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ANALYTICAL MODELING OF SPATIO-TEMPORAL SURFACE PRESSURES ON AIR-PERMEABLE CLADDING SYSTEMS

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SUMMARY:
This research presented herein demonstrates an approach to determine the net design wind pressures on an air permeable building cladding system. The research motivation stems from the higher-than-normal failure rates observed in these systems after hurricanes. In this study, spatio-temporal external pressure data taken above a 3.66 m by 3.66 m (12 ft by 12 ft) cladding specimen was used to characterize the net pressures on the cladding specimen. The study investigated whether artificial neural networks can be used to predict net pressures. Once the ANN system was trained, and validated, its output was used to demonstrate a robust probabilistic based framework to ascertain the net wind design pressures for air permeable building cladding systems, conveniently normalized as pressure equalization factors (PEFs). For this, a simulation methodology for surface pressure time histories was integrated with the ANN model, to produce PEF values that might arise from other spatio-temporal wind pressure distributions occurring in the bluff body separation zone. A Monte Carlo simulation engine was used to create 10,000 realizations, and for each, the ANN model predicted the resulting cavity (gap) pressures. The net pressure on the tested system was about 70% of the external wind pressure value in the high suction zones. The promising results from the study where the analytically determined PEFs closely matched experimental results, demonstrate a logical and universal approach for obtaining the net design wind pressures on air permeable cladding systems. The approach is consistent with existing literature on current limit state design methodology of extreme value analysis of wind loads.

Keywords: pressure equalization, discontinuous metal roofing, stochastic simulations, artificial neural network

1. INTRODUCTION

Multi-layer cladding systems are frequently used in buildings because they easily satisfy multiple design objectives, provide economical function and are easy to install. Many such systems consist of many individual panels interlocked at joints forming an envelope which is attached to the structural substrate by fasteners. The envelope is separated by a gap from the substrate, such that air flows occur driven by pressure gradients in the gap. Because such systems allow airflow between the gap to the outside of the envelope (through leaky joints) pressure gradients are driven by the external wind surface pressure, which impacts the net pressures on the systems needed to evaluate the appropriate design wind loads. Building envelope manufacturers have developed multiple ways and unique test methods to evaluate and approve their products. However, there exist no universal approach to evaluate the wind resistance of air permeable cladding systems.

Post-hurricane building performance studies have recorded the high failure rates of building envelope systems as compared with structural systems, concluding that this may be a sign of issues with current standard tests and product certification procedures. For example, in studies by Prevatt et al. (2019, 2020) analysing hurricane-caused damage ratios of houses constructed over several decades, found a downward damage ratio trend (5-year moving average) for the main wind force resisting systems (MWFRS) or structural systems, while there was no such trend in the performance of building envelope systems (or fenestrations). In other words, despite code improvements building cladding losses are unchanged, warranting further investigation of the test methods used to certify design limits.

Lafontaine (2021) developed a multi-pressure chamber test rig that simulates spatial-temporal external pressure over a test specimen cladding system, which was used to develop the net-pressure data result in this study. The use of multi-pressure chamber concept for evaluating air permeable system was invented at Western University and is documented in Miller et al. (2017). Each pressure chamber is connected to a pressure loading actuator (PLA) that can reproduce a time series of external pressure derived from full-scale or wind tunnel tests and a wide range of stochastic pressures. Lafontaine (2021) postulated that the test device must have an appropriate spatial pressure gradient mirroring the actual wind pressure's spatial and temporal characteristics in order replicate realistic gap pressure gradients driving across-panel (through-joint) airflow. This is not feasible with current standard test protocols that use single pressure chambers and monotonic increasing loading. Further details for this conference paper can be found in the PhD dissertation by Lafontaine (2023), and master's theses by Lafontaine (2021), Rahate (2017) and Desai (2015).

2. METHODOLOGY

In Lafontaine (2021), full-scale air-permeable cladding specimens (12 ft x 12 ft) were placed on the multi-pressure chamber and subjected to pressure time histories, while pressure data within the gap and above the system itself were collected at 20 Hz. The net pressure across the panel is the value for basing the design wind pressure. This paper first seeks to extend earlier work by utilizing machine learning to better define appropriate design wind pressures on air-permeable cladding materials. It uses an artificial neural network (ANN) algorithm on existing multi-pressure chamber data to train and characterize the input-output relationships between external and cavity (gap) pressures for an air-permeable building cladding system. The second objective of the work is to use the ANN output to demonstrate a robust probabilistic-based framework to ascertain the net design pressures for air permeable building cladding systems, conveniently normalized as pressure equalization factors (PEFs). Figure 1 presents a framework for the two parts of this work.

