Wind Technology to Blow the House Down

The Mechanics of Replicating Wind Loads

By Gary Kemp

Figure 1: Wind-storm causes extensive damage to light-frame houses in the Greater Toronto Area.

Structural engineers know the importance of test data when designing for wind loads. Where does that data come from? Typically, scale models of a structure are tested in wind tunnels. Imagine, however, improving underlying wind load analysis methodologies with data from full-scale testing. Engineers and physicists from Canada have developed a system which facilitates full-scale testing.

The University of Western Ontario in London, Ontario has built a facility for testing full-scale, low-rise dwellings under wind-loads up to the equivalent of a Category 5 hurricane. Called The Insurance Research Lab for Better Homes, or affectionately, the Three Little Pigs facility, it has been designed and built over a 5-year period and testing on the first structure will begin in the summer of 2008. The capability is based on a unique flow-reversing valve, developed by Cambridge Consultants, which allows a precisely controlled, yet rapidly varying air pressure to be applied to a wall section. A large set of pressure loading units surround the entire building and operate in synchronisation to replicate whole-building pressure loads as measured in wind tunnel tests on reduced-scale models. The flow-reversing valve has a single moving part and has been designed to minimize losses. It has a linearised control characteristic, which allows it to deliver air at a precise, yet continuously variable pressure, from full negative to full positive, over a range of flow rates and with a high rate of change to simulate the turbulent effects around buildings. The valve has a range of potential spin-off uses in structural testing and other fluid control applications.

Around the world, tropical cyclones 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 20,000 houses and causing $30 billion in damage. If the storm had tracked 50 kilometers further north, estimated damage would have exceeded $100 billion. Canadian engineers are active in the US and other countries that experience extreme wind speeds (Japan, China, the Caribbean), and their wind code provisions are influential in these countries. In Canada, severe windstorms tend to be more localized but still cause significant damage. In addition to rare events such as the Edmonton and Barrie tornadoes, or Hurricanes Hazel and Juan, there are also the severe east coast storms. The Institute for Catastrophic Loss Reduction (ICLR) was created to minimize the effects of natural disasters by reducing vulnerability through mitigation efforts. This not only applies to the well-publicised rare events, but also to the myriad of less dramatic incidents in which houses and light frame buildings are damaged in preventable circumstances.

Windstorms induce significant loads on buildings, which can result in widespread damage, both due to wind and also due to the ingress of water. (*Figures 1* and *2*)

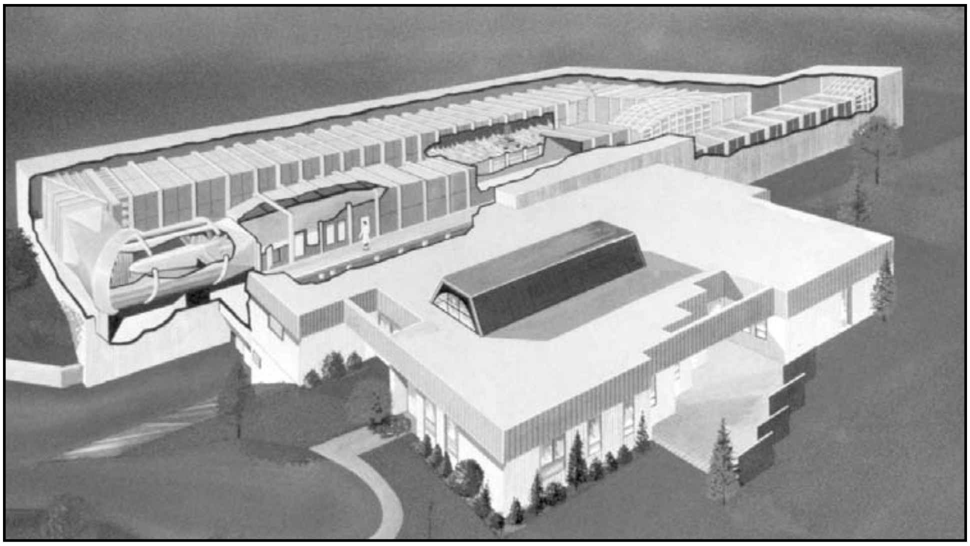
The University of Western Ontario has a Boundary Layer Wind Tunnel Laboratory that does both academic and commercial work. They use wind tunnel models and structural testing for research into the effects of wind loads on tall and low-rise buildings, as well as other structures such as bridges.

The new challenge is to study the effects of hurricane wind loads on houses at full-scale, with wind loads up to Category 5 strength, gusting up to 200miles per hour. Hurricanes cause damage through the combined effect of heavy rain and strong winds, so the test building may also be subjected to water inundation.

