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The "Three Little Pigs" Research Facility

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Abstract
Damage due to hurricanes and other windstorms has increased dramatically in recent years, incurring losses of life and property around the world. Houses are the most common structures and are also the most affected structures during extreme events. They are complex because of their highly redundant, yet vaguely defined, structural systems. A new full-scale facility for testing houses, and other light-frame buildings, to failure under realistic, simulated environmental loads has been developed. In order to apply extreme (Category 5 hurricane) wind loads, a novel, pressure loading actuator system has been developed to replicate time histories of the temporally- and spatially-varying wind pressures that would be observed in full-scale. Damage to cladding and large-scale structural failures will be examined in detail using this loading system and a system of sensors within the structure. In addition, the data captured will validate computer-based analyses of the complex load paths through to failure. This paper presents the goals of the project and describes the novel features of this new laboratory and the first tests which will be conducted over the next two years.

Keywords
wind loads, houses, full-scale testing

1. Introduction

Around the world, hurricanes regularly provide vivid illustrations of the devastation that strong winds and rain can produce in both developing and developed countries. In 1992, Hurricane Andrew hit south Florida, destroying or damaging over 20,000 houses and causing over US $30 billion in damage [1]. The total insured losses caused by the four hurricanes that struck Florida in the 2004 was about US $30 billion [2]. The disasters in 2005, due in particular to Katrina, Rita and Wilma were even worse. Hurricane activity in the North Atlantic has increased markedly since 1995 and, based on analysis of North Atlantic sea-surface temperature and vertical wind shear, the present high level could persist until about 2035 [3]. Climate change could possibly make this situation worse.

Figure 1 depicts some typical wind damage from Hurricane Katrina in the region near Biloxi, Mississippi. Winds in this area were below the design levels indicated in the ASCE 7 so that, in line with engineering theory, minimal damage would have been expected. Nevertheless, repeated failures were observed, among them siding loss, as indicated in the photograph. There were relatively fewer major structural failures on newer homes (this was the only one in the neighbourhood of about a hundred homes), although some poorer quality and older homes and town homes experienced significant damage. The house in the figure was apparently well-constructed (note the wood sheathing panels where the siding has come off). Internal pressure rise may have played a role, as indicated by the missing second floor window. This type of failure leads to life-safety issues, further possible damage to neighbouring houses due to wind-borne debris, and massive repair costs due to large amounts of water ingress. Damage surveys provide useful information about failures, although they certainly do not answer all questions, particularly about responses just prior to failure. For this reason, realistic full-scale testing is desirable.

This paper reports a new full-scale testing laboratory at the University of Western Ontario designed to answer these types of questions. In order to effectively communicate the objectives of the project to those outside the structural and wind engineering communities, it was nicknamed the "Three Little Pigs" Facility after the children's fable about a Big Bad Wolf who tries to blow down the homes of three pigs. The long-term goal of the research is to develop anticipatory mitigation strategies to save people's homes from the destructive environmental forces of nature. Houses are complex structures because, from a structural engineering point of view, the load paths are ill-defined, and, from a building science point of view, the moisture paths are ill-defined. The structural system is also the environmental barrier since the walls consist of bricks or siding, a vapour barrier, structural framing and the interior wall board meaning that the system behaviour can only be understood by examining both of these aspects. In addition, both aspects need to be considered in the development of mitigation strategies and in the design of new products and retro-fits. It is intended that research results from the project will be implemented by: (1) modifying building codes to advance safer, yet less expensive houses; (2) working with the insurance industry and government to develop implementation strategies; (3) developing cost-effective mitigation devices for retro-fitting the existing housing stock; (4) working with manufacturers to develop wind and rain resistant building products; and (5) developing quality-control strategies to minimize human error in construction. In 2004, CDN$ 7M was awarded from the Canada Foundation for Innovation, the Ontario Innovation Trust and the University of Western Ontario to construct the facility. Construction of the facility has been completed, prototypes of the novel wind loading system have been successfully tested and research has begun.

Figure 1. Wind damage to a house due to Hurricane Katrina near Biloxi, Mississippi. The arrows indicate, from left to right, siding loss, shingle loss, roof loss and a broken window.