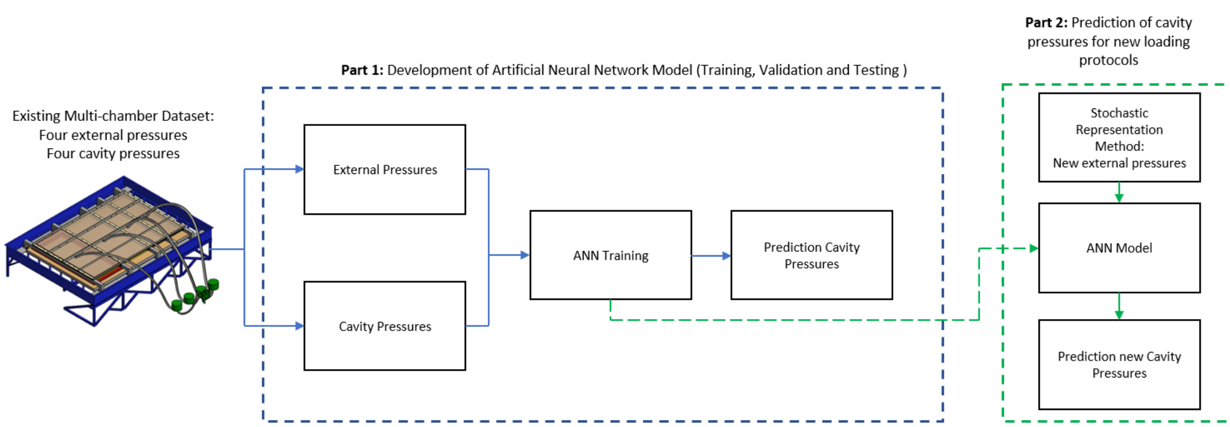

Figure 1. Framework for ANN training and integration with stochastic representation method.

2.1. Artificial Neural Network for Predicting Pressure Equalization Factors

Oh and Kopp (2014) analytically modelled air leakage through building cladding using the Multiple Discharge Equation, but it is not easy to generalize this approach for a wide range of systems. Instead, the authors created an Artificial Neural Network (ANN) that can be used to predict the cavity (gap) pressures below the cladding once the ANN is fed the external wind pressure time histories. A double hidden layer feedforward neural network was developed using the Deep Learning Toolbox in Matlab 2019a. The architecture begins by initializing the neurons with random weights and biases, placed in the input, hidden and output layers.

The ANN training process consisted of 1) test data from UF multi-pressure chamber testing device, i.e. the four external pressures and four cavity pressures time histories, that were used as inputs and outputs respectively; 2) feedforward stage (information moving from input nodes, through hidden nodes, and to output nodes); 3) prediction and stage by the ANN model and performance assessment by quantifying Mean Squared Error (MSE) between the predicted and target (PEF?) values. 4) adjusting neuron weights using the Levenberg-Marquardt backpropagation algorithm to minimize the output error. The optimal ANN model structure was found to be 4-5-5-4 (input-hidden-hidden-output). The dataset of pressures contains approximately 12,000 values, and 70% of which were used for training, 15% for validation and 15% for testing.

2.2. Stochastic Simulation Method

A simulation methodology was used in this study to account for variability and uncertainty of wind loads on structures while also reducing the need for physical testing needed. We used the Yang and Gurley (2015) multivariate spectral representation method and 3rd order Hermite polynomial translation to artificially produce four external time histories for the pressure chambers. In this way they had probability and power spectral density (PSD) characteristics which matched the pressure time histories extracted from Tokyo Polytechnic University's database of wind pressures. We predicted the cavity pressures and PEF values using the ANN model and four simulated pressure loading time histories, enabling researchers to generate many synthetic pressure data from which to reliably extract a representative design-level PEF value based with a stated probability of non-exceedance. By integrating simulated pressures with the ANN model, we produced PEF values that might arise from spatio-temporal wind pressure distributions and non-Gaussian flow properties in the flow separation zones of a bluff body. A Monte Carlo simulation engine was used to create 10,000 realizations, and for each, the ANN model predicted the resulting cavity (gap) pressures. Lastly, design level PEFs are evaluated by evaluating probability of non-exceedance based on chosen PEF threshold values.

3. RESULTS

Design level PEFs were evaluated using the integrated probabilistic-based framework and multiple realizations. All PEFs were evaluated at external pressures greater than or equal to 0.6 kPa suctions. Table 1 summarizes results for design level PEFs for threshold PEF values ranging from 0.5 to 0.7 for 10000 realizations. The results suggest an appropriate design level PEF value is 0.66 for this cladding system, with a return period (years) consistent with a Building Category 2 structures in ASCE-7 design guides.

Table 1. Multi-variate Integrated Probabilistic Framework Design Level PEF based on probability of exceedance for 10000 realizations.

PEF	Probability of exceedance	Return Period (R) (years)
0.5	0.9998	1
0.55	0.9948	1
0.6	0.2386	4
0.62	0.0386	26
0.64	0.0037	270
0.65	0.001	1000
0.655	0.0007	1429
0.66	0.0002	5000
0.7	0	-

There is good agreement between simulated PEF and target value PEFs for both general trends and magnitude. The marginal probability distributions and power spectrums are also well-matched between the target and simulated signals. This predicted results also aligns well with the experimentally obtained PEF values in the IBHS full-scale wind tunnel tests of vinyl siding, where they reported a PEF value of 0.7 using the Gumbel Best Linear Unbiased Estimator (BLUE) approach (Miller et al. 2020). The researchers conclude that this framework combining the ANN model and non-Gaussian simulation method is appropriate and robust analytical approach to determine design level PEFs and is more robust than previous methodologies.

4. CONCLUSIONS

The study validated an ANN approach for estimating design level pressure equalization factors of air permeable building cladding systems. Multiple pressure realizations can be analytically developed to simulate a scenario dataset. An approach was demonstrated to extract appropriate design level pressure equalization factors by combining limited experimental data, an artificial neural network, and simulation of non-Gaussian wind surface pressures on a building cladding system. This paper's contribution is the advancing of understanding for establishing appropriate design wind loads for air-permeable cladding systems.

High failure rates of cladding systems point to discrepancy between building code provisions of structural systems and the design methods of building cladding systems. By combining the multiple pressure chamber device, artificial neural network models and probabilistic modeling this study has shown how an advanced integrated probabilistic framework approach can be efficiently achieved and with good agreement with full scale experimental tests.

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