



# RESILIENT INFRASTRUCTURE

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## FULL-SCALE TEST METHODS FOR MULTI-LAYER CLADDING SYSTEMS: WIND TUNNEL VS. MULTI-CHAMBER AIRBOX

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### ABSTRACT

Wind loads on multi-layer wall systems are complicated because the loads on each particular layer are poorly understood and difficult to quantify. This is because of pressure equalization, which is the mechanism whereby the pressures on the external building surface are transmitted through the air-permeable outer layer to interior layers. Recent testing at IBHS in a full-scale wind tunnel has shown that the extent of pressure equalization is more limited than is assumed in the test standard, ASTM D3679-13. Multi-chamber pressure testing performed by the authors at the Insurance Research Lab for Better Homes was able to capture these features in these results using more commonly utilized ASTM-style (airbox) testing. The objective of the current study is to examine the effects that the pressure time history inputs have when comparing the full-scale wind tunnel method data with that from the multi-chamber airbox method. This is accomplished by comparing the power spectral densities of the external and cavity pressures, as well as fitting the peak pressure equalization factor data to a Gumbel distribution. From a comparison of the power spectral densities of each airbox vs. the relevant full-scale, wind-tunnel external pressures, it was noted that larger airboxes created a larger source of error of the peak pressures in the system.

Keywords: pressure equalization, full-scale, wind tunnel, airbox

### 1. INTRODUCTION

One of the most common failures observed in damaging windstorms is the wall system of residential, wood-frame buildings, particularly the exterior cladding layer (e.g., vinyl siding, etc.). With recent changes in climate, these losses are becoming more and more common. Figure 1 shows a photograph of a residence affected by the tornado in Angus, Ontario on June 17, 2014 where significant failure of vinyl siding occurred. Such failures can cause significant financial loss due to water infiltration. In this paper, full-scale wind tunnel data from the Insurance Institute for Business & Home Safety (IBHS) (Cope et al. 2012) is compared to the replicated data from the multi-chamber airbox study performed in the Insurance Research Lab for Better Homes (IRLBH) lab at The University of Western Ontario (Miller et al. 2015). Although the external pressure applied are exactly the same, there is a difference in the pressure equalization factor obtained when both results were analyzed. The differences in results may be due to the fidelity of the multi-chamber airbox in replicating the full-scale wind tunnel data.



Figure 1: House from Angus, Ontario tornado with failure of vinyl siding.

The purpose of this paper is to determine the magnitude that the errors in fidelity have on the overall results of the system. This will be analyzed first through a spectral analysis of the entire simulated wind event, comparing the full-scale wind tunnel spectra to the multi-chamber airbox spectra for both the external pressures and the cavity pressures of the cladding. After that, using an extreme value analysis, the peak data will be fit to a Gumbel distribution.

## 2. PRESSURE EQUALIZATION

Wind loads on multi-layer wall systems are complicated because the loads on each particular layer are poorly understood. This is because of the pressure equalization, which is the mechanism whereby the pressures on the external building surface are transmitted through the air permeable outer layer to interior layers (Suresh et al. 2000). Pressure equalization factor (PEF) can be represented as:

$$[1] \quad PEF(x) = \frac{P_{external}(x) - P_{cavity}(x)}{\hat{P}_{external}}$$

where  $PEF(x)$  is the pressure equalization factor along a location represented by  $x$ ,  $P_{external}(x)$  &  $P_{cavity}(x)$  are the external and cavity pressures respectively at that location, and  $\hat{P}_{external}$  is the peak overall external pressure over all airboxes.

In addition, effects of the flexibility of the external layer, such as for vinyl siding, are not well understood, but may also have a significant effect on performance near the limit state. Currently, there is little design guidance available; in fact, building codes provide no information at all, except to note that it occurs. Understanding pressure equalization is crucial to understanding how loading is transferred through multi-layer systems, and ultimately, to understanding how failures occur. For example, if pressures are applied uniformly and statically across the outer layer of vinyl siding, the gaps in the joints allow the pressure on the backside of the vinyl to become identical to the external pressure. As a result, when a uniform, static pressure is applied, the outer layer carries no net load. When the external pressures are uniform, but varying in time, the net load can be relatively small, depending on the geometric parameters of the cladding system. However, when there is an external pressure gradient across the wall, the net loads over the vinyl siding will increase substantially (Oh et al. 2014). This was demonstrated through recent IBHS testing (and can also be seen in the current work). Temporal variations contribute to the net load, but spatial variations have a much larger effect on the net loads over exterior cladding.

