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Probabilistic Analysis of Wind Effects on New Zealand House Roofs

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Abstract

A probabilistic analysis to quantify the effects of strong wind on roofs of common New Zealand house types has been performed. A relatively new method called the Component Approach that uses capacities of building elements has been followed here. The component capacities have been determined through experimental investigation. Roofs with common geometric and material characteristics have been analysed for wind loads. Fragility curves have been developed based on these two parameters. The results look consistent with storm damage observations.

Introduction

Windstorms have regularly hit New Zealand causing significant damage to properties and occasional losses of lives. There seems to be a trend of increased frequency of these storms in recent years possibly due to global warming and subsequent climates changes. There were at least seven windstorms recorded just in 2014 with nearly $150 million of insurance cost (ICNZ, 2014). With the increase in population, the number of properties continues to grow and damage is expected to more and more serious. The emergency management and territorial authorities need to have a means to estimate the expected losses in the future.

Observations of severe wind effects on buildings during recent storms overseas (FEMA, 1993; van de Lindt et al, 2008) suggest in typical residential buildings, the roofs are the often most vulnerable and consequently the more damaged part of a structure. With similar materials and construction practices that is also applicable to New Zealand. But there is currently insufficient knowledge and understanding of the subject to predict the effect on the local building stock.

BRANZ has initiated an investigation into the performance of various roof types in low rise (predominantly domestic) houses with the aim of producing fragility curves for different types of buildings (Beattie, 2009) that could be fed into the National Institute of Water & Atmospheric Research/Institute of Geological and Nuclear Sciences (NIWA/GNS) Riskscape project (NIWA, 2006; King and Bell, 2006). The expected outcome is better predictions for damaging wind events which can assist emergency management agencies and territorial authorities to plan and prepare for such an event.

Literature review

Significant work has been undertaken to the topic in recent years. A common approach to predicting damage has been the use of data from post-disaster investigations or insurance claims to develop vulnerability curves (Mitsuta et al, 1996; Sill and Kozlowski, 1997; Huang et al, 2001). These curves are highly dependent on the type of construction and practices common to the area represented. Other studies (Khanduri and Morrow, 2003; Ellingwood et al, 2004) have suggested improvements to make them more generally applicable. Further research (Pinellii et al, 2004) suggests they can still be unreliable because it is very difficult to properly take into account all the significant characteristics of the storms.

An alternate scheme, called the component approach (Cope et al, 2003; Pinelli et al, 2004) uses resistance capacity and wind load on building components to predict damage. The resistance capacity of a roof system is often governed by the connections between the members rather than the capacities of the individual members. Failure and damage is expected when the load due to wind on a member or connection is higher than its capacity to resist that wind. The uncertainties involved with both strength of structural components and load effects of the wind have to be taken into account. Relative values of the strength capacity and load demand, acting through the load path, determine the vulnerability of a component. The probabilistic capacity of building components to resist wind loads determines the probability of damage for a range of wind speeds. A concept has been implemented in the FEMA HAZUS model (Lavelle et al, 2003) for hurricane wind damage prediction.

The review of literature was focused on research information on the behaviour of the roof components under wind loading for the initial part of this study. Cochran et al (1999) observed that small individual roof cladding components such as tiles are particularly vulnerable to the high local wind suction effects. Boughton and Falck (2008) found that tie down of all structural elements in the roof is essential and wind uplift forces are significantly higher for sheet roofs compared with tile roofs. They particularly mentioned that the areas of weakness were the batten to truss connection and the truss to wall anchorage. Van de Lindt et al (2008) also reiterated that the use of straps and ties to ensure a continuous load path to the foundation were essential for satisfactory performance.

BRANZ studies

The objective of the BRANZ study was to provide the probability of roof damage for typical New Zealand residential building structures as a function of peak wind speeds. It was intended to be achieved through a number of steps:

1. Categorisation of roof properties of the current building stock and identification of components for damage prediction
2. Estimation of probabilistic capacities of individual capacities to resist loads
3. Quantification of wind loads on identified components for selected arrangements and load paths
4. Determination of vulnerability through probability-based evaluation of components

The resistance capacity of individual components was determined within a probabilistic framework. There are indirect ways to determine component capacities based on observed performances and post-damage reports. But far more reliable information can be achieved through direct measurements. For this research the capacities were determined from test results of actual connections rather than theoretical values based on assumed component properties.

The experimental investigation was limited to a selection of roof claddings and joints between timber roof framing elements that were considered to be typical of New Zealand low rise buildings (particularly houses). Several roof cladding materials commonly used were considered to represent typical New Zealand applications. Connections of corrugated steel roofing to two typical substrates – Radiata Pine (exotic) and Rimu (NZ native) – are common in modern and older house construction respectively. Common joints between battens or purlins and rafters or trusses were considered, along with the connections between rafters or trusses and wall top plates.

The intention was to conduct an experimental investigation on roof component connections from real structures with known age. Joints fabricated using timber salvaged from the demolition sites was used to re-create the real situation as best as possible.