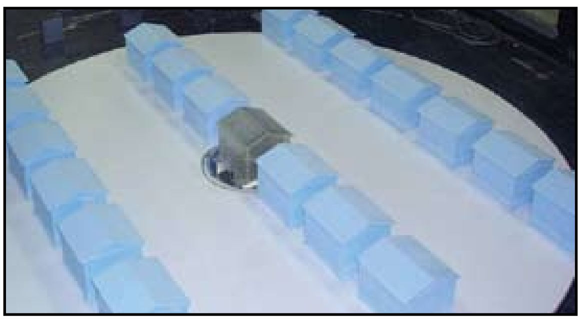
The Three Little Pigs Facility

The Three Little Pigs facility at the Insurance Research Lab for Better Homes in London, Ontario was conceived to enable full-sized houses to be tested repeatedly in realistic hurricane wind-loads. The concept is to apply a time-varying air pressure to each section of the house by attaching a box, like a suction cup, to the surface and then driving air in and out of the box. The system is designed to replicate precisely the pressure trace measured on the scale model tested in the wind tunnel for that part of the building. By surrounding the entire building with pressure boxes (including the roof) and synchronising the pressure-time characteristics for the wind tunnel measured array, a whole-building test is possible. By placing the building on a series of load cells, gross forces at the foundations can be measured. A single test may typically last 15 minutes, enabling the University to observe damage mechanisms, then repair and replicate the experiment many times.

Figure 2: Water is driven in by the wind causing further damage and leading to mould growth.



The University of Western Ontario Boundary Layer Wind Tunnel facility. Copyright 2004 Alan G. Davenport Wind Engineering Group.



Scale model of 2-story house for wind tunnel testing.

Different sizes of pressure boxes allow for fine detail where the spatial variation of pressure loading is greatest, typically in corners and around openings.

The whole building and box array is contained within a rigid steel frame. This keeps the backside of each pressure box fixed, while flexible sides (akin to a hovercraft skirt) allow the building surface to move within the frame while maintaining the seal to the box. This entire structure is then contained within a cover building, which can be slid back to expose the building under test to ambient weather conditions.

Each pressure box requires an air-delivery system (Pressure Loading Actuator), which can be controlled from a central computer system to deliver the time-varying air pressure to the building. As the building starts to fail, cracks may appear and the flow rate into the box will increase, a phenomenon that the Pressure Loading Actuator must allow for while maintaining the demand pressure. The central computer must control the whole array of Pressure Loading Actuators, ensuring that their pressure traces are synchronised and that the system operates within the limits of safety. The system is controlled from a building, which is separate to the cover building, as the environment within the cover building will be noisy and hot.

Such a system consumes a considerable amount of electrical power; therefore the facility has its own substation, with a 1MVA capacity, connected to the local power grid.

The Pressure Loading System

The pressure loading system must meet a number of requirements. Including:

- push and pull air in and out of a variety of sizes of pressure boxes, from 1 to 64 square feet,
- provide an accurate reproduction of the pressure demand at each point in time,
- deliver air pressures over a continuously variable range between +5 to -20kPa,
- vary the pressure at rates of up to 7Hz (*Figure 3, page 26*),
- sustain the demand pressure as leakage flow increases (gradually or suddenly) up to 30 cubic feet per second,
- work within the 1MVA power limit for the whole system, and
- fit within size and weight constraints.

For larger boxes, it should also be possible to connect a number of Pressure Loading Actuator (PLA) units together to achieve the required performance over larger areas of the building.

The pressure-loading unit is based around a powerful fan (regenerative blower) driving air through a novel 5-port flow-reversing valve. Regenerative blowers are designed to provide high pressure at moderate flow rates. The blower circulates air through the valve at a constant rate, while the valve selects push or pull and then directs more or less of the air to the pressure box and leaks the residual to the atmosphere. A pressure sensor on the box provides feedback into a closed-loop control system, which controls the valve to match the box pressure to the demand.

A variable speed drive is used to set the blower to a constant speed at the start of an experiment, rather than to vary the pressure as testing progresses. Set for the required peak pressure, this allows use of the full dynamic range of the valve at lower simulated wind speeds.

The unit was designed as a compact assembly, mounted on a steel chassis.