## 3. IBHS TESTING

Recent tests from the Insurance Institute for Business & Home Safety (IBHS) examined the loads on various siding systems using their full-scale wind tunnel (Cope et al. 2012) (Cope et al. 2014). The experiments were conducted on

the walls of a full-scale, single story wood-frame house. The building has plan dimensions of 9.1 m (30 ft.) x 12.2 m (40 ft.), a mean roof height of approximately 3.7 m (12 ft.), and a roof slope of 4-on-12. The walls of the test building were 2.4 m (8 ft.) wall and clad with 11.1 mm (7/16") OSB. A total of four siding products were tested: vinyl siding, foam backed vinyl siding, wood siding and fiber cement siding. In order to test all four products simultaneously the walls of the building were divided into eight sub-wall assemblies. The long walls were divided in half resulting in a test wall 6.1 m (20 ft.) long, while the short walls four test walls extended 3.7 m (12 ft.) from the corner leaving 6 ft. in the center of the short wall to access the interior of the building. All siding products were installed following the manufacturers guidelines; drywall was installed on the interior of the walls so that the wall assembly matched, as accurately as possible to real construction. Along the 6.1 m (20 ft.) walls the wind loads were measured at 16 locations, while along the 3.7 m (12 ft.) walls they were measured at 12 locations. Figure 3 shows a diagram of the pressure tap locations on wall #1. At each measurement location the external pressure, the net pressure across the siding and the net pressure across the OSB were measured simultaneously. Experiments were conducted in an open exposure (see Morrison et al, 2014 for full flow characteristics) at four different wind speeds. The orientation of the building to the wind was varied over a full 360° in 10° increments (Morrison et al. 2014). The results of this testing indicate that pressure equalization has a large effect on the outer layer (i.e., the vinyl siding) of these systems. In fact, results have shown that vinyl siding must carry a net load of up to 75-80% of the net load across the entire wall assembly.

#### 4. IRLBH TESTING

An experimental study was conducted to determine the role and extent of pressure equalization for walls with exterior cladding. Pressure Loading Actuator's (PLA) were used to generate the loading on the test specimen. A fan is used to generate the flow and create the pressure applied to the system. A rotating disk inside the valve, which is controlled by a servomotor, is used to regulate the pressures applied to the system. The pressure inside each airbox is monitored by a pressure transducer, which is then connected to the PLA. The pressure transducer sends data via an Ethernet network, and through the use of a PC-based controller, the position of the valve is updated approximately 100 times per second (Kopp et al, 2010). The PLAs are attached to the pressure chambers, where the wall assembly provides one of the surfaces in the pressure chamber. The PLAs are used to generate a negative pressure on the test specimen, which is the worst-case scenario and leads to the siding being pulled from the wall. Positive pressures were not examined in this study, as they do not create a critical failure mode.

Normally, when a specimen is tested at the Insurance Research Lab for Better Homes, multiple dynamic pressure-chamber systems are used to re-create realistic wind pressures obtained from wind tunnels. These pressure chambers are usually created using vinyl bags with steel rods as stiffeners. However, normal techniques to create a multiple airbox system on vinyl siding will not provide accurate results. This is because vinyl siding is a very flexible material, and it needs to be able to freely displace. Consequently, the technique of using a rigid membrane between each airbox will not work for such a flexible material. Therefore, a new testing apparatus must be developed. This apparatus must be able to successfully create pressure gradients across a sample of vinyl siding, without affecting the response of the vinyl siding. It must also create a perfect seal between each separate airbox. The testing apparatus also needs to be a repeatable and cost-effective process, allowing it to be implemented in other testing facilities as easily as possible.