Details of experimental investigations

As described just above, four types of joints were investigated, namely purlin-lead head nails, purlin-rafter, rafter-top plate and truss-top plate. Details of the joints are as follows:

1. Corrugated steel to radiata pine purlins – dry timber and new lead head nails
2. Corrugated steel to rimu purlins – dry timber and new lead head nails
3. Rimu purlins to rimu rafters – dry and new nails
4. Rimu rafters to rimu top plates – dry and new nails
5. Radiata pine trusses to top plates - wet and dry framing and new nails (also one set with wire dogs included).

The nails used in the joints were all new after it was observed that the majority of nails removed from the salvaged timber were still in very good condition. The radiata pine joints were fabricated with 90 mm long by 3.15 mm diameter D-head gun driven nails and the rimu joints were fabricated with 100 mm long by 4 mm diameter jolt head nails. The truss elements were built using MSG8 H1.2 framing. The radiata pine top plate elements were untreated MSG8 framing. Density and moisture content samples were taken from each specimen at the time of testing. Thirty replicates were made for the truss/plate joint variations. Lesser numbers were fabricated for the rimu specimens due to the short supply of rimu timber (13 for corrugated steel to rimu purlin joints, 20 for corrugated steel roofing to radiata pine purlin joints, 18 for rafter/plate joints, 26 purlin/rafter joints).

All of the tests were conducted in the Dartec Universal Test Machine in the BRANZ structures laboratory. The loading rate was set at the fastest speed that the machine could operate (600mm/s) to simulate the likely wind force in the field. An example of a truss/top plate test setup is given in Figure 1.

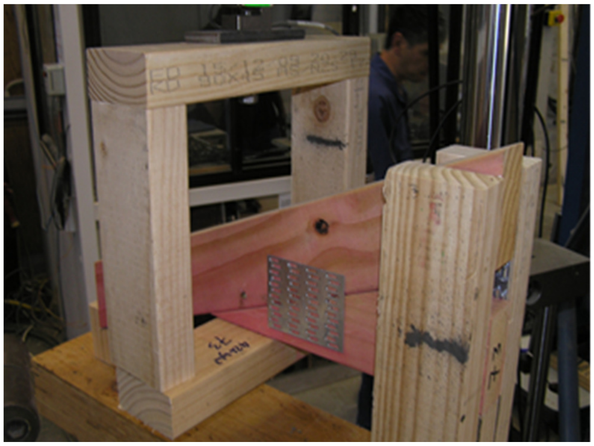

Figure 1. Test setup for component testing

Derivation of fragility curves

Various distributions were tested against the results of the tests. Generally, a normal distribution was found to provide a reasonable fit to the data and then from this a plot of the likelihood of failure (as a percentage) was made against the range of failure loads (the fragility curve). A sample plot of the fragility curve is presented in Figure 2.

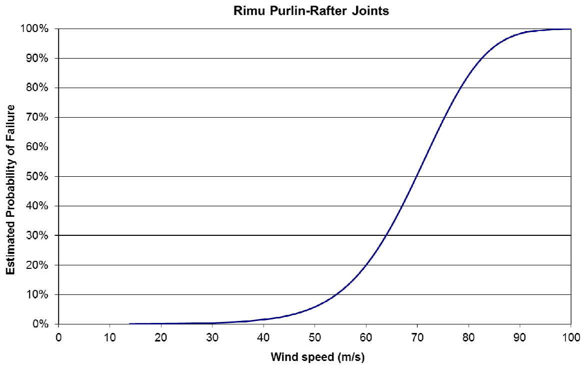

Figure 2. Sample plot of the likelihood of failure

The failure load was correlated with an associated wind speed. This was undertaken by a review of the prescriptive construction standards of the day for the Rimu framed structures and the Radiata pine framed structures. This provides the roof areas associated with the element fixings, from which a pressure range can be derived and then the associated wind speed. This will allow the Riskscape model to be populated with probabilistic resistance information for commonly encountered roofs.

Wind loads for typical structures

Wind loading characteristics are heavily dependent on the shape and component make up of any individual structure. Thus the accuracy and reliability of the damage prediction is dependent on characterization of the roof properties such as type, geometry and materials. Geometric shapes include the common types such as gable, hip and single slope roof and their combinations such as hip roofs L and T-shaped in plan (Figure 3). A study of roof geometry over major built-up areas over the entire country produced a list of statistically significant types. Information on commonly used roof materials was gathered from published building detail survey results. Some building properties including details such as wall height, eave overhang, truss spacing and roof pitch have been kept the same for different roof types.