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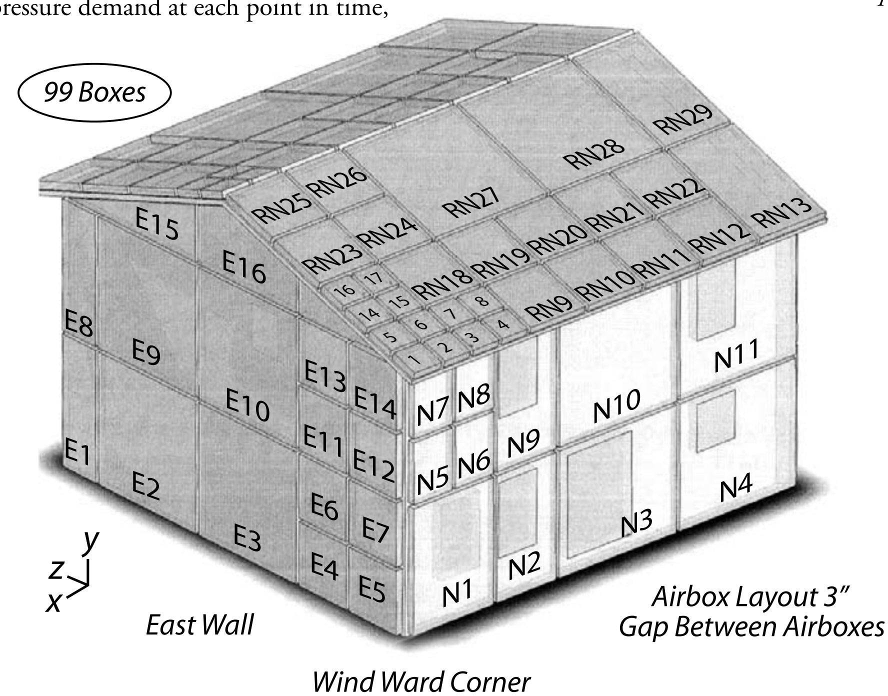


Plan for distribution of pressure boxes around a test house.

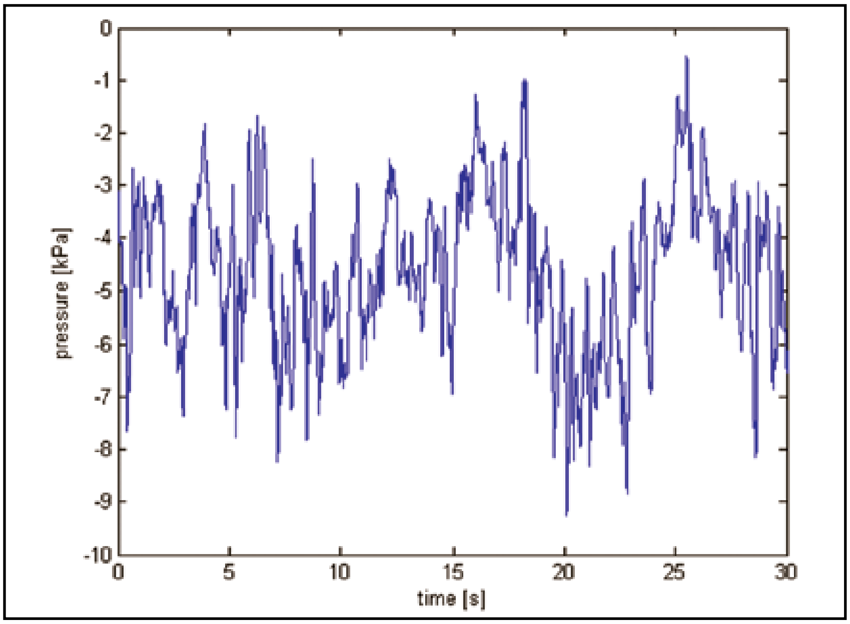
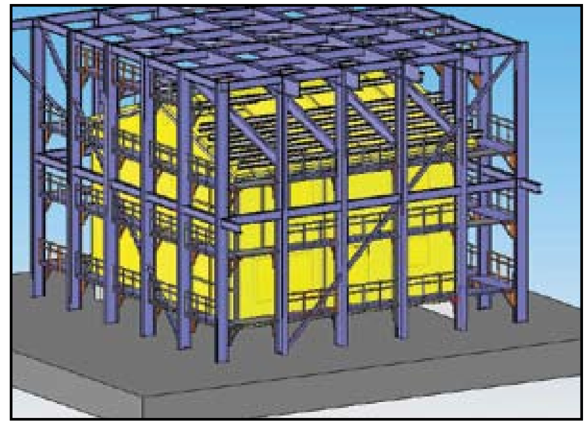


Figure 3: A typical 30-second pressure trace for a 155mph wind on one wall section. Rapid fluctuations are caused by turbulent flow around the structure. Pressures on the leeward side of the building can be negative.



