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Article

The effect of wind mitigation devices on gabled roofs

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SUMMARY

Hurricanes are dangerous storms that can cost both lives and millions of dollars' worth of damages each year. Much of the damage from hurricanes comes from winds that cause pressure differences and uplift forces that can make roofs blow off. Methods in place today to mitigate these forces primarily involve the strength and type of attachments of the roof to the walls of the house, but previous studies have shown how mitigation devices can redirect the airflow on a roof to reduce the uplift forces. The purpose of this study was to test devices installed on a gabled roof to see which reduced the actual uplift forces best. A wind tunnel made of PVC pipe, an acrylic sheet, and a leaf blower on a wooden base, simulated the hurricane winds. Three gabled birdhouse roofs were each modified with different mitigation devices: a rounded edge, a barrier shape, or an airfoil. The barrier edge had no significant effect on the time for the roof to blow off. The rounded edge and the airfoil had significant effects, with the airfoil taking the longest time for the roof to blow off. This suggests that the addition of airfoil devices on roofs, specifically in areas that are prone to hurricanes such as Florida, could keep roofs in place during hurricanes, thus reducing insurance bills, overall damage costs, and the loss of lives.

INTRODUCTION

Hurricanes are very large and extremely powerful storms that move around a central point called an eye. They can occur all over the world, although they go by different names in various regions. The word "hurricane" is used for storms in the north Atlantic or eastern Pacific Oceans, while the north Pacific and Philippines use the word "typhoon". Storms that develop in the south Pacific and Indian Oceans use the term "cyclone" (1). These storms cause a lot of damage. They can destroy homes, unroot trees, and even cause major damage or death to people and animals (1). Most hurricanes hit the United States in the South, along both the Gulf and Atlantic coasts. From 1900 to 2018, 206 hurricanes hit U.S. territory (2). Hurricane Katrina in 2005 was the single most expensive U.S. hurricane to date, costing \$116.9 billion in damages, although that annual amount was passed in 2017 by back-to-back Hurricanes Harvey and Irma, which cost over \$125 billion worth of combined damages in Texas and Florida (2-3).

Hurricanes can be classified into five different categories based on the average sustained wind speed over a period of one minute, excluding gusts. This scale of five categories is known as the Saffir-Simpson Hurricane Wind Scale (4). **Table 1** summarizes the classification of the scale based on wind speed and the roof damage in each of the categories (4).

Approximately forty-one hurricanes have been analyzed with the scale between 1960 and 2006 (5), although an earlier version of the scale included information about storm surge and central pressure of the storm (4). The current scale is based only on sustained winds and is used to prepare communities in the United States that are in the path of a hurricane by providing examples of the type of damage that can be expected from the winds in each category. Hurricane Katrina was recorded as a Category 3 hurricane at landfall, Hurricane Harvey was a Category 4 hurricane, and Hurricane Irma hit the Florida Keys as a Category 4 hurricane before being downgraded to a Category 3 as it hit the mainland coast of Florida (2). It is often the same regions that get hit with hurricanes of varying strengths repeatedly, causing people to lose their homes, and sometimes their lives. For this reason, it is important to try to find a solution to lessen the damage these storms cause.

The average house is very vulnerable during a strong hurricane, especially at the roof because of the uplift forces from the wind. Uplift forces are one of three types of wind load forces that affect buildings and need to be taken into consideration in their design. The three types of wind load forces are shear loads, which are horizontal forces produced by winds that would make the building tilt; lateral loads, which are the pushing and pulling forces that would cause a building to move off of its foundation; and upload forces, which are created from pressure differences of the wind flowing over the roof (pulling the roof up from above) and under the roof overhangs (pushing the roof up from below) (6). Wind uplift force is a function of the wind pressure (P), the surface area (A), and the drag coefficient for the shape of the roof (C_d):

$$\text{Wind Uplift Force} = P*A*C_d$$

Wind pressure, in the formula above, is a function of the air density (ρ) and the square of the velocity of the wind (v) (7):

$$P = 1/2\, \rho v^2$$

In a hurricane, a slightly higher wind means a lot more

Table 1. Saffir-Simpson Hurricane Wind Scale.