2. Application of Wind Loads

The facility will permit the application of realistically simulated temporally- and spatially-varying wind loads to full-scale structures, in a controlled manner, up to failure. The idea is simple: rather than instrumenting a house and waiting for a hurricane to come, or building an enormous wind tunnel capable of housing a full-scale structure, we replicate the basic effects of wind blowing over a structure, that is, we simulate the resulting fluctuating pressures. Basically, a scale model of each full-scale specimen is tested in a boundary layer wind tunnel to determine the time histories of the pressures experienced over all of the exterior surfaces of the building during extreme winds. These time histories are then scaled to full-scale and applied to the building with the loading system. This idea has been used before, in the testing of panels, with a system developed by Nick Cook and associates at the British Research Establishment [4]. The resulting panel testing system was called BRERWULF and it could apply spatially-uniform, temporally fluctuating pressures over a segment of cladding or roofing. The idea of spatially-varying loading using wind tunnel data was first developed by Ralph Sinno and colleagues and Mississippi State University [5] using a magnetic loading system which applied point 'suction-type' loads at 34 locations. The current methodology is essentially these two ideas put together into a single system. The major differences with the previous experiments are that (i) every building surface will be covered (except soffits and fascia) and (ii) the large leakage flows through typical cladding materials, such as bricks and siding, will be accommodated. Note that both the metal roofs tested at Mississippi State and the metal panels tested with BRERWULF were nominally sealed in contrast to the typical porosities of brick or siding. The new system is much more compact to allow high spatial resolution in regions where the pressures have high gradients, such as windward corners of the roof. Each loading actuator will have one input pressure trace to replicate, the pressure traces coming from the wind tunnel study.

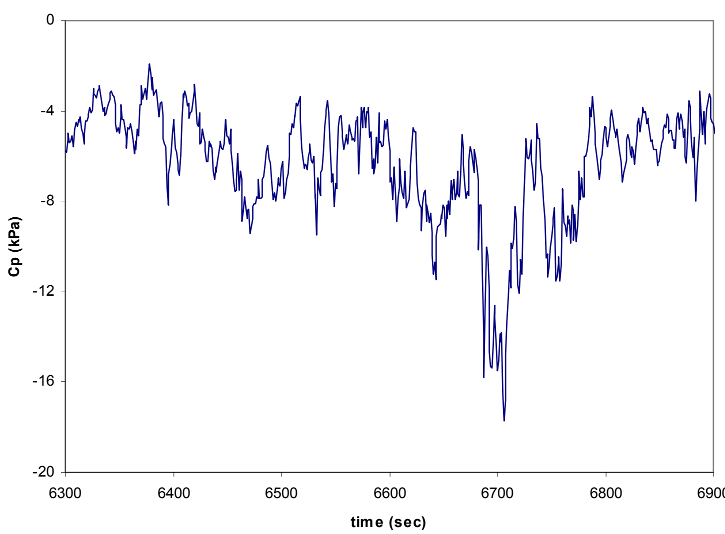

Figure 2. A 10-minute segment of the pressure acting on an area of 0.36 m^2 near a roof corner, scaled to a 3-second gust speed of 360 km/hr.

Figure 2 shows a time history of pressure from a 0.36 m^2 area near a roof corner, obtained from a wind tunnel experiment and scaled for a full-scale 3-second gust speed of 360 km/hr. This is a typical 10 minute segment of a pressure trace that a pressure loading actuator, for that area, must be able to replicate, and which the prototype loading system has already replicated to within 2%. The particular challenge, quite beyond what the BRERWULF system could accomplish, is to do this with high leakage flows. The requirements for the peak attainable pressures and flow rates are given in Table 1, as well as the required frequency response of the pressure loading actuators to smaller (1-2 kPa) fluctuations.

Figure 3. Photograph of two prototype pressure loading actuators connected to the (blue) pressure boxes, the flexible membranes connecting the PLAs to the house surface to allow the pressures to be applied.

