Wind Loads on Houses

A wind tunnel study

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Executive Summary

Damage due to natural hazards has increased dramatically in recent years, incurring losses of life and property around the world. Housing and other light-frame construction often bears the brunt of this damage because it represents a large percentage of structures and is typically non-engineered. The environmental loads that these structures must resist are relatively unknown. Wind tunnel experiments were therefore conducted at the University of Western Ontario to measure wind loads experienced by a typical Canadian two-story house. The different exposure conditions investigated included: a lone house without surrounding structures and a house among similar houses in a grid subdivision and a crescent subdivision. Pressure measurements were obtained at 422 locations on the house model, from which loads applied to cladding elements (windows, siding) and main structural components (such as roof trusses) were calculated. Results show that the wind loads applied to houses reduce dramatically when surrounding structures of similar size are present.

1. Introduction

The resistance of non-engineered light-frame construction to environmental loads such as snow, wind and moisture is largely unknown. The cost of engineering these structures is large relative to their construction cost; therefore the design of an individual house or small building is typically not feasible. Part 9 of the National Building Code of Canada (NBCC, 1995) governs the design of structures that are less than 3 storys high and have a plan area less than 600m^2. Most light-frame construction, including most houses, would fall under this category. Part 9 provides simple member size and spacing requirements without considering the overall load path through the structural system that transfers extreme environmental loads through the structure to the ground. Typically, construction of these structures is reviewed by building officials for conformance with municipal bylaws based on Part 9. Similar approaches to the design of light-frame construction are adopted around the world. This type of design is largely based on historical construction practices, and brings to light many questions: what problems exist for houses and light-frame construction both in Canada and internationally? Are the failures observed during extreme events acceptable? Are houses and other light-frame structures over-designed, resulting in an inefficient use of materials and resources?

The vulnerability of a structure to wind damage is dependent on a chain of factors (e.g. Davenport, 1961): (1) the wind loading, which is influenced by the climate, local terrain characteristics and the shape of the building, (2) the response of the building to the loads, which involves the building geometry, the dynamic properties of the building, and the interaction of load-bearing and non-load-bearing components, and (3) the quality of the construction. The research summarized in this report deals with the first link in the chain, i.e. the wind loading on a typical new Canadian house. Preliminary results from wind tunnel tests of a scale model of a two story house are presented.

Wind pressures act on the exterior shell of a structure, termed the 'cladding'. Cladding materials used in construction include vinyl siding, plywood sheathing, brick, and glass. The cladding transfers the wind load to the main structural system, consisting of roof trusses and sheathed walls, that carries it to the structure's foundation. In extreme wind events, either the cladding or the structural system can fail.

Figure 1 shows extensive failures of cladding on homes in Florida after Hurricane Andrew in 1992. This photograph demonstrates clearly that moisture can easily enter these houses, although relatively little damage occurred. Entire sheets of plywood are missing from the otherwise intact roofs, as are a large number of shingles. Rain during or after the storm would easily enter the structure through these damaged areas to destroy the house contents. It would also saturate the newly exposed wall and roof materials, setting the scene for potential mould growth. During Hurricanes Hugo and Andrew, the majority of the wind damage was caused by rain forced into the building around undamaged windows and soffits or through a breach of the building envelope. The resulting rain infiltration increased the value of insurance claims by a factor of two at low wind speeds and by a factor of nine where high wind speeds were measured (Sparks et al., 1994). It is thus very important to quantify the wind loads that occur on structures so that they can be designed to prevent this type of damage.

The photos in Figures 2(a) and 2(b) were taken before and after Hurricane Iniki struck the Hawaiian island of Kauai in September 1992. The damage to this house is an example of structural failure: the entire roof of the house was torn off and found approximately 100m away by the owners (see www.northshore.com/iniki/).

Current building code provisions for houses in Canada (Part 9, NBCC 1995) are prescriptive, specifying only member sizes and spacing and not actual allowable environmental loads. It is difficult to assess whether these standards are conservative or if the code specifications are unsafe in certain areas. Thus quantification of the environmental loads for typical house geometries would allow the main structural system of a house to be properly engineered, achieving optimum cost and reliability.