Category	Wind Speeds	Types of Roof Damage Due to Hurricane Winds
1	119-153 km/h	Very dangerous winds can result in damage to roof, shingles, vinyl siding and gutters. Mobile homes can be destroyed.
2	154-177 km/h	Extremely dangerous winds can cause major roof and siding damage or can cause roofs to fly off poorly built and older homes.
3 (major)	178-208 km/h	Major damage or removal of roof decking and the gable ends (the vertical triangular wall between the sloping ends of a gabled roof).
4 (major)	209-251 km/h	Catastrophic damage including loss of most of the roof structure and/or some exterior walls, even on solidly built framed houses.
5 (major)	252 km/h or higher	Catastrophic damage, with a high percentage of framed homes being destroyed from wall collapse and complete failure of the roof.

force (8). Most damage to roofs during a hurricane is caused by spiraling winds that form when the oncoming wind from the hurricane hits a bulky structure with sharply defined sides. This spiraling wind is known as a vortex. The vortices change the pressure distribution across the roof, causing the suction that results in damaging uplift forces on the roof (9). Certain house and roof types could improve the durability of the house during a hurricane. For example, very large overhangs on a roof could cause the entire roof to fly off, so reducing or eliminating overhangs is a good design for hurricane-prone areas. Overall, hurricanes cause significant damage to roofs because of uplift forces.

If the roof of a house or the house itself is slanted in the direction of the wind, then the house can have more stability. Circular roofs cause the wind to simply curve around the house. Holes in a wall allow the wind to pass through and lessens the amount of wind passing through, whilst acting like a regular wall. Raised houses let a lot of wind go under, not up against the house, and they allow water to accumulate under the house, preventing floods (10).

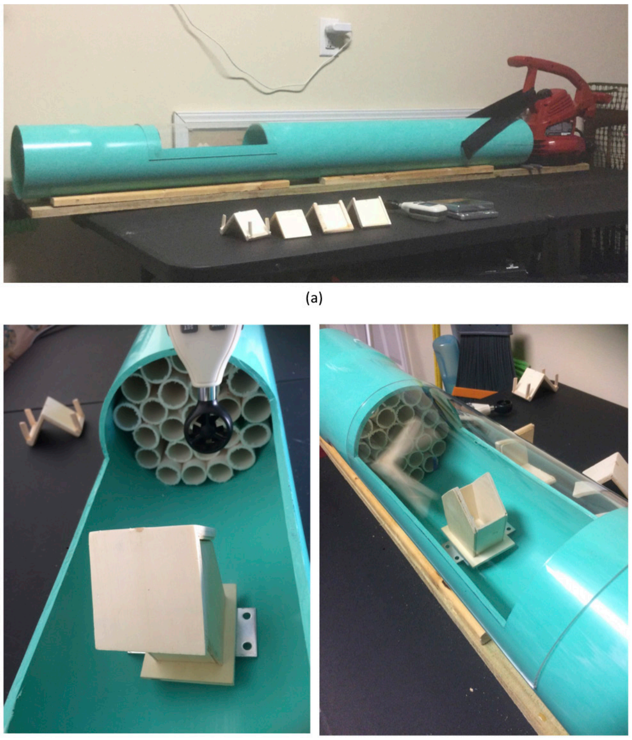
Previous experiments with mitigation devices have been conducted to try to lesson vortices on roofs, but they have been primarily on high- and low-rise buildings with flat roofs. In one experiment, the mitigation devices used were a barrier, a circular-out, a circular-in, a slope-out, a slope-in and an airfoil edge. Of these, the airfoil edge produced the smallest uplift loads (8). In another experiment, researchers examined vortex reduction using different roof attachment methods and a modified rounded edge design on a flat roof. The modified edge was useful in reducing vortices (11). In yet another experiment, different types of parapets successfully mitigated the effects of high winds on flat roofs (12). In researching the type of wind mitigation devices used in previous tests, parapets seemed to be the most effective in displacing or disrupting the formation of vortices, although rounded devices were also effective in reducing uplift forces, as they eliminate vortex-forming sharp edges (9). However, little research has been done on a gabled roof. Only one previous experiment was found in the research using a gabled roof, in which researchers tested trellises (pergolas), roof extensions of gable ends, ridgeline extensions, and sideways extensions of walls as the mitigation devices. The results demonstrated a reduction in peak suction with all these devices (13). In the current study, we used a gabled roof because it has been shown that the high rising feature of a gabled roof makes it more resistant to vortex formation during a hurricane than a flat roof and because it is a more common design in modern day residential buildings (8).

