Modelling damage to residential buildings from wind-borne debris – Part 1. Methodology

J.D.Holmes[1] M. Wehner, C. Sandland, M. Edwards[2]
[1] *JDH Consulting, Mentone, Victoria*
john.holmes@jdhconsult.com
[2]*Geoscience Australia, Canberra, ACT*

1 INTRODUCTION

Damage from windborne debris is a major contributor to the total damage produced by extreme wind of all types. Therefore, it is important to incorporate this component into a complete wind-induced damage model, developed for disaster management or insurance purposes.

This paper describes the basic methodology for windborne debris damage modelling developed for Geoscience Australia, as part of the WindSim model. WindSim is a software tool currently under development that models damage to buildings from severe wind. The implementation of the windborne debris damage model is described by Wehner *et al*. [1].

2 PREVIOUS WORK

Debris damage models were reviewed by Holmes [2] recently. In particular, probabilistic, engineering debris damage models developed by Twisdale *et al*. [3] and Lin and Vanmarcke [4], [5] were considered before commencing development of the present models.

The main elements of a debris damage model can be summarised as follows:

- ***A debris generation module***
- ***A debris trajectory module***
- ***A debris impact and damage module***

The main features of these as proposed to, and adopted by, GA will be outlined in the following sections.

3 DEBRIS GENERATION MODULE

The debris generation region is taken as 20 times the target building height upwind, and within a 45 degree angular sector. It is considered unlikely that debris from the roof of a low-rise building, even in a tropical cyclone, will travel more than about 100 metres horizontally, without hitting either the ground or another building. That distance is 20 times the average roof height of a two-storey building.

Windborne debris from a roof will be generated when the local wind speed is sufficiently high, a) to produce a structural failure of a cladding element or its fastening, and b) to generate aerodynamic forces exceeding those of gravity and thus initiate flight. It can probably be assumed that if the wind speed is high enough for (a) to occur, then (b) will also occur. Thus the generation of debris may be associated with the failure of roof elements and hence related directly to a wind load/pressure vulnerability model. However a simplified version was implemented for roof elements only based on the simple heuristic vulnerability curves already developed by GA.

The recommended proportions of debris types (using the classifications of Wills *et al.* [6]) are tabulated in Table I.

Table I.
Recommended proportions of debris types for Australian suburban conditions

Type	Examples	Proportion (capital cities, ex Darwin)	Proportion (tropical towns)
Compact	Loose nails screws, washers, parts of broken tiles, chimney bricks, air conditioner units	20	15
Sheet/plate	Roof cladding (mainly tiles, steel sheet, flashing, solar panels)	50	45
Rod	Parts of timber battens, purlins, rafters	30	40

For the number of debris items, a factor, f, was defined. This is a constant of proportionality relating the average number of debris items associated with a damage increment on the vulnerability curve for the source building.

$$\text{i.e.} \quad \Delta v_V = f.\Delta D \tag{1}$$

where Δv_V is the incremental number of debris items generated in a single wind velocity increment – i.e. between two discrete wind velocities. Similarly, ΔD is the increment in wind damage produced by the same increment in wind speed.

4 DEBRIS TRAJECTORY MODULE

Detailed studies of debris trajectories have indicated that the ratio of horizontal velocity of the windborne debris object to the wind gust velocity can be directly related to the horizontal distance travelled, x, by the following Lin *et al.* [7]:

$$\frac{u_m}{V_s} \cong 1 - \exp\left[-b\sqrt{x}\right] \tag{2}$$

where u_m is the horizontal velocity of the debris object
V_s is the local (gust) wind speed
x is the horizontal distance travelled
b is a dimensional parameter depending on the shape of the object and its drag coefficient, and its mass:

$$b = \sqrt{\frac{\rho_a C_{D,av} A}{m}} \tag{3}$$

where ρ_a is the air density
$C_{D,av}$ is an average drag coefficient (averaged over all rotations during flight)
A is the frontal area
m is the mass of the object

Following Lin and Vanmarcke [5] the ratio of missile speed to wind gust speed is modelled as a random variable with a Beta distribution, which can only take values between 0 and 1. The mean value is assumed to be given by Equation (2).