Computer rendering of the reaction frame assembly. The pressure boxes push and pull on the house while remaining rigidly fixed to the reaction frame.

The valve has a single moving part, which is a low-inertia rotating disc, completely enclosed within the valve casing. The disc is a balanced design and has a pair of apertures. As the disc turns, it opens and closes pathways between two chambers on one side, which connect to the blower push and pull ports, and three chambers on the other, connected to the box and the input/output to the atmosphere. The valve is subject to a UK patent application.

The valve has been optimised for low loss using computational fluid dynamics (CFD) analysis to achieve the specified pressure/flow characteristic. It is constructed from a pair of aluminium castings and a completely enclosed slotted disc. A powerful servomotor provides a direct drive to the disc (without the need for a gearbox) and is matched to the disc moment of inertia.

The valve has also been designed to have a linearised control characteristic, through appropriate shaping of the port openings and chambers. This means that the pressure vs. disc angle is approximately linear, and the control loop remains stable over the full pressure and flow range of the system. Linearising control for pressure makes it much easier to design and run a control system that achieves the desired response for rapid pressure changes in the Pressure Box. The pressure in the box tends to drop rapidly when a small leakage to atmosphere is introduced; therefore, the valve chambers have been shaped to reduce the leakage rate at small valve angles. Further, the design allows internal leakage to be reduced by using small gaps rather than rubbing seals; hence, friction and wear is avoided and responsiveness improved.

A twin rotor blower unit is used on the PLA, which can be connected in series or parallel to get either more flow rate or more pressure, or split and used to drive 2 separate valves into 2 boxes. In conjunction with a regenerative blower running continuously in one direction, it is used to generate rapidly fluctuating pressures in the Pressure Box that accurately simulate full scale wind loads, up to Category 5 Hurricanes.

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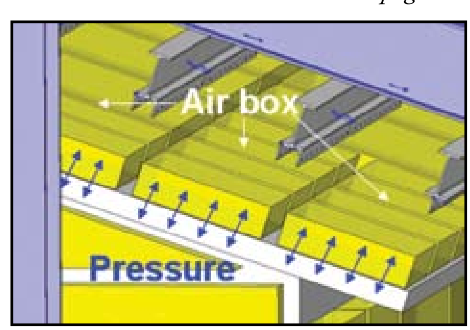


Detail of pressure box mounting on the test house roof.

System Installation, Commissioning and Test Program

The University has now built 100 Pressure Loading Actuator units and is in the final stages of construction of the first test house, concentrating on the internal fittings.

The first test house is a standard timber frame house with a non-structural brick cladding. Testing is due to begin on the house in the summer of 2008, starting with a series of roof pull tests, where the fixings will be progressively strengthened between tests, then repeating the same wind load pattern. There will also be destructive testing on windows. The test building is expected to last approximately 2 years before it is destroyed.

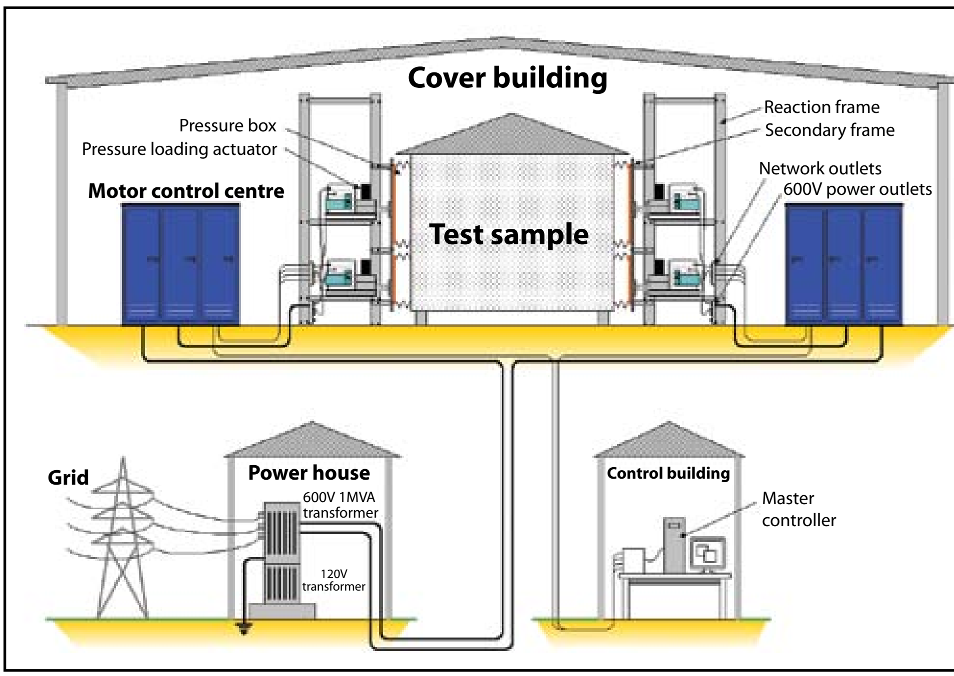
The University has also constructed a panel test rig, which uses a set of 10 PLA units to test large sheets of building materials and a glass test rig, which uses a high-speed video camera to capture the propagation of fractures as window glass fails under wind load.