After examining the literature and previous research done on this subject, the hypothesis for this experiment stated that if a barrier, a rounded shape, or an airfoil mitigation device were put on a gabled roof and tested against simulated hurricane winds, then the roof with the airfoil shape mitigation device would take the longest amount of time to blow off. The hypothesis was based primarily on the research done by Aly (8), in which an airfoil edge was the most effective device to mitigate winds, and Suaris and Irwin (12), in which different parapets proved effective in mitigating the effects of wind on flat roofs. The perpendicular airfoil in this experiment is a unique design that combines Aly's airfoil edge with Suaris and Irwin's raised parapets.

We simulated Category 2 winds on three different mitigation device designs and found that the upright airfoil design performed best in keeping the roof attached for the longest amount of time. The results from this experiment suggest that the aerodynamics of an upright airfoil could present a solution for the problem of roofs flying off houses when subjected to hurricane wind forces and should be in studied further detail.

RESULTS

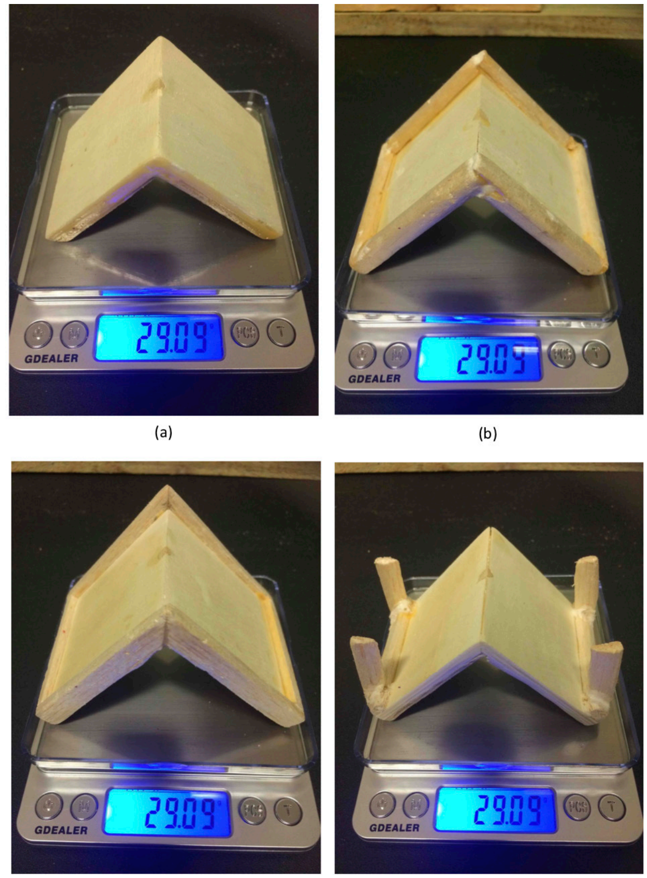
We tested three different types of wind mitigation devices against simulated hurricane winds to see which device reduces the uplift forces the most compared to a common gabled roof. We tested gabled roofs on small birdhouses with winds simulated by a homemade open wind tunnel, constructed using a leaf blower and PVC pipe (**Figure 1**). This design was an inexpensive but effective way of testing the effects of strong winds, using a birdhouse that was approximately a 1:200 scale model of the size of a real gabled roof house. The mitigation devices were a rounded shape, a barrier, and a



(a)

(b) (c)

Figure 1. Wind tunnel. a) The experiment was conducted in a homemade open wind tunnel made of PVC pipes, acrylic, a leaf blower, and a wooden base. **b)** A roofless birdhouse was bolted onto a metal plate in the tunnel and each roof was placed on top for testing. The wind speed was measured prior to testing the control roof. **c)** An acrylic cover was placed over the test section and the leaf blower was turned on as the timer was started. The wind hit the roof against one of the slanted sides until the roof completely flew off the birdhouse and the timer was stopped.