2. Wind tunnel tests of non-engineered construction

Other wind tunnel tests have been conducted on geometries of houses and small buildings that are traditionally non-engineered. Meecham (1988) investigated wind loads on hip- and gable-roofed buildings and determined that the cladding and main structural elements of the hip roof were much less severely loaded than those of the gable roof. Peterka et al. (1998) measured wind pressures on a narrow edge section of the windward roof of a full-scale test house and compared these with pressure data obtained from the testing of a scaled model in a wind tunnel. The measurements were concentrated in a small area to highlight cladding loads, and the wind tunnel pressure coefficients area-averaged over a small area were in good agreement with those measured in full-scale.

An extensive wind tunnel study of wind loads on tropical houses has been conducted in Australia (Holmes, 1994). Models of houses with varying roof slopes were investigated, and the effects of surrounding houses on the pressure coefficients were examined. The relative effect of the surrounding houses was accurately quantified but unfortunately, problems with the experiment involving surrounding houses invalidated the pressure coefficients observed. As a result, it is difficult to compare new wind tunnel data with those obtained from these experiments. Different configurations of rows of model houses situated upwind and downwind of the tested model were investigated. It was concluded that the mean pressure coefficients were sensitive only to the relative horizontal distance between a house and the surrounding houses, and not the relative heights.

In the present investigation, wind tunnel tests of a house model were conducted in UWO's Boundary Layer Wind Tunnel II. This wind tunnel simulates the atmospheric boundary layer, which is the lowest layer of the atmosphere, in the order of 1 km thick. The frictional forces caused by trees, grasses, and structures significantly reduce the wind speed in the atmospheric boundary layer and introduce turbulence (or wind gusts) into the wind flow. To reproduce the turbulence appropriately, blocks with varying height are placed along the wind tunnel floor upstream of the model. A suburban terrain was simulated in the current experiments. Non-instrumented house models can be placed around the instrumented model to study the effects of nearby houses in a subdivision on the wind pressures. The instrumented model and surrounding non-instrumented models are mounted on a turntable in the wind tunnel, to allow the investigation of the effects of different wind directions. Figure 3 shows a photograph of the instrumented wind tunnel model, and Figure 4 shows the different surroundings investigated that correspond to (a) an isolated house, (b) a house in the middle of a subdivision with a grid configuration, and (c) a house in the middle of a subdivision with a crescent configuration. The spacing between the model houses is representative of typical streets, front yards, and boulevards.

An exploded view of the 1:50 scale model tested is shown in Figure 5. It represents a two-story house with a full-scale width of 9.1m, a length of 10.4m, a mean roof height (h) of 7m and a roof slope of 4:12. Pressure measurements were obtained at 422 locations on the instrumented model, shown in Figure 5, allowing both local loads on cladding and overall loading on the main structural system to be studied in detail. The equivalent full-scale wind speed is the 30-year return period value specified in the NBCC (1995) provisions for London, Ontario. A very large quantity of data was obtained for wind directions from 0° to 90° with respect to the roof ridge as defined in Figure 6. Loads applied to the main structural system were calculated by a weighted integration of these instantaneous local pressures, and the statistics of the loads were obtained for different components in the system. This report will consider the loads induced at the ends of roof trusses where they connect with the side walls of the house.

3. Results

3.1 Cladding pressures

Each pressure measurement recorded at a single point on the model is assumed to act uniformly on the small tributary area surrounding it. This localized pressure is proportional to the wind load acting on the corresponding cladding component in the full-scale house. Particular attention is given to areas where high suctions might occur and so typically experience severe damage during storms, such as the roof edges, corners, and regions adjacent to the ridge. Figure 1 illustrates that Hurricane Andrew tore plywood sheathing and shingles off the roof at these locations. Due to the turbulent nature of the wind, the high suctions in these areas vary in both time and space. The local pressure at the centre of the windward wall is also of interest, although it is not as variable in time and space as are the suctions on the roof. The pressure measurement (tap) locations shown in Figure 6 are representative of the areas of interest for cladding loads.

Figure 7 compares the pressures measured for different wind directions at the centre of the predominantly windward wall (see Figure 6) of the model when adjacent houses in a subdivision are present or absent. The pressures measured on the lone house are significantly larger in magnitude than those obtained for the same house in a subdivision, and particularly as the wind direction approaches 90° to the ridge, which is perpendicular to the wall (see Figure 6). The pressures are insensitive to the configuration of the subdivision because, when the wind direction approached 90°, the neighbouring houses were positioned directly upwind of the instrumented house for both configurations.

