Modelling damage to residential buildings from wind-borne debris – Part 2, implementation

Martin Wehner[1], Carl Sandland[2], John Holmes[3], David Henderson[4], Mark Edwards[5]

[1]Geoscience Australia, martin.wehner@ga.gov.au
[2]Geoscience Australia, carl.sandland@ga.gov.au
[3]JDH Consulting, John.Holmes@jdhconsult.com
[4]Cyclone Testing Station, James Cook University, david.henderson@jcu.edu.au
[5]Geoscience Australia, mark.edwards@ga.gov.au

1 INTRODUCTION

Of the damage sustained by residential buildings during a severe wind event, a significant portion can be caused by impacts from wind-borne debris. Furthermore, where such impacts form dominant openings in windward walls, large internal pressures can be generated, consequently leading to substantially increased loads on the building's structure and hence increased damage to the building's envelope. Geoscience Australia, together with its collaborators the Cyclone Testing Station at James Cook University and JDH Consulting, have commenced development of a software tool, called WindSim, to quantitatively model vulnerability of residential buildings to severe wind. This paper describes the implementation of the methodology presented in Part 1 [1] into the WindSim program to model wind-borne debris induced damage.

2 LOGIC

2.1 Overview

The damage from wind-borne debris is calculated by the program for each simulated residential building (hereafter referred to as a house) at each gust wind speed increment. Within a single simulated house, damage from previous gust wind speed increments is remembered so that the progressive build-up of debris damage with increasing wind speed can be tracked.

The debris damage section of WindSim can be split into four modules:

1. A debris generation module,
2. A debris trajectory module,
3. A debris impact module and
4. A debris damage costing module.

To represent the vulnerability of a house to debris damage, the walls of the house are broken down into 'coverages'. Each coverage represents a different piece of cladding, e.g each window is a different coverage; each different type of wall cladding is a coverage. A coverage has a predefined area and a failure momentum which is assigned by the program through randomly sampling from a lognormal distribution with a predefined mean and standard deviation for that coverage's material type. The variation in size, number and type of coverages around the house is modelled by assigning different coverages to different walls.

2.2 Debris generation module

WindSim models debris generated from an array of upwind source houses with defined vulnerability curves within a user-defined sector (radius, angle, source house spacing and pattern). The vulnerability curves are defined by defining alpha and beta terms in Eq (1). For a given increment in gust wind speed the program determines the number of debris items from each source house by sampling a Poisson distribution with a mean defined by Eq (2),

$$DI = 1 - e^{-\left(\frac{V_{10m,3\sec}}{e^{\beta}}\right)^{\frac{1}{\alpha}}} \quad (1)$$

$$\text{Mean}_{(vc)} = \text{int}(\text{DI}_{(vc)} - \text{DI}_{(vp)}) \times \text{N}_{items} \quad (2)$$

Where $\text{Mean}_{(vc)}$ is the mean number of debris items generated at the current gust wind speed, $\text{DI}_{(vp)}$ is the damage index evaluated at the previous gust wind speed, $\text{DI}_{(vc)}$ is the damage index evaluated at the current gust wind speed and N_{items} is the maximum number of debris items per source house specified by the user. The generation of debris items is proportional to the slope of the source building's vulnerability curve. As the slope approaches zero at high wind speeds the item supply is effectively exhausted. A 'region' defines the statistical nature of the debris field composition and the source house vulnerability curves. It provides statistical properties for item mass and frontal areas, to be sampled for each new debris item. Each region has a certain ratio of rod, sheet and compact debris item types.

2.3 Debris trajectory module

For each debris item, the program calculates flight time by sampling a lognormal distribution as recommended in [2] and calculates a dimensionless flight time parameter Kt* as defined in [2]. The program uses quadratic relationships (different quadratics for different debris types) between a dimensionless flight distance, Kx*, and Kt* that closely match the fifth order polynomials given in [2] for low values of Kt* and provide sensible results at higher values to calculate the flight distance. The debris item's momentum can then be calculated by using equation (1) in [1] to calculate a mean and then sampling a beta distribution as recommended in [1]. Thus a cumulative distribution function of debris momentum is generated.