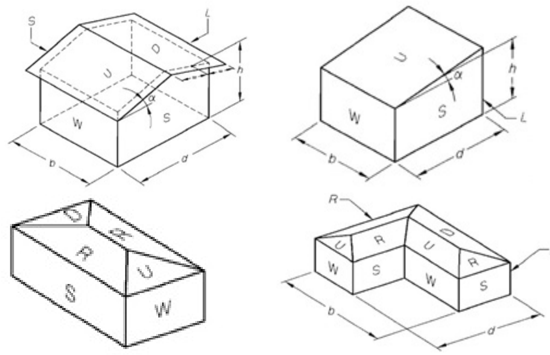

Figure 3. Examples of Common Roof Geometries (from AS/NZS 1170.2)

The overall distribution of wind loads and load on each selected component are based on the guidelines of local standard AS/NZS

1170.2 (Standards New Zealand, 2012). The methodology stated in the standard was followed for calculating the loads for structures with different properties. Appropriate factors suggested for taking the other factors into account were also adopted.

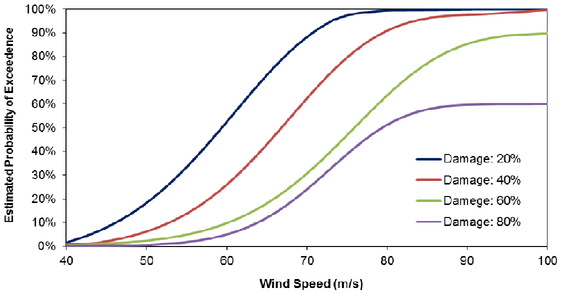

Figure 4. Fragility curves for different damage levels

Structural damage potential

The analysis deals with multiple variables. Individual buildings with a particular roof geometry and material are subject to multiple angles of incidence. The wind speed varies for the ranges of the other variables. Wind load on a roof component is derived as a series of combinations of all the variables. Failure of each component is determined by comparison between the wind load demands and probabilistic strength of the connection.

A sequence of most likely event based on the load path is identified for each type of roof. Failure checks are performed for individual components following the order of events. Combinations of damage of the components makeup the level of the overall damage. For a given wind speed there is a distribution of overall percent damage across the range of roofs of the same type. Fragility curves were developed to estimate the probability that a certain level of damage will be met or exceeded at a given wind speed. These curves give estimates of the number of buildings of a similar type in an area expected to experience at least a certain level of damage.

To develop the fragility curves, separate damage distributions at different wind speeds are obtained. Integrating the area from the threshold point to the positive extreme of each distribution gives the data point for the fragility curve at each wind speed. A family of curves is generated for different damage thresholds for the total population (Figure 4). Each curve shows the likelihood of exceeding that damage level at various wind speeds.

Roof Damage Observations

In July 2014 a series of windstorms created damage to number of properties mostly in Northland, the northernmost part of New Zealand. The recorded peak wind speed was 168kph at Cape Reinga and 130kph at Kerikeri (Stuff, 2014). The storm continued over several days accompanied by heavy rain and flooding in places. A brief reconnaissance survey was performed to observe the damage and identify important characteristics. It was carried out in a number of areas around Kaitaia, Waipapa and Whangarei. The properties damaged were mostly residential buildings along with a number of commercial premises. Typical damage observations in Northland storms included:

- Total or partial loss of roof cladding
- Cladding-purlin connection failure
- Roof truss connection failure

A view of typical observed roof damage is shown in Figure 5.

Figure 5. Roof damaged in Northland storm

Information on other details such as maximum wind speeds, connection details and component properties was difficult to accumulate within the short time period. There was also little opportunity for any detailed analysis within the scope of the original research. Based on the limited observations, the findings were consistent with the analytical results. As expected, only a small percentage of the buildings were damaged. In most structures the roof was the only part that suffered major damage. Varying levels of damage were observed, depending on the type, geometry and exposure to wind but only a fraction of the buildings suffered serious damage, as predicted by the research.

Riskscape and Wind Damage Hazard

Riskscape is a decision-support tool for land use and emergency management planners jointly under development by NIWA and GNS (NIWA, 2006). The model incorporates data on a range of natural hazards, including severe winds, to enable planners to take into account the risk posed by each hazard. Output from the current research is planned to be supplied to be used in the overall hazard model. The parameters have to be consistent across the hazards to allow objective comparisons. Fragility curves indicating likelihood of damage to types of houses with different roof types and materials will be provided. The model is intended to incorporate average values with expected upper and lower limits. Application of the model can help with preparation for emergency management as well as decisions on general planning aspects such as investment of infrastructure and land development.

The current investigation provides information only on the likelihood of damage to buildings under variable wind speeds. For a complete wind damage prediction model capable of calculating financial losses, two other components will be necessary: likelihood of occurrence of the wind velocities and cost of repair of the damage. A complete model should be applicable to the whole country taking all the local conditions into account.

Conclusions

The component approach is a relatively new way of predicting wind damage to buildings. It is more reliable since it only uses experimentally obtained capacities of building elements rather than data from post-disaster damage assessments or insurance claims. The predictions can be validated through comparison with data from previous storms and wind damage. The current research provided important information for implementing the approach. The results are expected to be useful in the development of the multi-hazard Riskscape model.

Acknowledgments

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