In order to create multiple chambers in this airbox, barriers that met the following material requirements was required:

1. Flexibility – In order to obtain accurate results, the barriers had to not affect the performance or deformations of the vinyl siding. This meant that the barriers essentially had to have zero stiffness and minimal weight in order to not change how the vinyl siding acted while the wind loads were applied.
2. Non-Permeable – Since the objective was to create a multiple airbox chamber, the main function of the barriers was to create a relatively perfect seal between the two test chambers. Not only did the connections have to ensure this, but the barriers as well had to be non-permeable.
3. Strength – Any tears or rips in the barriers would cause for inaccuracies in the results, and therefore the material had to be strong enough to withstand large differential pressures from across two airboxes.

After taking these material properties into consideration, a latex barrier system was chosen to fulfill all of the material requirements. Small scale testing showed that latex worked well in all of its required functions, and therefore was implemented on to full scale testing.

As the objective was to replicate the IBHS results, the test specimen was built to similar standards and dimensions. The wall was 12 ft. long by 8 ft. high, which is the same as the IBHS wall. 2"x4" were used as the studs, followed by the placement of 3/4" plywood on top. The plywood is much thicker and of much higher quality than used in typical North American construction. However, because the objective of the study was to solely look at the response from the exterior cladding, thicker materials were used so that only the exterior cladding could fail under these loads. A polyurethane sheet was placed in between the studs and the plywood to seal the airbox chamber. House wrap was then placed over the plywood to replicate typical construction practices. Pressure taps were then installed on to the plywood at similar locations to the IBHS wall. Vinyl siding was then nailed on to the wall using No. 10 1" roofing nails at 8" intervals along the length of the wall. All pieces of vinyl siding were cut to be 12 ft. long in order to not have any lap splices in the test chamber. Starter strips, ending strips and utility trim were also used to model typical construction practices. Pressure taps were then installed directly above the plywood pressure taps, again at similar locations to the IBHS wall. The latex was then glued on to the vinyl siding wall to create five chambers for this test: Four chambers which are 2 ft. long and one chamber which is 4 ft. long (all along the length of the vinyl siding). The chambers were built to contain one set of pressure taps in the horizontal direction. A hook was then installed on to the top of the wall so that a crane could pick up the test specimen and put it in place in the constructed test chamber.

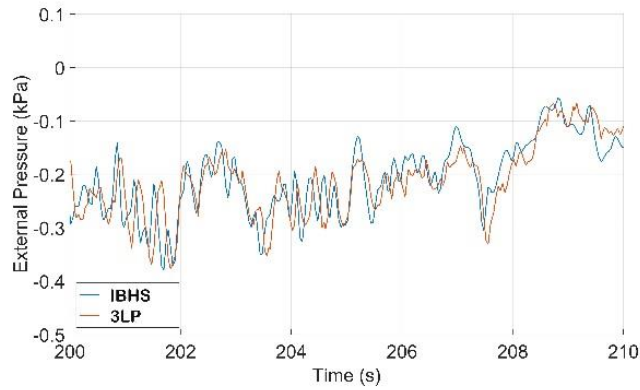
The main conclusions of the study was that the concept of creating a multi-chamber, pressure-based, testing apparatus that can accurately model the physics and effects of pressure equalization on a wall system with flexible cladding has been proven to work. This was accomplished by the creation of multiple flexible latex barriers to enable the application of multiple, discreet, time-varying loads across a test specimen. After plotting the differential pressure (net load across vinyl siding) vs. time, it was clear that spatial variations across the test specimen made a large contribution to the differential load across the exterior layer of cladding. The temporal variations also play an important role, but not as important as the spatial variations.

## **5. DIFFERENCES IN RESULTS**

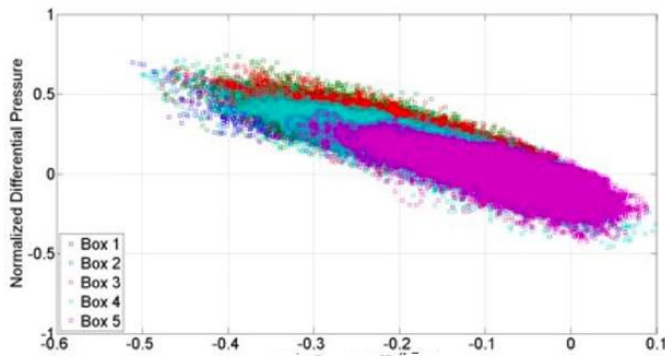
Although much effort was put into commissioning and tuning the PLA's before the multi-chamber airbox testing, there are still differences in the PEF results between the two different test methods. Some of it may be due to the simplification made by turning a pressure gradient into 5 uniform pressures across the wall, however the largest contributing factor is believed to be due to the PLAs themselves due to their accuracy (fidelity), and phase shifting, both of which are described below.