The task for the pressure loading actuators (PLAs) is to replicate a pressure trace which is applied to a portion of the building surface. To do this, its outlet must be connected through a nominally-sealed membrane that is connected to the building surface. These membranes, which we have termed “pressure boxes”, are what allow the spatially gradients to be applied. Figure 3 shows a prototype of two PLAs connected to pressure boxes. These are the bulging blue membranes shown in the left of Figure 3, while the PLA prototypes are shown on the right side of the photograph. The pressure boxes were designed to meet several criteria. First, they must be at least nominally airtight so that the pressure traces can be controlled reliably with leakage only coming through the building surface (such as brick, or cracks). In fact, how far into a failure the system can go is expected to be governed by the maximum flow rate of the fans as pieces begin to break. Second, the actual membrane (i.e., the blue material) must be flexible since the building will deflect globally (on the order of 10 cm) under the wind loads in addition to local deflections of the cladding. The deflection of the reaction frame, to which the “lids” of the pressure boxes will be connected, will have significantly less deflection. Third, the connection of the membrane to the test specimen surface must be robust and flexible, as well as not having material incompatibilities. Fourth, since all building surfaces are to be covered by the pressures boxes, they must be able to be installed onto the specimen surface from the inside of the box only, as access to the outer surfaces of the bag will not exist. Finally, to have a robust control system, the bags cannot cover the entire surface because gaps must be present to allow for bulging when under pressure (as can be seen in Figure 3). This means that correction algorithms must be applied to input pressures in order to get the overall magnitude of the loads correctly. (The reactions caused by membrane also need to be accounted for.)

Overall system constraints include the explicit limitation of power at 1 MVA. This limits motor sizes and, from a practical point of view, fan flow rates and the overall building leakage. As well, only a limited range of sizes of pressure boxes are being considered in order to keep construction costs low. Currently, 0.6m x 0.6m, 1.2m x 1.2m and 2.4m x 2.4m boxes are being considered, although a single fan is currently expected to cover this size range. Prototypes of 10 boxes will be delivered and assembled in June 2006 in order to assure system scalability.

In order to measure how the load is transmitted through the structure to the ground, a system of load cells is installed at the base of the test specimen to record the load paths, and so verify and validate computer analyses of the structural behaviour. A panel testing rig is also being developed to measure response and failures of cladding materials including siding, brick, plywood, glass and metal. Figure 4 depicts the current design, although at the time of writing, this was still under development. The figure also shows a partial layout of the PLAs, which must fit within a 0.6 m x 0.6 m x 1.2 m volume in order to meet the spatial requirements of the reaction frame and the pressure box layouts.

Table 1. Design specifications for the Pressure Loading Actuators

Pressure Box Dimensions	Quantity	Maximum Pressure (kPa)	Minimum Pressure (kPa)	Leakage Flow Rates (m^3/s)	Frequency Response (Hz)
0.6 m x 0.6 m	16	+5	-18	0.2	6
1.2 m x 1.2 m	36	+5	-15	0.7	4
2.4 m x 2.4 m	47[1]	+4.5	-11	1.0	4

3. Moisture and Other Environmental Loads

Rain and moisture penetrates building envelopes because of the kinetic energy of the raindrops, pressure differentials, surface tension, and capillary action. Wall design for controlling rain penetration has changed considerably over the years and now includes the concept of a rainscreen and pressure equalization. However, the detailed physics behind the rainscreen principle and rain and moisture penetration are still not well understood for full-scale walls. Testing of full-scale panel specimens has been done at the National Research Council of Canada, however, the detailed spatial variation of wind pressure, nor the development of naturally cracked wall panels and interfaces cannot be evaluated. It is anticipated that the Three Little Pigs facility will be able to contribute in this area.

Recent research has found evidence of an association between upper respiratory disease and the presence of indoor mould. This outcome is especially pronounced in children. Mould growth in the built environment coincides unfailingly with superfluous moisture. In cavity wall construction, air and moisture infiltration and exfiltration may lead to moisture conditions within the wall assembly conducive to the initiation and sporulation of moulds. Certain materials, such as drywall, are anecdotally known to be more susceptible than other materials to contamination by problematic moulds; however, the susceptibility of different construction materials to mould contamination remains poorly defined. As well, detection of mould problems in indoor environments poses great challenges in the absence of obvious signs of deterioration. Comparative studies of bioaerosol sampling devices have not evaluated relative performance for detecting the presence of hidden mould growth such as contamination contained in the interior of cavity walls.