(a) (b)

(c) (d)

Figure 2. Control and modified roofs. Craft store birdhouse roofs were modified with different mitigation devices. **a)** Control roof with no mitigation device. **b)** Rounded edge mitigation device. **c)** Barrier edge mitigation device. **d)** Upright airfoil mitigation device.

perpendicular airfoil shape. We chose a rounded edge (**Figure 2b**) because domed houses have been found to survive hurricanes (14); a flat edge barrier mitigation device (**Figure 2c**) because of the previous study with a barrier edge on a flat roof (15); and an upright airfoil design (**Figure 2d**) because of the research mentioned earlier showing evidence that airfoil edges and parapets are effective at mitigating uplift forces on flat roofs. By combining the design of an airfoil edge and a parapet, the resulting mitigation device was an upright airfoil, which resembles a winglet on an airplane. Further research into winglets showed that their main purpose is to redirect vortices on airplane wings, thus reducing drag and providing fuel savings to airlines (16). Since the rationale behind this experiment was to find a mitigation device that could reduce the vortices that cause uplift forces on a roof, an upright airfoil was a promising design to test on the roof.

The airfoil significantly outperformed the other roof wind mitigation devices in all ten trials, with the time from when the blower was turned on to when the roof completely flew off the house ranging from 9.12 to 21.05 seconds (**Figure 3**). The rounded edge also took a large amount of time to fly off, more than the other two devices, over a range of 5.78-9.45 seconds. However, the airfoil did a substantially better job than the rounded edge. There was little difference between the control roof (2.97-5.84 seconds) and the roof with the barrier edge mitigation device (3.61-7.29 seconds, **Figure 3**). The averages of the control and barrier roof, 4.19 seconds and 4.31 seconds respectively, were each less than one-third of the average time for the airfoil, at 13.77 seconds. All of the results are within three standard deviations, except for the airfoil, which was slightly above (σ = 3.11), due to an outlier on the first trial.

P-values for this experiment were calculated on an Excel spreadsheet, using a default alpha of 0.05, and those independent results were validated through a Holm-Bonfferoni correction. With a p-value of 0.40, the barrier edge did not significantly impact the amount of time it took for the roof to fly off when compared to the control roof with no mitigation device. However, the rounded edge and the airfoil configurations both had p-values of $p < 0.01$ (**Figure 3**), meaning that those devices significantly increased the time it took for the roofs to fly off when compared to the control roof.

DISCUSSION

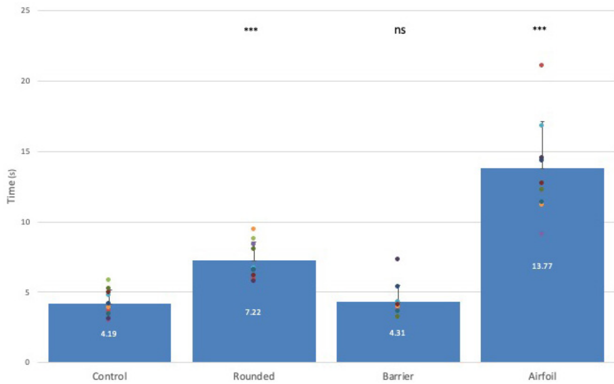


Figure 3. Time for roof to blow off using different mitigation devices on a gabled roof. The control roof and each roof with a mitigation device were tested 10 times, with the timer starting as soon as the leaf blower was turned on to full power and ending when the roof completely blew off the house. The blue bars indicate the average time it took each roof to fly off over ten trials, represented by the scattered dots. The error bars show standard deviation. On average, all roofs with mitigation devices stayed on longer than the control roof, although the improvement with the barrier roof was nonsignificant (ns, p = 0.40). The roof with the rounded edge performed much better than the control roof, staying on the house almost twice as long, and the roof with the airfoil mitigation device performed the best, staying on the house over three times as long as the control roof. Both the rounded edge and airfoil roofs had p-values < 0.01 (***), indicating that they contribute significantly to the reduction of uplift forces on a gabled roof when compared to the roof with no mitigation device.

Of the three mitigation devices tested in this experiment, the airfoil design had the greatest effect on mitigating the winds on the gabled roof from the simulated hurricane. The roof with the upright airfoil configuration stayed on the roof more than three times longer than both the control roof and the roof with the barrier edge. The barrier edge produced a non-significant improvement over the control roof, but the other two devices showed significant increases in the time the roofs stayed attached to the house before flying off when compared to the control. The experiment supported our hypothesis that if the same three mitigation devices were tested against simulated hurricane winds on a gabled roof, then the roof with the airfoil shape mitigation device would take the longest amount of time to blow off. This hypothesis was based on previous research that used an airfoil edge and another that used parapets to mitigate the uplift forces, but an upright airfoil design had never been tested before. By adding modifications to the edge of a gabled roof, the experiment showed that the destructive airflow patterns caused by high winds can be easily changed. The roof with the airfoil design stayed on almost twice as long as the rounded edge by redirecting the vortices that create the uplift forces, making it the most promising device for mitigating those damaging forces on gabled roofs.