### **5.1 Fidelity of Pressure Loading Actuators**

Overall, the PLA system was not fully able to replicate the applied external pressure time histories from the IBHS results, Figure 2 shows the pressure equalization factor plotted against the external pressure for both the full-scale wind tunnel method (top), and the multi-chamber airbox method (bottom) for direct comparison while examining the fidelity errors. Minor smoothing of the peak pressures occurred, causing some inaccuracies in replicating the pressures from the full-scale wind tunnel study. Figure 3 shows a zoomed-in section of the external pressure comparison, showing peak smoothing. Recent model scale testing of multi-layer roof systems (Oh et al. 2014) suggests that the short duration, localized peak pressures control the cavity pressure, and the resulting net wind loads, to a significant extent. As mentioned earlier, temporal variations also contribute to the net load, but spatial variations have a much larger effect on the net loads over exterior cladding and is considered the driving force in the resulting magnitude of the net load. For these reasons, the fidelity of the system can be a contributing factor to why the magnitudes are slightly different than the IBHS results. As mentioned before, short duration peak pressures control the cavity pressures, and if they are being smoothed, the magnitude of the system will tend to be slightly lower. However, if they are overshooting the target pressures, the magnitude of the system will tend to be slightly higher. Even though the magnitudes are slightly different due to smoothing or overshooting of the system, a definite similar trend is shown between the two sets of data.



**IBHS**



**IRLBH**

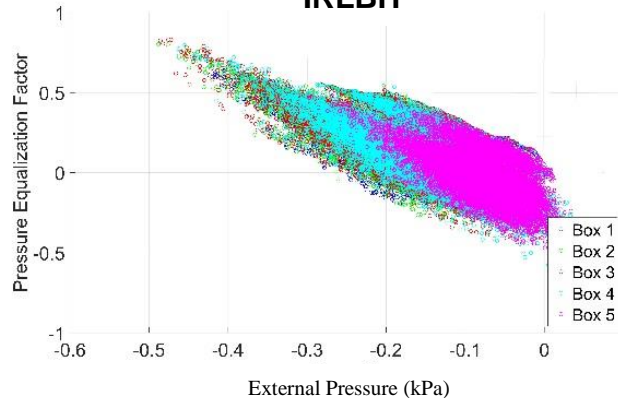


Figure 2: A direct comparison showing the effect that the fidelity of the multi-chamber airbox method has on the pressure equalization factor results.

## 5.2 Phase Shift

Another error that is due to the lag of the peak external pressures (referenced as a phase shift) between the full-scale wind tunnel data, and the replicated external pressures from the multi-chamber airbox approach. Figure 3 shows a

zoomed in section of the external pressure comparison, showing a phase shift. It is caused by a lag in communication from the feedback loop between the PLA, and the computer running LabView software. The phase-shift is generally smaller than 0.05 seconds and for that reason, the phase shift will not have an overall large effect on the spectral analysis of the two sets of external pressure. This is due to the fact that the spectral analysis does not take into account at what point in the time history that the external pressure occurs. However, when examining the peak pressure equalization factors of the system, and when they occur, the phase shift will play an important role in comparing the pressure equalization factor at certain times directly.

