obtained in the structural analysis phase are compared to relevant damage measures. For the aluminum storm panel considered in this study, the *EDP*s considered were Δ_{max} and Δ_{pl}, and the limit states were (1) failure of the panel itself, (2) failure of the window behind the panel, and (3) complete penetration of the projectile. These three limit states are graphically illustrated in Figure 35, where pictures of experimental results corresponding to failure for each of the three limit states considered are provided in the insets. Figure 35(a) shows the limit state corresponding to failure of the panel only. In this scenario (panel failure), WBD impact causes the aluminum storm panel to reach an excessive plastic deformation, which renders the panel unusable in future hurricane events. This limit state failure is met when the value of the *EDP* Δ_{pl} recorded is larger than or equal to the threshold *DM* ξ_{pl} assumed to warrant replacement of the panel (i.e., $\Delta_{pl} > \xi_{pl}$). In this study, ξ_{pl} is assumed deterministically equal to 2.50in (6.35cm). Figure 35(b) illustrates the limit state corresponding to excessive deformation of the panel resulting in the failure of both the panel and the window behind the panel. This limit state failure occurs when the *EDP* Δ_{max} obtained from testing is larger than or equal to the threshold *DM* ξ_{max}, which is defined as the minimum distance between the aluminum storm panel and the window protected by the panel (i.e., $\Delta_{\mathrm{max}} > \xi_{\mathrm{max}}$). In this research, ξ_{max} is assumed deterministically equal to 5.00in (12.70cm). Figure 35(c) illustrates the penetration of the panel and window after WBD impact. A test corresponding to a missile penetration is considered a failure with respect to the other two limit states of interest. The value of

$\xi_{\max}$ adopted in this research represents a realistic value of the mean distance between panels and windows for common installations. However, for specific applications, appropriate statistics should be obtained from data regarding the specific window installation under study in the specific hurricane prone region of interest.

Figure 36 plots the fragility curves corresponding to the three limit states considered in this research as derived in Herbin and Barbato (2012) through numerical simulations. Figure 36 shows also the experimental results obtained in this study for an *IP* level of $KE_m = 0.500$kJ. These experimental points were obtained from 14 impact tests with random impact location.