Figures 8 and 9 show pressures measured at the roof corner and at one end of the ridge, respectively (see Figure 6) for the three exposure conditions. The suction (negative pressure) at these locations can be significant, depending on the wind direction. As for the windward wall, there is a significant reduction in the magnitude of the measured pressure when the adjacent houses are present. The pressures measured for both grid and crescent subdivision configurations are similar at both locations for all wind directions. The most dramatic reduction in pressure magnitude is 60% and occurs for the windward corner of the roof as shown in Figure 8.

It can be concluded from these general observations that surrounding houses significantly reduce wind loads and this should be taken into account in any design of these structures. The quantification of the magnitude of these local loads allows the design of cladding to efficiently resist these loads.

3.2 Structural responses

Certain structural responses to the wind load can be critical; for example, the entire roof of a house can be blown off in an extreme wind as shown in Figure 2(b) if the connections tying the roof down to the walls are inadequate. Wind tunnel tests can provide expected peak loads during an extreme wind event and so expedite optimal structural design.

The structural response depends on the load path through the structure that collects wind pressures from the roof or wall surface and carries the load to the foundation where it is resisted by the ground. Houses are very complex structures that do not have readily defined load paths: the gypsum wallboard, wood framing, ceilings, and other features participate in the load path resisting the applied wind loads. However, only certain structural elements such as roof trusses and wall studs are conventionally assumed to transfer the load through the structure. Forces to be resisted by these structural elements can be determined by integrating the pressures obtained at each tap location during wind tunnel testing using weighting factors that depend on the load path assumed.

As an example, the wind uplift force on a truss/wall connection is presented here. The sign convention is consistent with that previously adopted: a positive force pushes down on the roof, helping to hold it down, and a negative force represents suction on the roof, lifting it up. Figure 10 shows the peak uplift load for truss 1 (see Figure 5) calculated using the wind tunnel data. As for the cladding loads, the adjacent houses in a subdivision significantly reduce the uplift force at this connection, particularly if arranged in the crescent configuration.

4. Implications in full-scale

How are results from tests such as these useful? The knowledge of wind loading gained through model testing is difficult to apply to determine whether existing houses are sufficiently safe because very little is known about the manner in which these structures distribute the load. Conventional computer structural analysis programs cannot be used to analyze light-frame construction, due to the unknowns associated with the load paths (for example, does the gypsum wallboard in a house resist the wall loads or do the vertical wall studs?). To determine the actual load path, full-scale structure to destruction (i.e. until part of the structure fails) is necessary but very expensive and time-intensive, so component testing is more common in practice.

Full-scale testing of houses subjected to simulated wind and snow loading was conducted by the U.S. Forest Products Laboratory (Tuomi and McCutcheon, 1974) and by the National Research Council's Division of Building Research (now the Institute for Research in Construction) (Dorey and Schriever, 1956). However current knowledge of wind and snow loads has significantly advanced since these tests were completed. Also, advances in load application and data acquisition technology can capture the response of a full-scale house more accurately. Full-scale house testing under equivalent static wind loads (i.e., no temporal and limited spatial variation) has been conducted at the James Cook University Cyclone Testing Station (CTS) in Australia since 1977 (e.g. Boughton, 1983). However, connection details, building materials, methods, and the climate are markedly different in Australia so these test results have limited application to Canadian houses. Nevertheless, the CTS facility has provided extremely valuable evidence of how the Canadian and North American housing industry could benefit from full-scale testing. For example, bracing requirements specified in Queensland building regulations for houses were relaxed by approximately 50% after full-scale tests at the CTS indicated that non-structural elements provided sufficient bracing (Reardon, 1988). It was also found that light-gauge metal truss hold-down straps of a timber-framed house failed prematurely under cyclic loading typical of typhoon winds (Reardon, 1985).

A multi-disciplinary research team, involving structural and wind engineers from the University of Western Ontario (UWO) and UWO's Boundary Layer Wind Tunnel Laboratory (BLWTL), therefore has the long-term objective of investigating the effects of simulated environmental loads on full-scale light-frame structures that are typically non-engineered. Specific goals are: 1) to better predict the complex behaviour of housing and small building systems, 2) to remove flaws, and 3) to reduce over-specification, if it exists. The full-scale test facility will allow the investigation: (i) time and spatially varying wind loads which damage buildings under severe storm conditions, (ii) simulated snow loads that may coexist with wind, and (iii) rain loads that penetrate damaged and undamaged houses.