This experiment may lead to the addition of certain mitigation devices on roofs, specifically in areas that are prone to hurricanes such as Florida. This would decrease the number of roofs being blown off during hurricanes, saving thousands of dollars in insurance claims and roof repair. The mitigation device is cost effective because it would not mean putting a new roof on houses, just adding the device to existing roofs. The airfoil mitigation device on the roof would redirect and reduce the formation of vortices, increasing the time taken for roofs to blow off and lessening insurance bills.

The wind measured at the beginning of the wind tunnel was 7.7 meters per second (m/s), or 27.7 km per hour, and the birdhouse was approximately a 1:200 scale model of the size of a real home. Although the leaf blower was rated at approximately 67 m/s, the air expands quickly after exiting the leaf blower nozzle and slows even more as it travels through the smaller PVC pipes. This considerably slows the output air down before reaching the test window. Because the wind created enough uplift forces to lift the roof off the house in all trials, the equivalent wind could have been comparable to at least a Category 2 hurricane (based on the Saffir-Simpson Hurricane Wind Scale descriptions of damage possible for each category). However, it is hard to make an accurate estimate of the hurricane category of the winds simulated in this experiment because the roofs used in this experiment were those of birdhouses, not of real houses, and the because the wind came from a homemade wind tunnel, not an actual hurricane. Also, these roofs were made from unfinished craft wood and the mitigation devices were made from balsa wood; not solid construction-grade wooden frames with metal, asphalt, shingles, or tiles to protect and weigh them down. Finally, the roofs were not attached in any way to the birdhouse as a real roof would be attached to the structure of the house. This was another factor that differentiated this experiment from a real hurricane situation but did not detract from the results of this experiment, because the lack of attachment was consistent for all roofs being tested, including the control. This experiment was not testing construction strength or materials. Instead, it tested aerodynamic forces acting on the roof during high winds.

Before testing, a trial run with the wind tunnel was performed. During that initial trial run, the roof did not fly off at all because the airflow straighteners were lined up with the beginning of the test window, making the air coming out too laminar when it hit the roof and not allowing the formation of vortices. By moving the straighteners back toward the leaf blower by about an inch, vortices were able to form on the roof edges. The straighteners stayed in this new position for all testing, which allowed the straighteners to serve their function of keeping the angle the wind hit the roof to be constant throughout all trials, yet still allow vortices to form.

A systematic error in this experiment was that most wind tunnels are used for looking at wind patterns, not for simulating hurricanes. This may have made the wind flow differently from wind in a hurricane. Some random errors in this experiment were that the stopwatch and knob on the wind tunnel turn on at different speeds. The knob takes longer to reach full power (the amount used for testing), while the stopwatch is instantaneous.

This may lead the results to be a few milliseconds off.

Additionally, wind vortices change the pressure distribution on the roof. If the roofs fly off because of pressure differences, an idea to consider would be inserting a PVC pipe through the house. The pipe would have small holes, allowing air to pass through, but not rain or strong wind gusts. This or some other pressure release valve/system combined with the airfoil roof could eliminate roofs flying off all together.

In addition, it would be interesting to contrast between the constant wind used in this experiment and simulated gusts of wind. In this experiment, a constant wind was used because the Saffir-Simpson Scale uses sustained wind speed to determine a hurricane's category. However, gusts could be utilized to show how the same roof design may hold up to other types of natural disasters or during the eye of the hurricane when the wind stops temporarily before increasing rapidly again. The gusts could be simulated by making a mechanical device, such as a metal plate attached to a lever, that would block the output from the leaf blower that could be moved to different positions without taking the acrylic top off the wind tunnel. The design of the roofs themselves can also be altered. For example, it would be interesting to see if there is a direct relationship between the weight of the roof and the time it takes before it blows off, or if combining both the rounded edge and the airfoil mitigation device onto one roof significantly changes the results. Finally, the roof's aerodynamic properties could be simulated in a Computational Fluid Dynamics (CFD) analysis, which would make it easier to manipulate and understand all the forces acting upon them. CFD has been used more and more since the 1970's as a way of studying airflow around buildings because it is more practical, faster, and cheaper than using wind tunnels, and it allows them better control of the data being studied (17). The results from this experiment could be validated and expanded using computational tools.