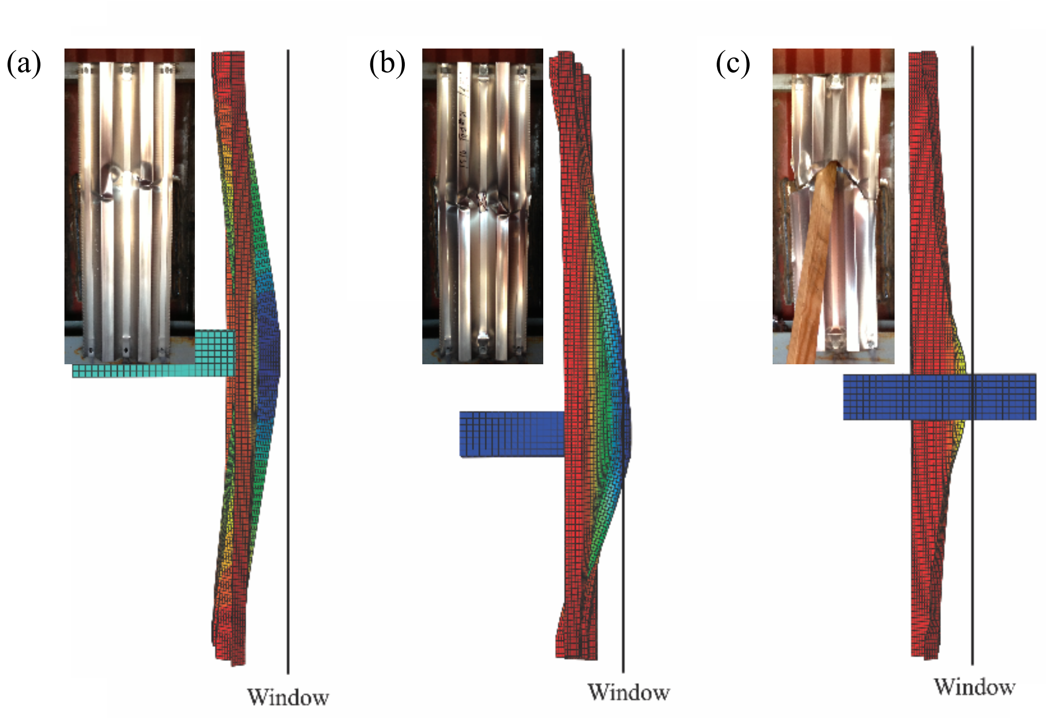


Figure 35: Damage limit states: (a) failure of the storm panel, (b) failure of the window, and (c) penetration of the missile.

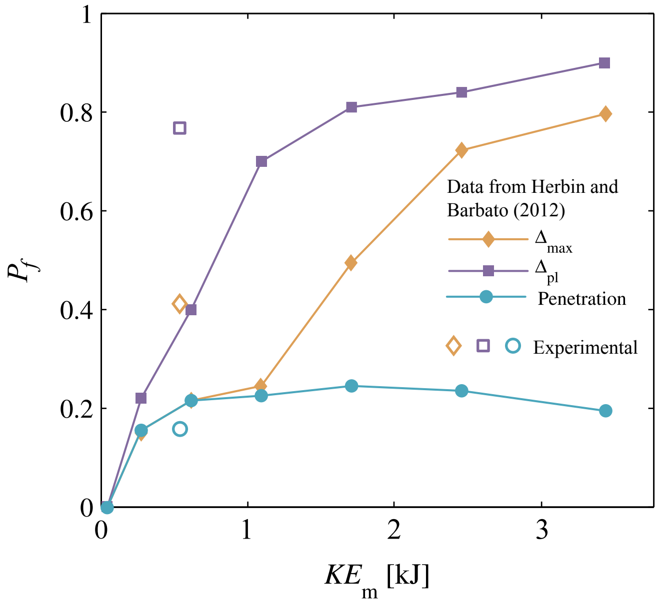
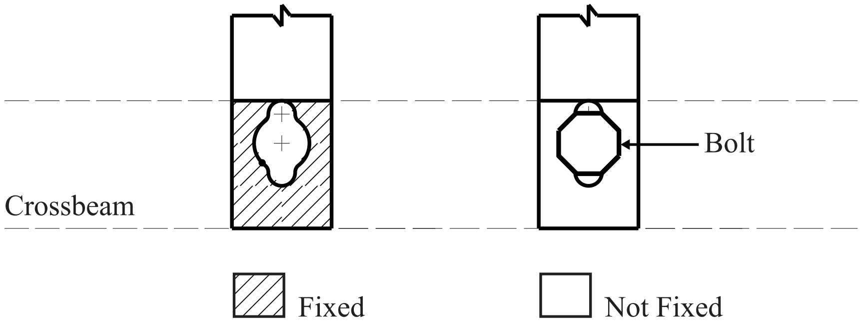


Figure 36: Fragility curves for aluminum hurricane storm panels: comparison of experimental and numerical results.

When comparing the experimental results and the numerically derived fragility curves, a significant quantitative difference is observed between the corresponding estimated failure probabilities. In particular, the fragility curves derived in Herbin and Barbato (2012) provide significantly lower probability of failure values at the equivalent *IP* level, when compared to the experimental results. This discrepancy is most likely due to the fact that the modeling assumptions for the boundary conditions made in Herbin and Barbato (2012) did not correspond to the behavior that was observed experimentally for the bolted connections between the storm panel and the support frame. The reference boundary conditions considered in this study consisted of three bolted connections at the top and bottom sides of the panel (corresponding to the panel's shorter dimension). Through these connections, the panels were secured to the crossbeams located on the target support frame by using ¾" bolts, as recommended by the installation instructions provided by the manufacturer (see Figure 37(b)). In Herbin and Barbato (2012), these connections were modeled using fixed boundary conditions, i.e., by assuming that the portion of the panels surrounding the bolted connection was rigidly connected to the supporting frame (see Figure 37(a)). However, during the experimental testing, it was found that the panel's strength limit (i.e., the point after which failure of the panel was almost sure) corresponded to KE_m=1.150kJ. For impact kinetic energy values higher than or equal to this strength limit, the panel began tearing from the crossbeams, splitting the aluminum below the bolt and separating the panel from the target support frame (see Figure 25). This type of failure could not be modeled based on the modeling assumptions made in Herbin and Barbato (2012). As a consequence of the inaccurate modeling assumptions for the boundary conditions, the stiffness and strength of the aluminum panel were significantly overestimated in the numerical study, as demonstrated by the results presented in Figure 36.