5. Conclusions and Recommendations

The exterior surface pressures on a 1:50 scale two-story house model with a 4:12 gable roof were measured in a wind tunnel that closely simulates the atmospheric boundary layer. Cases where the house is isolated or surrounded by neighbouring houses of similar size arranged in grid and crescent subdivision configurations were investigated. Generally, the neighbouring houses sheltered the instrumented house model, reducing the wind loads on both the windward wall and the roof.

Future wind tunnel tests are planned involving other house and low building configurations and considering the effects of internal pressures. The wind loads obtained from these future tests can then be applied to a full-scale test house in a proposed test facility.

8. References

Boughton, G.W. (1983). Testing of a full-scale house with simulated wind loads. Journal of Wind Engineering and Industrial Aerodynamics, 14, p. 103-112.

Davenport, A.G. (1961). The application of statistical concepts to the wind loading of structures. Proceedings of the Institution of Civil Engineers, 19, p. 449-471.

D'Costa, M.J. (2000). Structural performance of a corrugated fibreboard shelter. M.E.Sc. Thesis, Faculty of Graduate Studies, The University of Western Ontario, London, Ontario, Canada.

Dorey, D.B. and Schriever, W.R. (1956) Structural test of a house under simulated wind and snow loads, ASTM Special Technical Publication No. 210, Philadelphia, PA, p. 29-49.

Holmes, J.D. (1994). Wind pressures on tropical housing. Journal of Wind Engineering and Industrial Aerodynamics, 53, p. 105-123.

Meecham, D. (1988). Wind action on hip and gable roofs. M.E.Sc. Thesis, Faculty of Graduate Studies, The University of Western Ontario, London, Ontario, Canada.

NRCC (National Research Council Canada) (1995). National Building Code of Canada 1995 (NBCC (1995)); includes User's Guide – NBCC 1995 Structural commentaries (Part 4), NRCC, Ottawa, Canada.

Peterka, J.A., Hosoya, N., Dodge, S., Cochran, L., and Cermak, J.E. (1998). Area-average peak pressures in a gable roof vortex region. Journal of Wind Engineering and Industrial Aerodynamics, 77&78, p. 205-215.

Reardon G. F. (1988) Simulated wind loading on houses. International Conference of Housing & Construction in the Age of Technology. Gold Coast.

Reardon G. F. (1985) Mitigation of wind damage by testing building components. Proc. 5th U.S. National Conf. on Wind Engineering. Lubbock, Texas.

Sparks, P.R., Schiff, S.D., and Reinhold, T.A. (1994) Wind damage to envelopes of houses and resulting insurance losses. Journal of Wind Engineering and Industrial Aerodynamics, 53, p. 145-155.

Stathopoulos, T. (1979). Turbulent wind action on low-rise buildings. PhD Thesis, The University of Western Ontario, London, Ontario, Canada.

Tuomi, R.L. and McCutcheon, W.J. (1974) Testing of a full-scale house under simulated snow loads and wind loads, USDA Forest Service Research Paper, PFL 234.

Figure 1. Cladding damage on houses after Hurricane Andrew (1992). Photo courtesy of Applied Research Associates, Raleigh, North Carolina, USA.

(a)

(b)

Figure 2. House on the Hawaiian island of Kaui (a) before and (b) after Hurricane Iniki struck in September, 1992. Photos taken by the homeowners and are available at www.northshore.com/iniki/.