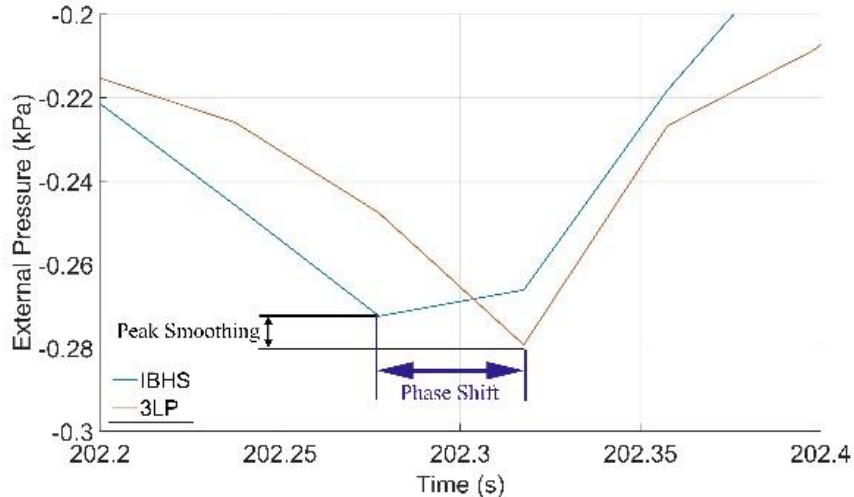


Figure 3: A zoomed in section of the external pressure comparison between full-scale wind tunnel data and multi-chamber airbox testing showing a) peak smoothing b) phase shift

## 6. SPECTRAL ANALYSIS

Using the Fast Fourier Transform method, the power spectral density was calculated using the external pressures from the IBHS data, and the IRLBH data (from Miller et al, 2015). The power spectral density was then plotted against the frequency. Because of the multi-chamber airbox system, the power spectral density was calculated for each of the 5 airboxes, and compared to the relevant full-scale wind tunnel data. These plots can be found in Figure 4.

In the lower frequencies, where the higher energy occurs, the similarities between the external pressures of IBHS & 3LP is very high. These regions corresponds with the peak pressures of the time history. However, in the regions of lower energy, the correlation between the external pressures of IBHS & 3LP is lower than the higher regions. The lower regions tend to be following the same pattern, with the 3LP results at a slightly lower magnitude of energy compared to the IBHS results. These regions corresponds with the peak pressures throughout the system. At 10 Hz, the energy of the two systems becomes completely unrelated. This is due to the fact that the PLA system cannot replicate any frequency higher than 10 Hz and creates white noise in its place.

Looking at the comparison between the power spectral densities of the external pressures, it is encouraging to note the peak pressures are for the most part being accurately replicated. As mentioned in the fidelity section, the driving force for the net load in the system is the spatial variation on the system. Furthermore than that, the peak pressures are responsible for creating the largest net loads on the exterior layer of cladding. To see that the energy is very well correlated for the higher pressures means that the net load (and consequently the pressure equalization factors) should be well related as well. This is further examined in the extreme value analysis.

Another item to analyze is the individual airboxes. Due to the multi-chamber airbox testing, the full-scale wind tunnel was broken up into discrete uniform loads across the wall, leading to 5 separate graphs comparing the power spectral density of each airbox. Examining the graphs visually, two main concerns present itself from the analysis. Airbox #1, is much less correlated at the higher frequencies when compared to the airboxes. Airbox #1 contained some of the most drastic and rapidly changing peak pressure. Consequently, it's also the location of most of the peak pressure equalization factors. This could have a large effect on the correlation of the peak net loads of the structure. This is

further examined in the extreme value analysis. The second item to note with the airboxes, is that Airbox #5 loses correlation much faster than the other airboxes. A number of reasons could be possibly causing this, however, the most suspect reason is difference in the size of the airboxes. It can be noted that Airbox #5 has double the volume of all of the other airboxes to accommodate the location of the pressure taps from the IBHS system. This difference in volume causes the PLA system to have to work harder to keep up with applying the external pressures from the full-scale wind tunnel. Thanks to this analysis, this problem has now been identified, and smaller airboxes can be potentially used in the future to help improve the fidelity of the two airbox system. Although this hypothesis cannot be fully confirmed due not enough time to complete the appropriate testing, it is quite likely that this relationship is valid based on the power spectral density graphs. Further testing shall be done in the future with varying airbox sizes to confirm this hypothesis.