(a) Assumed Boundary Conditions in Herbin and Barbato (2012)

(b) Actual Boundary Conditions

Figure 37: Boundary conditions: (a) boundary conditions assumed in Herbin and Barbato (2012), and (b) actual boundary conditions

5. CONCLUSIONS AND RECOMMENDATIONS

The research presented in this thesis focused on the derivation of experimental fragility curves for windborne debris (WBD) impact risk assessment of building envelope components (BECs) with ductile behavior (in particular, aluminum storm panels) within the performance-based hurricane engineering (PBHE) framework. Fragility curves represent the cumulative distribution functions of damage measures (*DM*s), corresponding to relevant limit states and physical states of damage, expressed as functions of response quantities, referred to as engineering demand parameters (*EDP*s), or of appropriate interaction parameters (*IP*s), describing the intensity of the WBD impact. The following three *DM*s and the corresponding limit states were identified in this research: (1) damage to the storm panel (with *EDP* corresponding to the maximum plastic deformation of the panel, Δ_{pl}); (2) damage to the window protected by the storm panel (with *EDP* corresponding to the maximum total deflection of the panel, $\Delta_{\max}$); and (3) complete penetration of the panel by the projectile.

A first set of experimental tests was performed to identify a sufficient *IP* for the three limit states considered in this study. It was found that the impact kinetic energy, KE_m, is a sufficient *IP*, while impact velocity and impact linear momentum are not sufficient *IP*s for BECs with ductile behavior.

A second set of experimental tests was performed to derive an experimental fragility curve. Three typologies of impacts were identified: (1) ordinary impacts (i.e., impacts occurring in areas of the panel not prone to penetrations of boundary impacts); (2) boundary impacts (i.e., impacts occurring in the area of the panels that is connected to the support frame, whose effects are mainly dependent on the installation details of the storm panel and on the strength of the supporting wall); and (3) complete panel penetrations. It was also found that the location of impact on the panel plays a large role in determining the impact type and level of damage to the structure.

A third set of experimental tests was performed to evaluate the effects on the performance of aluminum storm panels of their installation details. It was found that even a small overlap between the storm panel and the supporting wall on the sides of the panels that are not directly connected to the wall decreases significantly the vulnerability of the panel to penetration. There results suggest that the addition of a minimum overlap requirement in the building code's specifications for storm panels could have a very beneficial effect on the safety of structures subjected to WBD impact hazard. This requirement would produce only a minimal change in common application practices and an insignificant additional cost for the building's owners.

The development of fragility curves for BECs is a key component of a probabilistic PBHE framework. Additional research is needed in the field of fragility analysis of BECs subject to WBD impact hazard. Based on the insight gained from the present study, the following recommendations for future research are made:

(1) Additional experimental tests for varying levels of impact kinetic energy are needed to generate a complete fragility curve for the aluminum storm panel considered in this study.

(2) A new finite element-based numerical study should be performed to derive more accurate numerical fragility curves for the storm panel under consideration. The numerical study could benefit from the experimental data obtained in the present

study, particularly regarding the actual mechanical behavior of the boundary conditions of the panel.

(3) Research results available in the literature highlight the importance of the type of WBD on the performance of BECs. Thus, the experimental and numerical studies on fragility curves for aluminum storm panels should be extended to consider WBD other than rod-type.

(4) While existing literature has considered the performance of BECs with brittle and ductile behavior, there remains a need to assess the vulnerability of BECs with intermediate behavior.