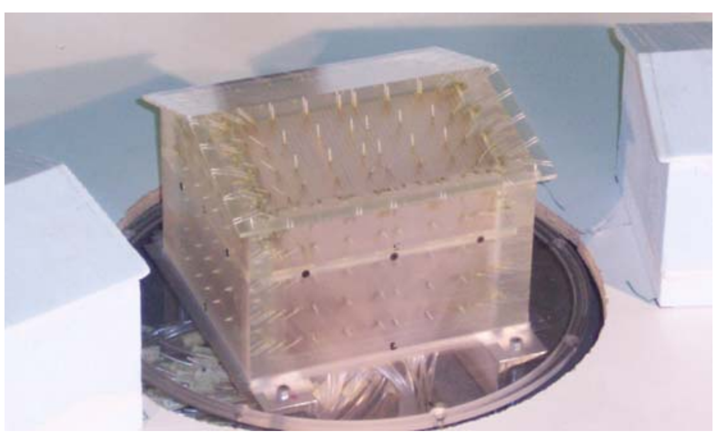
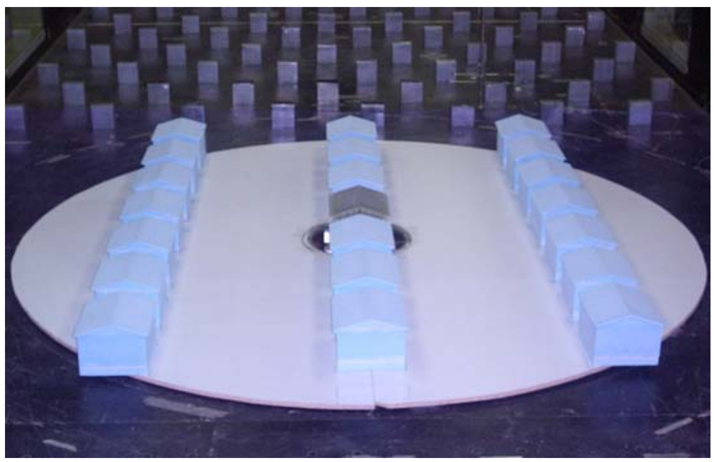
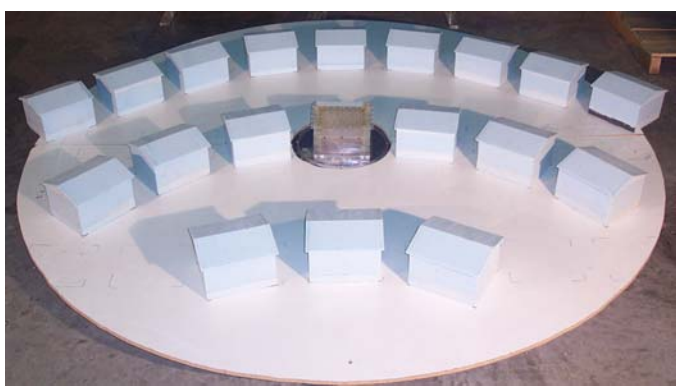


Figure 3. Instrumented wind tunnel model used in the current study.

(a)



(b)



(c)

Figure 4. Range of surroundings investigated: (a) lone house, (b) the grid subdivision configuration, and (c) the crescent subdivision configuration.