The next step in testing the airfoil design would be to test different configurations of airfoils, including airfoils of different heights and multiple airfoils spread across the edge of the roof. Several roofs with the same devices should be made for experimental replication, and the wind should be tested hitting the house from different directions other than just directly onto the broad side. This would allow a study of how the wind vortices can form on different parts of the roof, as winds typically shift during hurricanes. The house could also be mounted on a rotating platform to see how the wind affects it from multiple directions with only a quick period of time in each direction. Another way of achieving this same purpose would be to make the house stationary but attached to a point outside of the wind tunnel via a cutout in the wind tunnel, and then have the wind tunnel on a rotating disk so it would circle around the house. If the results of either of these methods for variable wind direction are the same as the results from this experiment, that would strengthen the support for the airfoil shape as the most favorable mitigation device for keeping the roof on the house as stated in the hypothesis of this experiment (if a barrier, a rounded shape, or an airfoil mitigation device were put on a gabled roof and tested against simulated hurricane winds, then the roof with the airfoil shape mitigation device would take the longest amount of time to blow off). Ideally, this could lead to a full-scale test. Florida International University's Wall of Wind Experimental Facility is one example of a full-scale wind tunnel specifically designed to study the effects of wind on infrastructure and to find possible solutions to mitigate the problem. Full-scale testing of a model with a roof that is physically attached to the house in actual hurricane winds would validate the results presented in this paper.

In this experiment, a total of three modified roofs were tested against uplift forces on a gabled roof. The roofs were modified with the following types of mitigation devices: a rounded edge, a flat edge barrier device, and four upright airfoils. The roof with the flat barrier edge showed a non-significant change in the amount of time it took for the roof to fly off when compared to the control roof, but the roofs with the rounded edge device and the airfoil device stayed on significantly longer than the control roof. T-test results showed p-values < 0.01 for each of those two roofs. The mitigation device that made the roof stay on the longest in simulated hurricane winds and the roof with the lowest p-value was the airfoil. Staying on almost twice as long as the roof with the rounded edge and over three times longer than both the control roof with no mitigation device and the roof with the barrier edge, this last design has the best potential of all of the designs studied in this paper to minimize the potential of roofs flying off in hurricanes, thus possibly saving lives and millions of dollars' worth of property damage.

MATERIALS AND METHODS

Wind Tunnel Construction

The homemade wind tunnel was built using a 152.4 cm length, 15.24 cm diameter Schedule 40 PVC pipe and a Toro Ultra Electric Leaf Blower with a high-speed nozzle, rated at 0.702 air horsepower. A viewing window approximately one-third of the way from the edge of the pipe was made by cutting a 29.0 cm opening with a depth midway through the pipe. A window, using a cut sheet of acrylic that was heated in an oven and molded over a slightly smaller pipe until cool, was placed over the viewing window to prevent air from escaping. Two sets of twenty-five 20-cm sections of 1.9 cm diameter PVC pipe were joined together separately and gently tapped into the large pipe on either side of the viewing window with a rubber mallet. These small pipes straightened the airflow that came out of the leaf blower. A test bed was made and attached to the inside bottom of the large pipe in the center of the viewing window, and then the wind tunnel was bolted onto a plank of wood to keep it from rolling. A plastic kitchen funnel with approximately the same inside diameter as the large PVC pipe was taped onto the leaf blower high-speed nozzle to diffuse the air coming out of the leaf blower, and the leaf blower nozzle was then inserted into large PVC pipe on the side farthest from the viewing window. Using Velcro, the leaf blower motor was then attached to the wooden plank to keep it from shifting from vibration when turned on. **Figure 1a** shows a photo of the completed wind tunnel. **Figure 1b** shows the placement of the birdhouse inside, and **Figure 1c** shows the operating tunnel with the acrylic window in place. **Figure 4** shows a CAD drawing of the wind tunnel with dimensions and includes an expanded view of the birdhouse in the tunnel with its dimensions and position relative to the wind from the leaf blower.