Other Applications

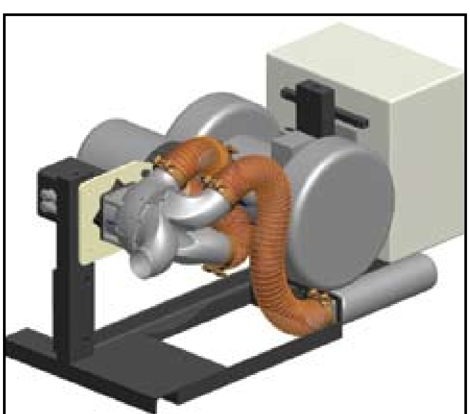
The valve described above is a 5-port flow-reversing design, with 3 states: Pressure, Suction and Neutral. Variable levels of pressure and suction are provided by intermediate positions of the valve. A 4-port flow design is being developed, which is more suitable for closed-circuit installations.

Structural testing applications for these valves, other than the above, could include testing aircraft structures or parts, such as wings and windows. Other non-structural applications include back-flushing systems for filters, feed systems for grain hoppers, series-parallel switching in pneumatic systems and regenerative braking on vehicles using stored gas pressure.▪

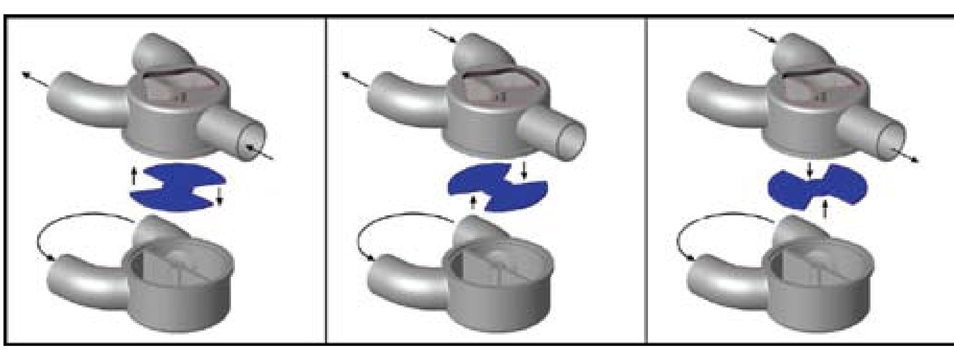
The 3 Little Pigs facility at the London airport site. The cover building has been rolled back to show the test house inside the steel reaction frame.



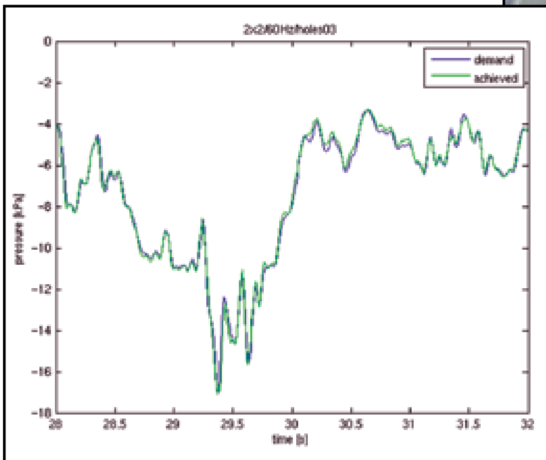
System diagram showing the test house with presure boxes attached, reaction frame, racks of pressure loading actuators, all within the cover building. Separate buildings contain the master controller and a 1MW electricity substation.



A pressure loading actuator unit, designed to fit within a 2-foot square slot next to the house.



The flow reversing valve delivers continuously variable suction or pressure, while the regenerative blower operates continuously in one direction.



Pressure trace for a 200mph wind into a 2-foot x 2-foot pressure box. The pressure delivered by the pressure loading actuator matches the demand, even as the structure starts to crack and leakage flow increases.

The first test house will undergo a series of tests over a 2 year period and will be ultimately tested to destruction. Tests can be repeated precisely for the evaluation of incremental building improvements.

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