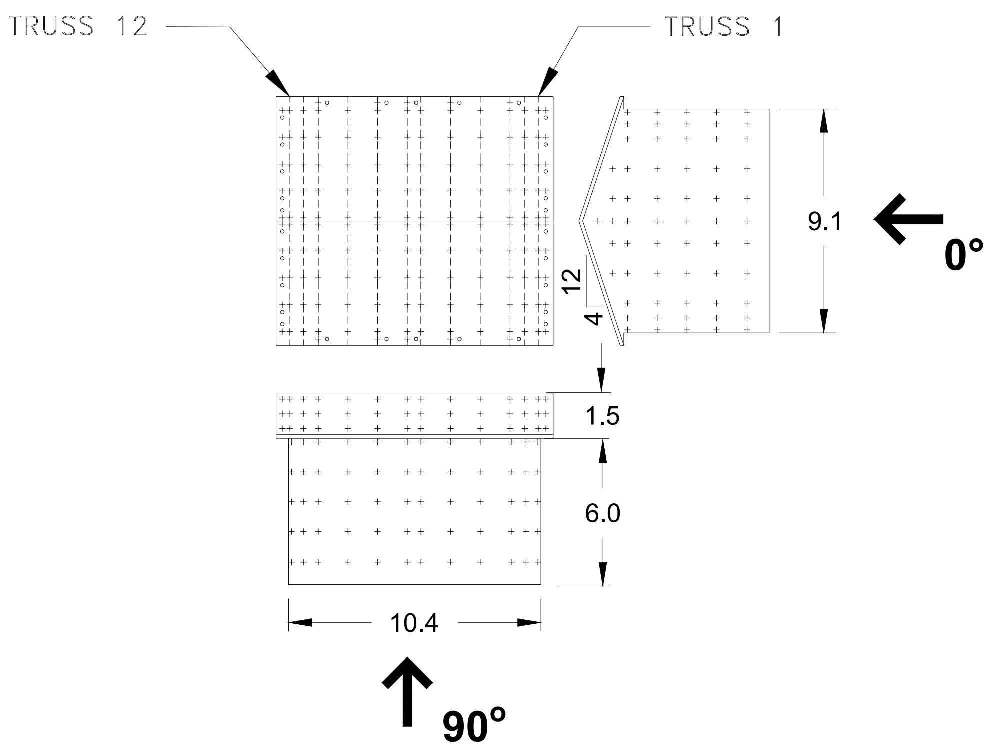


Figure 5. Exploded view of wind tunnel model, illustrating pressure tap and assumed truss locations. All dimensions are in full-scale metres.

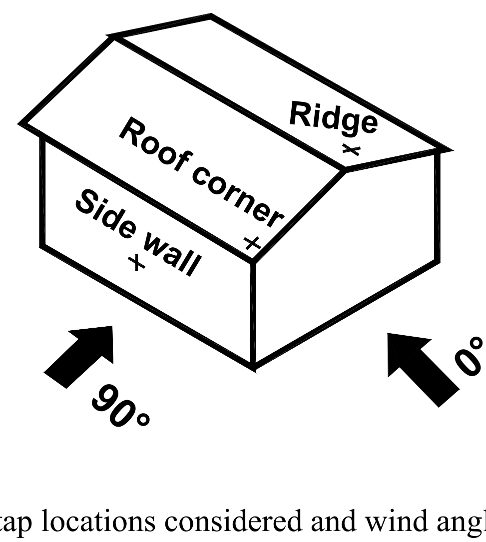


Figure 6. Pressure tap locations considered and wind angles investigated.

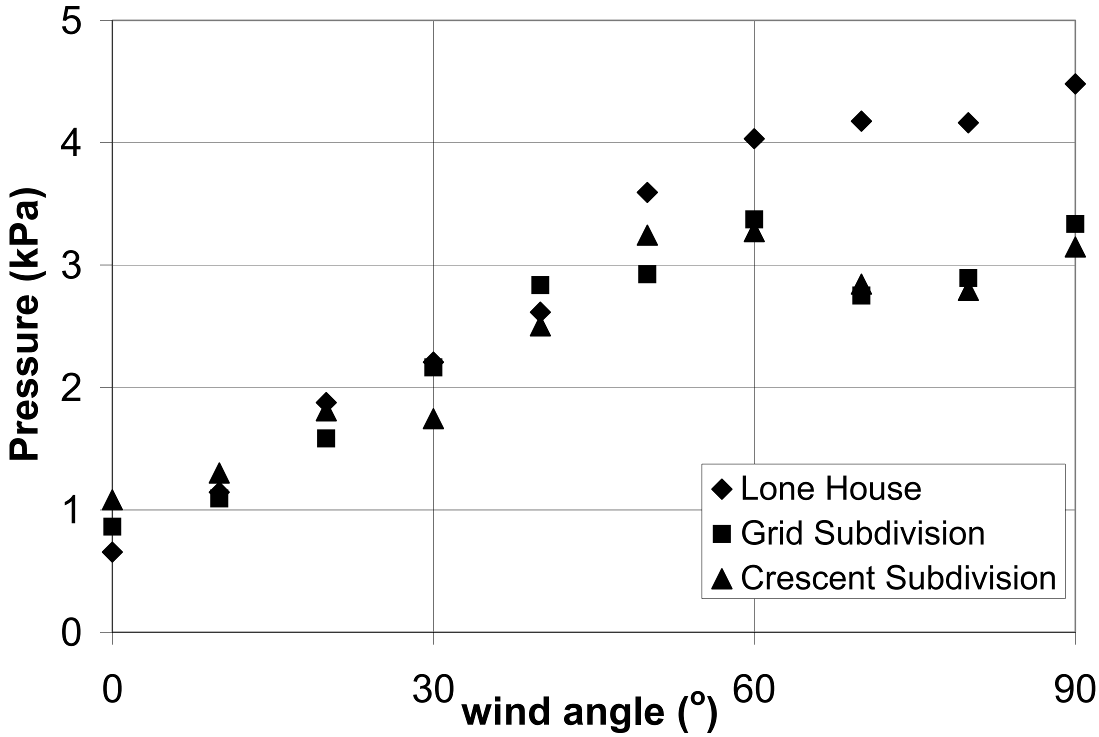


Figure 7. Side wall pressures (kPa) for cladding design in London Ontario.