5 DEBRIS IMPACT AND DAMAGE

The proportion of missiles of a given type that impact on a downwind building needs to be determined. Following Reference [4], the probability distribution of the point of landing of the debris in a horizontal plane is assumed to be described by a bivariate Gaussian Distribution :

$$f_{x,y}(x,y) = \frac{1}{2\pi\,\sigma_x \sigma_y} \exp\ -\left[\frac{(x-d)^2}{2\sigma_x^{\ 2}} + \frac{(y)^2}{2\sigma_y^{\ 2}}\right] \tag{4}$$

where x and y are the coordinates of the landing position of the debris assumed as random variables, (x is along the mean wind direction)
d is the mean or expected landing position
σ_x, σ_y are the assumed standard deviations for the coordinates of the landing position.

Information on the parameters for the above distribution is available from wind-tunnel studies and/or numerical simulations. The mean landing position, d, can be related to an assumed time of flight, as used by Lin and Vanmarcke [4].

By sampling from the above distribution, simulations of the landing point of each simulated debris item can be made. If the landing point so sampled falls within the footprint of the target building, then it can be assumed that an impact has occurred, and an increment made to the count of impacts, N_V, for a given gust wind speed.

The final stage is to establish the material damage resulting from impacts of debris objects with known mass, horizontal velocity, momentum and kinetic energy.

The probability of damage is assumed to given by Equation (5) based on the Poisson Distribution:

$$P_D = 1 - \exp\{-N_V.q.A[1 - F_\xi(\xi_D)]\} \tag{5}$$

where P_D is the risk of damage due to impacts on a given surface per unit time, at a wind gust speed, V, in a given storm,
N_V is the average number of impacts per unit time on the building footprint for wind speed, V
q is the vulnerable fraction of the building envelope
A is the total area of the building envelope
$F_{\xi}(\xi)$ is the cumulative distribution of impact momentum

Information on the threshold of momentum or energy for damage, ξ_D, for various building materials, including glass, is available. The thresholds of momentum for 6mm glass of various were derived from a paper by Minor [8].

6 DISCUSSION AND CONCLUSIONS

A skeleton for a windborne debris damage simulation model has been outlined. Methodologies have been provided for a debris generation module, a debris trajectory module, and a debris impact and damage module. Appropriate probability distributions, mean values and coefficients of variation have been suggested. Monte Carlo simulation techniques, in which values of each parameter are randomly sampled from the assumed distribution, have been adopted. The final calculation of probability of damage produced is done by application of Equation (5).

7 REFERENCES

[1] Wehner M., Sandland C., Holmes J.D., Ginger J.D., Kim P. & Edwards M. (2010). "Modelling damage to residential buildings from windborne debris. Part 2. Implementation". 14th Australasian Wind Engineering Society Workshop, Canberra, A.C.T., August 5-6.
[2] Holmes, J.D. (2010). "Windborne debris and damage risk models: a review", Wind and Structures, 13, 95-108.
[3] Twisdale L.A., Vickery P.J., & Steckley A.C. (1996). Analysis of hurricane windborne debris impact risk for residential structures, Report prepared for State Farm Mutual. Applied Research Associates, Raleigh, North Carolina, Report 5303. March 1996.
[4] Lin N. & Vanmarcke E. (2008). "Windborne debris risk assessment". Prob. Engg. Mech., 23, 523-530.
[5] Lin, N. and Vanmarcke, E. (2010). "Windborne debris risk analysis – Part 1. Introduction and methodology". Wind and Structures, 13, 191-206.
[6] Wills J.A.B., Lee B.E., &. Wyatt T.A. (2002). "A model of windborne debris damage". J. Wind Eng. Ind. Aerodyn., 90, 555-565.
[7] Lin N., Holmes J.D. & Letchford C.W. (2007). Trajectories of windborne debris and applications to impact testing. J. Struct. Engg. (ASCE), 133, 274-282.
[8] Minor J.E. (1994). "Windborne debris and the building envelope". J. Wind Eng. Ind. Aerodyn., 53, 207-227.