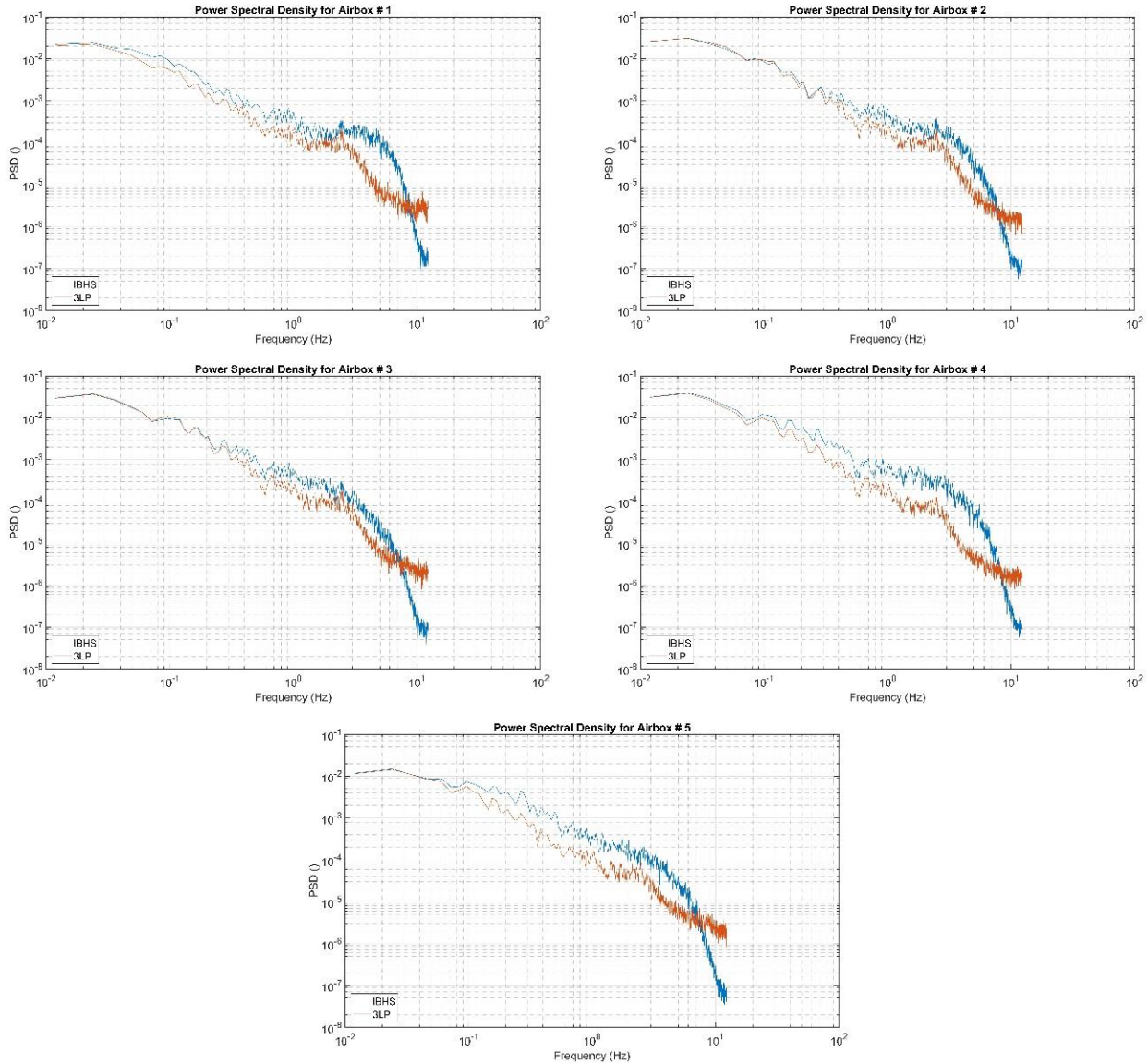


Figure 4 – Power Spectral Density vs. Frequencies of external pressures for 5 airboxes from IRLBH testing, with comparison to the power spectral density from IBHS testing.