To determine the landing location for a particular debris item, the program assumes a bivariate normal distribution about the nominal landing site of flight distance directly downwind from the source house. The standard deviation along the direction of flight is taken as one third of the flight distance and the standard deviation normal to the direction of flight as one twelfth of the flight distance in accordance with recommendations in [2]. The program samples the bivariate distribution for each debris item and checks to see if the landing location is within the footprint of the target house. If it is, the number of impacts is incremented. An example of a debris field generated by WindSim is shown in Fig 1.

2.4 Debris impact module

The program calculates the probability of each coverage being damaged and then randomly samples this probability to determine damage following the method recommended in [1]. In doing so it samples the cumulative distribution function of debris item momentums generated earlier to determine the probability of the momentum of the debris item exceeding the failure momentum of a particular coverage.

If a window is damaged, it is assumed that the entire window area is damaged and the house has a dominant opening in a windward wall leading to full internal pressurisation.

For non-glass coverages the program needs to calculate an *area* of damage, not just whether it is damaged or not. The program determines this for a coverage by sampling a Poisson distribution with a mean of λ to determine the number of damaging impacts where λ is determined by Eq (3). N_v is the total number of debris items that impact the target house. $[1-F_{\xi}(\xi_D)]$ is the probability that a debris item has a momentum greater than the failure momentum of the coverage in question.

$$\lambda = N_V\left(\frac{Coveragearea}{Windwardwallarea}\right)\left[1 - F_{\xi}\left(\xi_D\right)\right] \quad (3)$$

For a given coverage, the damaged area is taken to be [the number of damaging impacts times the impact size times an amplification factor]. The total debris damage to walls is taken as the sum of the damaged areas for all coverages divided by the total wall areas.

2.5 Debris damage costing module

The repair cost due to debris is calculated using the percentage of wall area damaged by debris. This cost is added to repair costs of other parts of the building envelope prior to calculating the damage for the wind speed in question. To avoid double costing, where a wall is damaged by racking and/or collapse as well as debris then the percentages for racking and/or collapse are deducted from the percentage debris damage. This is because the costing modules for wall racking and wall collapse already cost repair to the wall cladding. Wall cladding damage due to wind pressure is assumed to be non-coincident with debris damage as it will occur in areas of suction (leeward walls) rather than windward walls where debris damage will occur.

3 RESULTS AND CALIBRATION

The program reports debris damage in two ways:

- The gust wind speed at which a breach is formed in the windward wall and thus internal pressurisation occurs.
- The percentage of debris damage to walls is reported.

Fig 2 and Fig 3 show results generated by WindSim by the debris damage section of the program.

Damage investigation survey data from tropical cyclones such as Larry, Vance and Tracy [4,6,7] were reviewed for types and numbers of buildings damaged as well as types and distances debris travelled. For example, following Cyclone Vance, a survey of a newer suburb in Exmouth revealed that 30% of the houses had been hit by wind driven debris. However, approximately 20% of the houses were subjected to internal pressure, which also included failures of roller doors, soffits, etc [6]. Boughton [3] noted in the overall population of newer buildings across the town, 35% had suffered internal pressurisation resulting from either failure of elements (roller doors, fascias, etc) or debris damage. The newer housing located in the older suburbs were subjected to a higher level of wind driven debris attack from less robust older construction. Whereas during Cyclone Althea approximately 70% of the houses surveyed in a suburb were subjected to internal pressure, with the majority then suffering subsequent significant structural failures [5].

The collated survey data for the varying building types and reported wind speeds were used in the calibration of the model with the primary assumption of approximating the reported proportions of buildings subjected to internal pressure. The WindSim parameters that best represented the relevant survey findings for older construction was a radius extended to the maximum of 200 metres, an angle defining the sector of source houses reduced to the minimum of 20 degrees and the number of source items increased to 250.

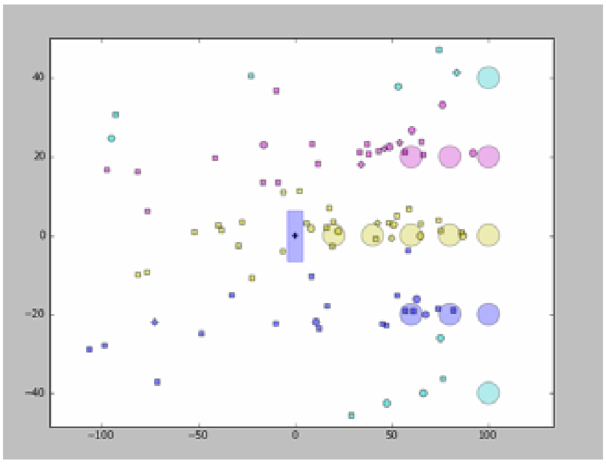

Fig 1. Sample debris field from WindSim. The blue rectangle is the target house. Source houses are represented by the coloured circles. Debris items are represented by the small dots and are colour coded to their file of source houses. Axes are metres offset from the target house.