(5) Since structures are subjected to several different hazards in addition to WBD impact during hurricane events, the effects of interacting hazard on the structural performance is of interest. Thus, it is suggested to investigate the effects of the interaction between WBD impact and other hazards that are present during hurricane events, e.g., wind pressure.

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APPENDIX: TESTING PROCEDURE AND SAFETY GUIDELINES

1. Make sure all operators wear the appropriate personal protective equipment (PPE).
2. VERY IMPORTANT: Before entering into the space in front of the cannon, first open all valves that are capable of sealing pressure within the pressure tank.
3. Mount the deflection measurement system securely 8” in front of the cannon barrel and approximately 5” below.
4. Mount the test specimen onto the target frame. Use supplied ½” bolts, washers, and nuts (if applicable) with testing specimen. If not, attach specimen using four adjustable clamps, clamping the specimen at the four corners directly to the crossbeams.
5. Use the red laser located at the bottom of the cannon barrel to locate the intended impact location.
6. If the location is correct, mark the location on the specimen before firing to compare intended location and actual location. If not, use the winch for vertical movement, and the hand winches for horizontal movement. If the cannon is moved vertically, find the desired vertical height and then use the four trolley pins to safely pin the location of the trolley within the frame. Release the pressure on the winch by allowing the winch to unwind and place full pressure on the trolley pins.

   Attach the sabot to the 2x4 lumber by fastening the corresponding screws. The correct position of the sabot is illustrated in Figure 18. The user must make sure that the sabot is placed in the area shown and is in contact with the barrel surface once it is inserted. NOTE: After several shootings, the sabot may become loose. In order to better fasten the sabot to the 2x4 lumber, insert wooden chips into the holes where the screws are drilled.

7. Insert the 2x4 lumber into the barrel. The missile must be placed to the very back of the barrel. Carefully insert the missile into the barrel. Subsequently, use a designated device to push the missile towards the back of the barrel. Slowly push the missile until it touches the stops. Do not continue pushing once it touches the stops.
8. VERY IMPORTANT: From this moment until the firing is completed, all users and observers must remain within the safe zone located behind the yellow lines for the trolley pin locations.
9. Open the valve with the hose connector to the pressurized the tank, and close the leaking valve. The pressure gage should show 0 psi.
10. Connect the direct line to the valve that is in the open position. Let the tank reach a pressure about 15% higher than the one desired. The purpose of this is to minimize errors during the test due to air leaks.
11. Once the desired pressure is reached within the pressurized tank, close the valve and disconnect the hose.
12. Connect the direct line to the valve connected to the butterfly valve actuator (Figure A-1). The minimum pressure at which the actuator operates is 40 psi. The direct line is connected to a regulator that maintains the pressure of the line at 40 psi. Thus, the actuator should be almost immediately ready to operate once it is connected.

Figure A-1: Connection of direct line to valve actuator valve

13. Adjust the pressure inside the tank by slightly opening one of the valves linked to the pressurized tank. It is more efficient to have two operators, one slightly leaking the valve, and the other observing the exact pressure on the user interface until it reaches the desired pressure.
14. The user is now ready to turn the key on the firing switch. Ensure all users and observers are aware of the launch that is going to be executed. Perform a countdown (3, 2, 1) that is loud and clear while simultaneously blowing a small warning horn and push the red button on the firing switch box and holding it until the missile is fired.
15. Once the impact is completed the user must immediately turn the key of the back to the “off” position and open both valves connected to the pressurized tank in order to release any pressure left inside the tank.
16. Record all needed data.

VITA

Taylor Claude Alphonso was born in 1988 in New Orleans, Louisiana. He graduated from Holy Cross High School in New Orleans, Louisiana in May 2006 and began his undergraduate studies at the University of Louisiana at Lafayette in the fall of the same year. He received his Bachelor of Science degree in Architecture from the University of Louisiana at Lafayette in May of 2011. After graduating, he began his graduate studies as a dual degree masters student at Louisiana State University in August 2011. He is expected to receive his Master of Science degree in Civil Engineering and Master of Architecture degree in May of 2013.