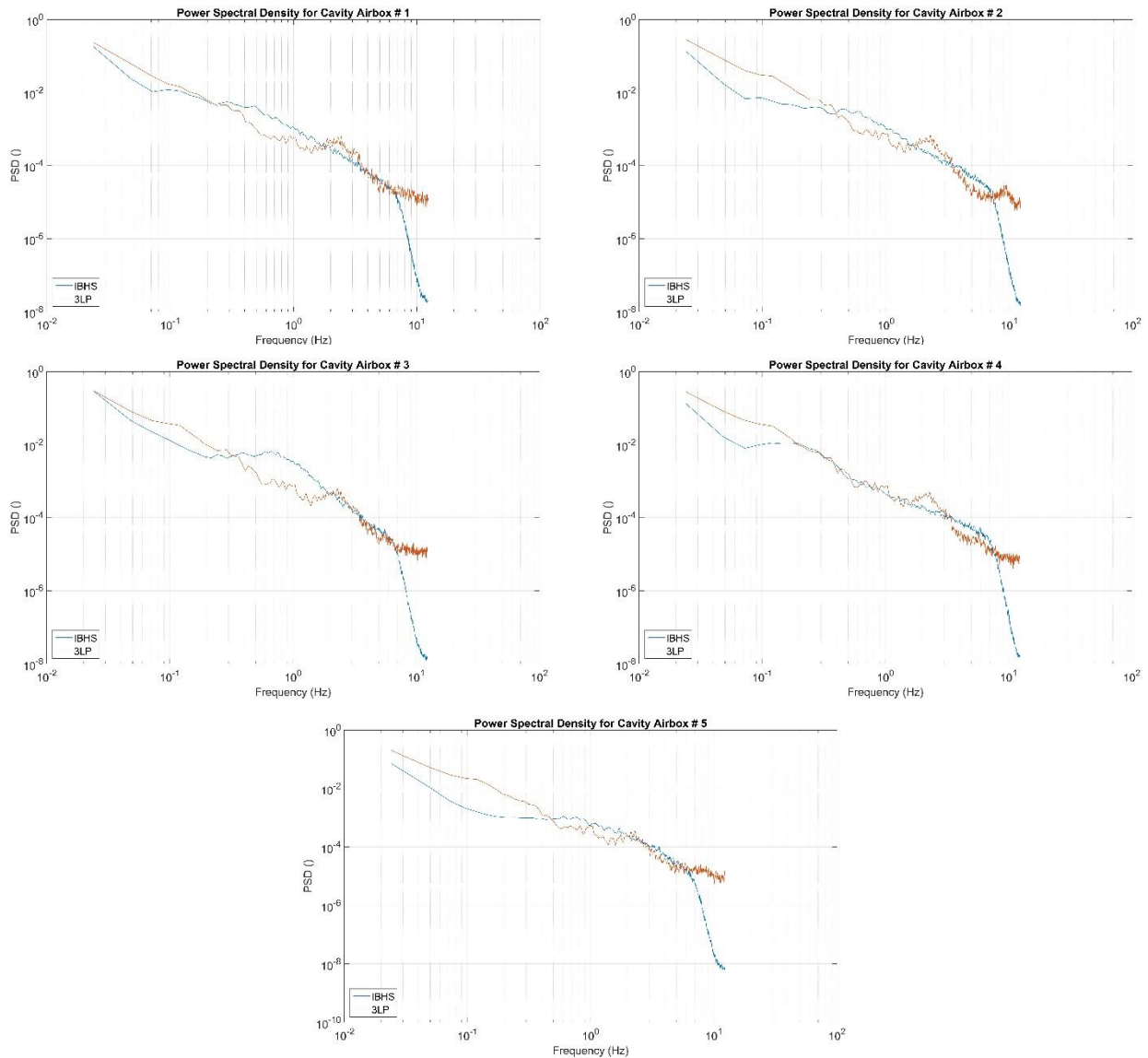


Figure 5: Power Spectral Density vs. Frequencies of internal pressures for 5 airboxes from IRLBH testing, with comparison to the power spectral density from IBHS testing.

Figure 5 shows the same spectral analysis for the internal pressures (rather than the external pressures) of each airbox. It is noted that the internal pressures seem to (on average) match the higher frequencies better between IBHS & IRLBH. Because the external pressures do not match as well, it suggests that a greater proportion of energy is transferred to the cavity in the airbox method compared to the full-scale wind tunnel. The result also suggests that if the PLAs were better tuned, the PEF values would be even higher than they currently are.