House and Mitigation Device Construction

Four natural unfinished wood birdhouses (Birdhouse by ArtMinds, Model 308374) were purchased from a local craft store for testing. The roofs were removed and all but one roofless birdhouse wall discarded. The trim and hanging string were removed from the roofs and the perch was removed from the house. All holes were completely sealed with wood or glue to prevent air from entering the house while testing. The roofless birdhouse was then bolted onto the test bed of the wind tunnel. The mitigation devices were made using a 1 cm x 0.5 cm x 91.44 cm balsa wood stick, an Exacto knife, and sandpaper. Each mitigation device was designed so the barrier and rounded edges matched the edge length of the roof. The remaining wood from the stick was cut into 4 equal pieces that would become the airfoil designs. Each piece of the balsa wood stick was then sanded into the desired shape. The mitigation devices were then each attached to a roof using wood glue, ensuring that each of the roofs weighed the same when completed so that just the aerodynamic effects of the devices were observed (**Figure 2**). The weight of each roof was adjusted by either sanding any excess weight off or adding wood glue to the bottom side as needed.

Mitigation Device Testing

Before testing, the wind was measured by holding a JRLGD Model 816A-EN-00 digital anemometer at the beginning of the test window and turning on the leaf blower to full power (**Figure 1b**). For this experiment, the wind was recorded at 7.7 m/s. The roofs were then positioned onto the birdhouse bolted inside the wind tunnel and were not attached in any way - allowing just the geometry to hold it in place. Next, the acrylic window was placed over the test section and the leaf blower was turned on to full speed. An iPhone stopwatch was used to measure the amount of time it took for the roof to fly off the birdhouse, starting the timer immediately as the blower dial began to be turned on to full speed and stopping it when the roof detached from the roof (**Figure 1c**). The results of each of the 10 trials per roof were recorded, starting with 10 sequential trials of the control roof, followed by 10 trials of the rounded edge roof, then 10 trials of the barrier edge roof, and finally 10 trials of the roof with the airfoil mitigation device. The roofs were inspected for damage and reweighed after each trial before being positioned back on to the birdhouse. Wind speed, weight of the house, the weight of each roof being tested (including mitigation devices), the angle the wind hit the roof (angle of incidence), the placement of the roof on the house without using attachments, and the orientation of the house in the tunnel were constant across groups.

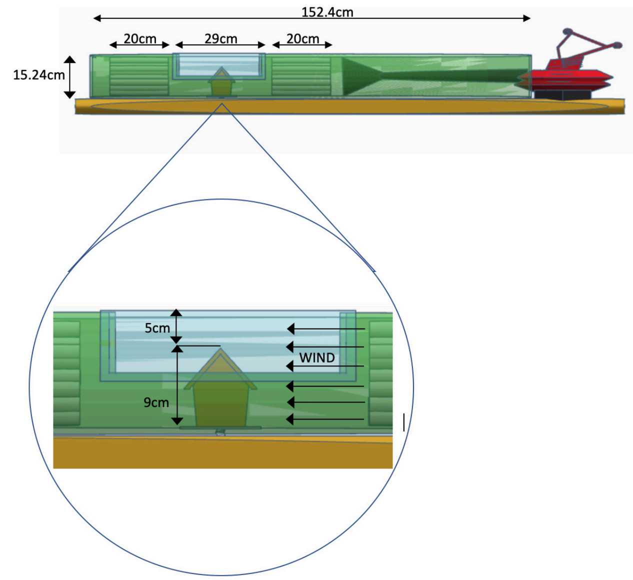


Figure 4. Wind tunnel dimensions and birdhouse placement. A wind tunnel was built using a 152.4 cm length 15.24 cm diameter PVC pipe and a leaf blower. A funnel was duct taped onto the end of the leaf blower nozzle to control the expansion of air exiting the blower. The air then passed through twenty-five 20 cm length pipes (1.90 cm diameter) to reduce random turbulence that would skew the results before hitting the side of a 9 cm tall birdhouse with the gabled roof placed on top. A gap of 5 cm between the top of the roof and the acrylic viewing window allowed room for the roof to lift off the house, as observed from the 29 cm test window cutout in the large pipe.

Statistical Analysis

The data from this experiment was recorded in a table which was put into an Excel spreadsheet. From the table, the data was analyzed in Excel by calculating averages and standard deviation and by performing a two-sample t-test assuming equal variances to calculate the p-values. This allowed a determination of the probability that none of the devices would make a difference as to how long each roof stayed on, when compared to the control roof. For the *p*-value calculation, the Excel default alpha of 0.05 was used, and then a Holm-Bonferroni correction was performed to correct for the three independent comparisons and confirm the experiment's results.

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