The research on this aspect of the project traces the role of moisture in building envelope failure. Two facilities are used in this work, namely, the test house specimen and a second building at the site, the “control building”. The full-scale house specimen will be instrumented with temperature, moisture and pressure sensors to determine moisture movement through the building in new

[1] This number includes 33 irregularly shaped boxes to fit in gable ends, etc.

condition (prior to structural testing) and in a damaged condition (following structural testing). While the structural tests will be performed under the cover of the “hangar” building (so-called because of the Laboratory location at the London International Airport), shown in Figure 5. This building is mounted on rails so that it can be moved back to expose the house to the natural elements required for the building envelope experiments. The photograph in Figure 5 shows the hangar building with the bi-fold door open and the first test house under construction. The size of the door was governed by the need to move the hangar building with it in place.

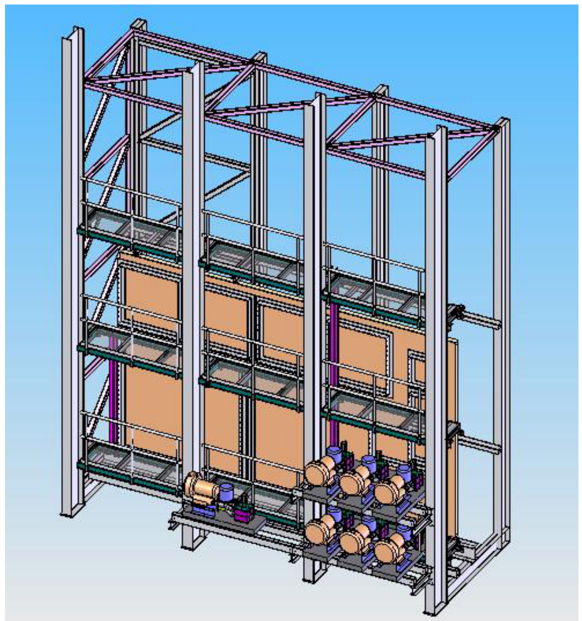

Figure 4. CAD drawing of the Panel Testing Rig with some of the Pressure Loading Actuators.

The goals of the research program will be achieved be measuring the rain quantities and distribution on the surface of the control building and first house specimen through the use of a wall- and ground- mounted disdrometers for measuring rain droplet size distribution. Simultaneously, the history of the cavity environment condition (humidity, temperature, pressure, bioaerosols and airflow) will be determined. These data will help predict the use and usefulness of bioaerosol samplers in predicting cavity conditions. Finally, remote, non-destructive assessment of mould initiation and growth rates using a novel, in-situ, wireless sensor will be performed for the first time. This will lead to the validation of standard building material test procedures for mould susceptibility.

4. Variability in Construction

The well-known proverb says "to err is human". Damage surveys following extreme events indicate that many structural failures are due to human error rather than the inadequacy of the design codes. Most design codes are developed or calibrated based on nominal target reliability levels. Yet human errors, which are the main cause of structural failure, have not been assessed thoroughly using probabilistic methods or the so-called heuristic and bias approach (Kahneman et al. [6]). These errors are often hidden and unknown before the failure occurs and their consequences could differ significantly. The incomplete assessment is perhaps due to the unavailability of data. The errors alone or in combination with strong wind loading are likely to lead to consequences of different magnitudes.

Figure 5. The hangar building covering the first house specimen (under construction).

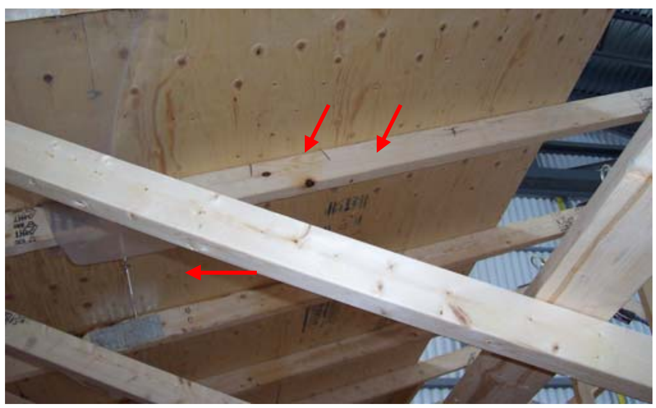

Figure 6. Photograph showing nails that missed trusses (upper arrows) during the construction of the first test specimen as well as air gaps, which allow water ingress after shingle loss, between the plywood sheathing (lower arrow).