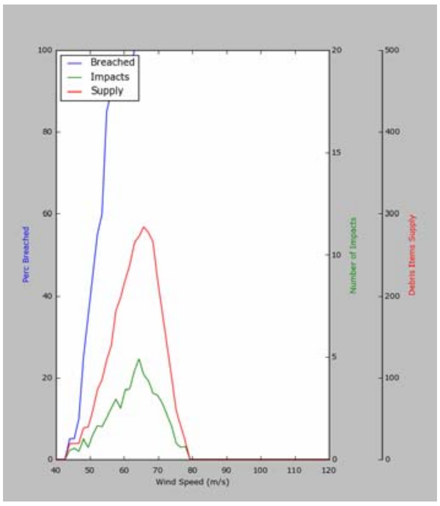

Fig 2. Screen shot of WindSim debris damage output showing percentage of houses breached (blue), number of debris items generated (red) and number of impacts on target house (green) averaged over 20 simulations. X axis is 3s gust wind speed at 10m height (m/s).

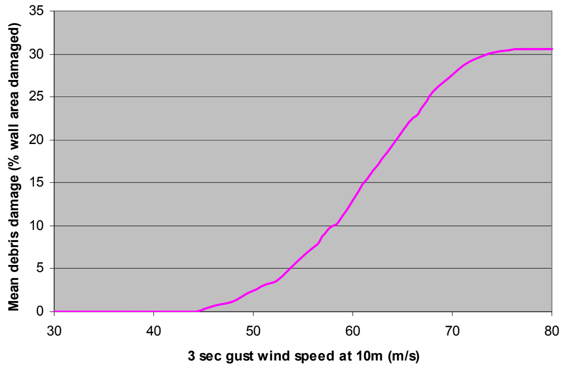

Fig 3. Plot of percentage wall damaged by wind borne debris versus gust wind speed averaged over 50 simulations for a single wind direction. Note that Percentage is damaged area as a percentage of total wall area for the house.

4 CONCLUSIONS

The simulation of damage from wind borne debris by the WindSim program follows a logic that attempts to mimic real debris behaviour within the constraints of available computing power. The simulation of debris damage is integral to the calculation of overall damage index and hence vulnerability curves for residential structures. By varying the parameters defining the debris sources and regions it is possible to calibrate the program against available post-storm survey data.

5 ACKNOWLEDGEMENTS

This work was co-funded by the Department of Climate Change and Energy Efficiency whose support is gratefully acknowledged.

6 REFERENCES

[1] J.D. Holmes, M. Wehner, C. Sandland & M. Edwards (2010) “Modelling damage to residential buildings from windborne debris. Part 1. Methodology”, AWES 14 Workshop, Canberra, August 5-6, 2010.

[2] Lin N. & Vanmarcke E (2008) “Windborne debris risk assessment”, Probabilistic Engineering Mechanics 23, 523-530.

[3] Boughton, G. (1999). "Tropical Cyclone Vance - Damage to buildings in Exmouth." Dept of Local Government, Perth.

[4] Ginger, J. D., Henderson, D. J., Leitch, C. J., and Boughton, G. N. (2007). "Tropical Cyclone Larry: Estimation of wind field and assessment of building damage." Australian Journal of Structural Engineering, 7(3), 209-224.

[5] JCU. (1972). "Cyclone Althea." Report and recommendations prepared by the Engineering Dept, JCU, Townsville.

[6] Reardon, G., Henderson, D., and Ginger, J. (1999). "A structural assessment of the effects of Cyclone Vance on houses in Exmouth WA." TR48, James Cook University, Townsville.

[7] Walker, G. (1975). "Report on Cyclone Tracy – Effect on buildings – Dec 1974." Australian Dept of Housing and Construction.