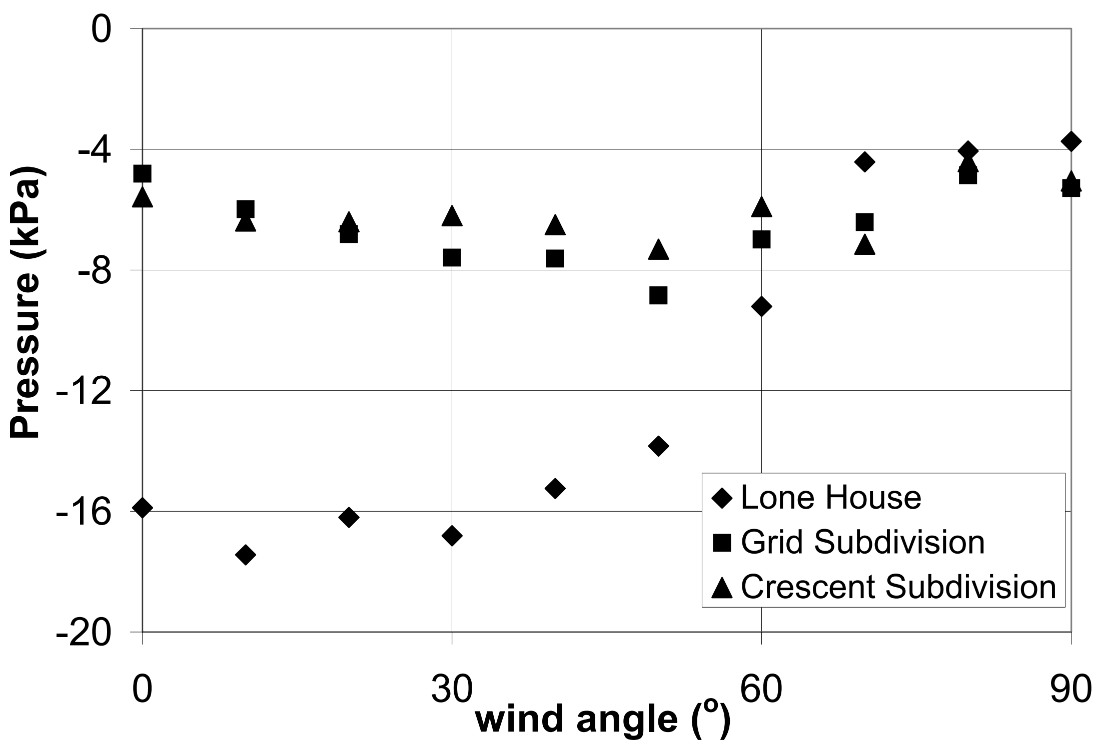


Figure 8. Roof corner pressures (kPa) for cladding design in London Ontario.