A video recording system is installed in the hangar building for monitoring the construction of the test house specimen and recording flaws in the construction resulting from human error. A statistical analysis of the construction flaws will be carried out for the recorded construction practice. The construction flaws will be correlated with the structural performance of the house structure under simulated wind loads to assess the impact of human error on housing performance under service loading. Figure 6 shows a typical error of nails in roof sheathing panels (i.e., plywood) missing trusses in the test house. The construction of the test house has been in accordance with the relevant Canadian building code provisions using standard practices. The house builders have been under unobtrusive supervision to ensure construction is typical. As well, the house itself is to be independently checked by a building inspector to ensure compliance and to note if any details are better or worse than seen in common practice.

5. Set-up for the First Experiments

The first full-scale test specimen, shown in Figure 7, is currently under construction. The photograph shows the house just prior to the roof sheathing being applied. The wall cladding will be brick. Testing of full-scale components (i.e., cladding and sheathing) will start in June 2006, when the ten PLA modules (discussed above) are due to arrive. In order to perform the first structural tests, several additional aspects need to be completed. A steel reaction frame will be erected by Spring 2007, as shown in Figure 7. The steel reaction frame, constructed of modular components, that envelopes the specimen to facilitate the application of load to the roof, end walls and side walls and transfer these loads to a strong floor. Parts of the steel frame are removable and adjustable to suit the configurations of different test specimens. The first structural tests on the house will begin in 2007 with about 100 PLAs mounted to the reaction frame and connected to the pressure boxes attached to the house surfaces. Testing will occur over 2 years, until ultimate destruction in late 2008.

Figure 7: 3D CAD drawing of the two-storey test house with the reaction frame surrounding it (left) as well as a photograph of the house in December 2005 (right).

As we noted above, houses are complex structures because of their highly redundant and vaguely defined structural systems. For example, resistance to lateral movement is largely derived from the drywall nailed to both load-bearing and non load-bearing walls inside the house. The Three Little Pigs Facility will generate necessary data to validate the next generation of computational analyses of houses that will accurately predict behaviour up to failure. Full-scale component tests, and even the static loading of complete structures, do not adequately predict true behaviour under transient peak wind loads that fluctuate dramatically over the surface of the building. Thus, the precise response mechanisms up to failure are not yet known. The pressure loading actuator system of the Three Little Pigs Facility offers the opportunity to "engineer the wind" and so apply rigorously controlled temporally- and spatially-varying loads to full-scale light frame components and structures in order to fully understand the complete structural system. This will allow accurate assesssment of the relative performance of different forms and materials of construction, and different connection details, and also the "calibration factors" for various component tests and then to relate these to the component response within the system. The panel testing rig is being developed in order to study pressure equalization and water penetration through different wall systems and to understand how standard ASTM-type tests under static, uniform pressures relate to real system behaviour under dynamic loading.

6. Acknowledgements

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7. References

Cook N.J., Keevil A.P. and Stobart R.K., "BRERWULF – The Big Bad Wolf", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 29, 1988, pp. 99-107.

Goldenberg S.B., Landsea C.W., Mestas-Nunez A.M. and Gray W.M., "The Recent Increase in Atlantic Hurricane Activity: Causes and Implications", *Science*, Vol. 293 20 July 2001, pp. 474-479.

Kahneman, D., Slovic, P. and Tversky, A., "Judgment under uncertainty: Heuristics and biases", Cambridge University Press, Cambridge, 1982.

Munich Reinsurance Group, "08 November 2004 Press Release", http://www.munichre.com/ accessed 15 March 05.

Ross T. and Lott N., "A Climatology of 1980-2003 Extreme Weather and Climatic Events", *Technical Report 2003-01*, National Climatic Data Center, US Department of Commerce, NOAA/NESDIS, available at www.ncdc.noaa.gov/oa/reorts/billionz.html, 2003.

Sinno, R.R., Surry, D., Fowler, S. and Ho, T.C.E., "Testing of metal roofing systems under simulated realistic wind loads." *Proceedings of 11th International Conference on Wind Engineering*, 2003, pp. 1065-1072.