## 7. EXTREME VALUE ANALYSIS

The most common method of extreme value analysis is to fit the values to a Gumbel distribution. Doing this, the difference between the peak PEF values between the full-scale wind tunnel, and the multi-chamber airbox method were examined. To perform this, the top 500 PEF values (out of approximately 500,000 values) were taken across all airboxes, and fit to a Gumbel distribution. The results can be found in Figure 6. From this Figure, the first 496 values have a very similar slope with a variation at the highest pressures. The 4 highest values were deemed statistically insignificant, and they were removed from the analysis. The results showed that the slope of the IBHS & 3LP data



were 0.0418 and 0.0468 respectively, and the intercepts were 0.4875 and 0.5830 respectively. This shows that the peak smoothing / over-shooting does not affect the distribution of the peak PEF values, but it does have a significant effect on the magnitude of the results. Overall, the multi-chamber airbox seem to over-estimate the results of pressure equalization factors by a factor of 1.2. To further evaluate the peak PEF values, a Gumbel distribution was fitted to each individual set of airboxes. This was to help determine whether certain airboxes were performing better than others.

Examining data from the individual airboxes (not shown here), it is clear that some airboxes perform better than others. Box 5, which in the spectral density analysis was shown to have less correlation due to the size of the airbox, is performing very well in gathering peak loads. This is seemingly due to the fact that Box 5, although it was the largest box, it received the lowest external loads. Since the peak pressures are what drive the higher pressure equalization factors, it is likely that the peaks were smaller, and therefore the PLA system was able to replicate the pressures with a higher fidelity. On the contrary, Box 1, which contained the highest pressure equalization factors, the PLA tended to smooth the peaks more than they did over-shoot the values. Box 1 contained the highest peaks along with the fastest changing pressures, and it is likely that the PLA system had a hard time keeping up with the peak pressures. Analysis on the overall effects of each airboxes is very useful. It allows us to determine which boxes are either underperforming, or over-shooting the target PEF values. It is also a better method to develop a correction factor as it is more accurate to create factors for each individual airbox, since not every airbox is over-performing. This will be discussed further in the conclusions of this report.

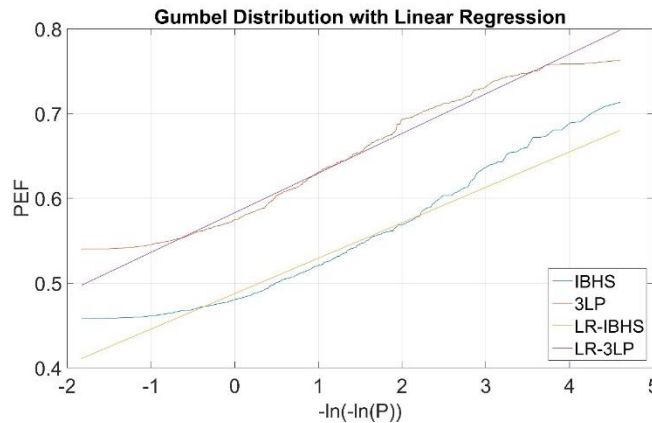


Figure 6: Gumbel distribution fit for the peak PEF data from both 3LP & IBHS methods along with linear regression fits to the Gumbel distribution.

## 8. SUMMARY & CONCLUSIONS

The goal of this paper was to determine statistical parameters that could aid in comparing two different full-scale wind testing methods for multi-layer cladding systems. Full-scale wind tunnel testing and multi-chamber airbox testing methods were compared from recent testing performed at IBHS & the IRLBH lab. Since the IRLBH testing was tasked with replicating the IBHS results, it allowed for a robust comparison. The first analysis performed was a spectral analysis. After plotting the spectral analysis for all airboxes, it was shown that the peak loads are being matched very well, however the background response is varying fairly widely. It was also noted that airboxes that were larger in area, or were subjected to the highest peak loads did not perform as well. The second analysis performed was an extreme value analysis using a Gumbel distribution with a linear regression. It was shown that using the extreme peak values over all airboxes, the resulting distribution resulted in similar slopes with the intercepts (magnitude of distribution) being different. Over multiple rounds of testing, the average ratio was found to be that the IRLBH results were higher by a factor of 1.2.

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