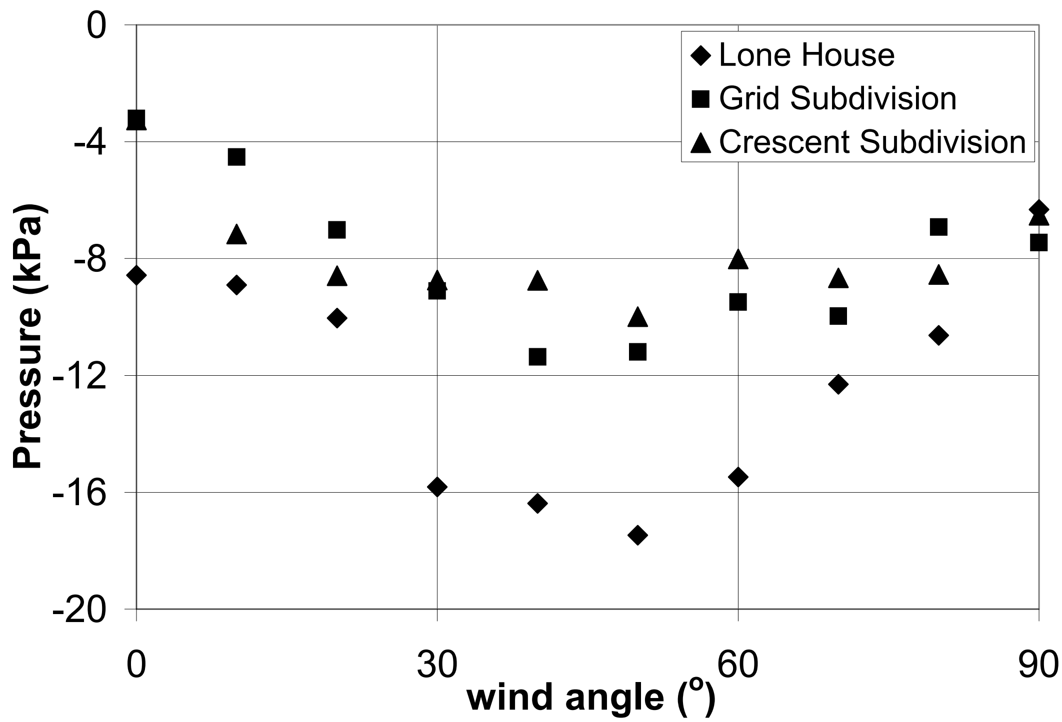


Figure 9. Ridge pressures (kPa) for cladding design in London Ontario

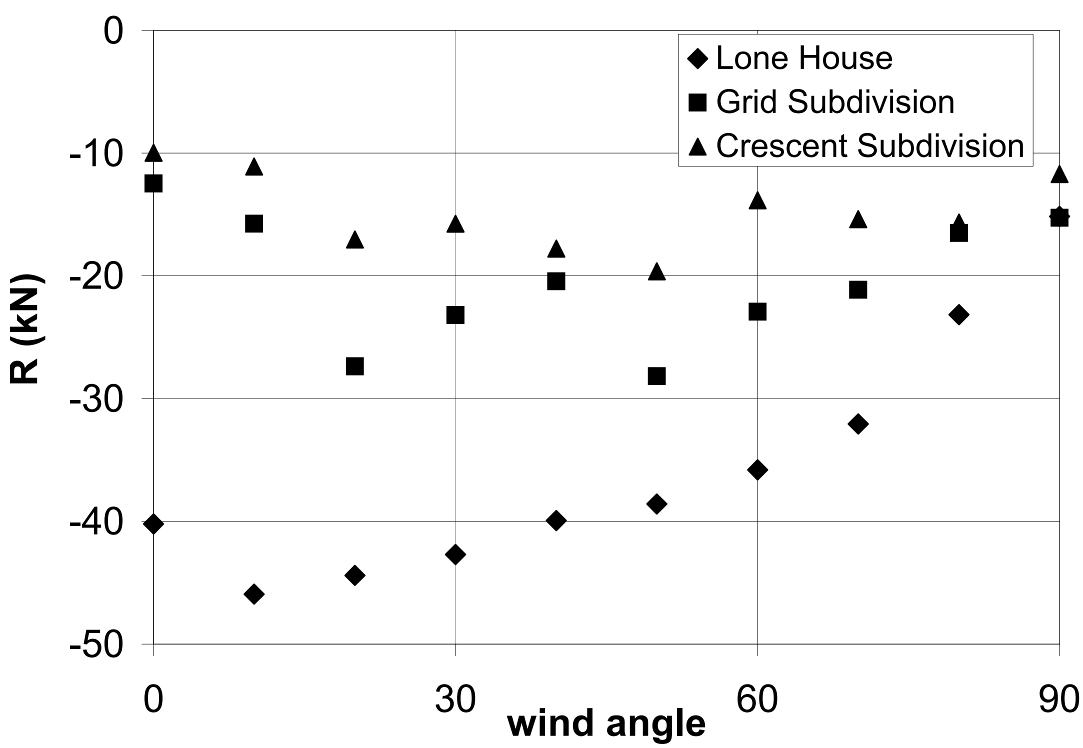


Figure 10. Peak vertical end reaction (kN) at Truss 1 for London, Ontario.