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Special Issue paper on Windborne Debris

Windborne debris and damage risk models: a review

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Abstract. This review paper discusses research from the last few years relating to windborne debris risk models and the essential elements of engineering damage prediction models. Generic types of windborne debris are discussed. The results of studies of debris trajectories that are relevant to damage models are described – in particular the horizontal component of debris velocity as a function of distance travelled. The merits of impact momentum versus impact kinetic energy as a relevant parameter for predicting damage are considered, and how published data from generic cannon impact tests can be used in risk models. The quantitative variation of debris impact damage with wind speed is also discussed. Finally the main elements of previously-proposed debris damage models are described.

Keywords: damage; hurricane; risk; trajectory; tropical cyclone; windborne debris.

1. Introduction

Anecdotal evidence in observations following severe windstorms such as tropical Cyclone 'Tracy' in Darwin, Australia in 1974, and Hurricane 'Andrew' in southern Florida in 1992, suggests that windborne debris may produce nearly the same amount of wind damage as direct wind loads on buildings in urban areas (Fig. 1). Although studies sponsored by government agencies, and by insurance companies, have made steps towards quantitative predictions of damage induced on buildings and their contents by flying debris, with a few exceptions (e.g. Twisdale, *et al.* 1996; Wills, *et al.* 1998; FEMA 2007; Lin and Vanmarcke 2008), these have been generally quite empirical in nature. Thus the increase in damage produced by windborne debris might be accounted for by a simple factor to the damage calculated due to direct wind loading. A further complication is that the damage produced by debris impacts is often heavily coupled to that caused by direct wind action. Thus in Cyclone 'Tracy' in 1974 a 'chain reaction' effect was observed: missiles generated by wind loads on an upwind row of buildings would subsequently impact on the windward walls of downwind buildings, generating high positive internal pressures and resulting in high net roof pressures on those buildings, and a new generation of windborne debris.

Recent experimental and numerical studies of windborne debris trajectories (e.g. Baker 2007, Lin, *et al.* 2007, Visscher and Kopp 2007) have greatly improved knowledge of debris impact velocities, particularly the horizontal components, and hence of the impact momenta and kinetic energies. However, knowledge of the trajectories should form just one part of a larger debris damage model

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Fig. 1 Debris impact damage (photo by Texas Tech University)

which would also incorporate debris generation, impact probabilities and impact damage scenarios.

This review paper discusses previous research relevant to windborne debris risk models, the essential elements of engineering damage prediction models, and those results from trajectory studies that are relevant to damage models. The paper discusses the merits of impact momentum versus impact kinetic energy as a relevant parameter for predicting damage, and how published data from generic impact cannon tests can be used in risk models. The quantitative variation of debris impact damage with wind speed is also discussed. Finally the main elements tof previously-proposed debris damage models are described.

2. Types of windborne debris

Surveys of windborne debris after the 1995 Hurricanes 'Erin' and 'Opal' in the United States (Twisdale, *et al*. 1996), clearly showed that most damaging windborne debris in urban areas originates from the roof cladding and structures of buildings. Cladding elements such as tiles, shingles and metal sheeting, and timber structural members from the roofs of low-rise buildings are particularly strongly represented in surveys of damaging debris. The elevated origin of the debris results in longer trajectories in which higher horizontal velocities will occur, and also most wind loading damage on low-rise buildings originates at roof level.

Other well-represented types of debris include wall cladding and structure – particularly from higher levels, and parts of elevated signage and hoardings. The latter is quite common in U.S. hurricanes, based on the author's own experience. Yard items such as rubbish bins and letter boxes have also been observed in surveys, although it is unlikely that such items will be 'picked up' near ground level by the wind and subsequently develop sufficient horizontal velocity to do much damage to downwind buildings. However larger items, such as garden sheds, and empty water tanks, can develop sufficient forward velocity in sliding or rolling to produce significant damage, due to their high mass. An estimated distribution of damaging windborne debris in Australian conditions is listed in Table 1.

Wills, *et al.* (2002) defined three generic types of windborne debris shapes in relation to their lift-off characteristics. It is also a useful classification system for their trajectories. Fig. 2 shows the three basic shapes: '*compact*' (or 'particle') type, '*rod*' type (including roofing members of rectangular cross section), and '*sheet*' type.

Table 1 Estimated sources of damaging windborne debris in Australian tropical cyclone conditions (Holmes 2008)

Source	(%)
Roof cladding	50
Roof structural elements	10
Wall cladding & elements	20
Roof attachments (guttering etc.)	10
Backyard items	10

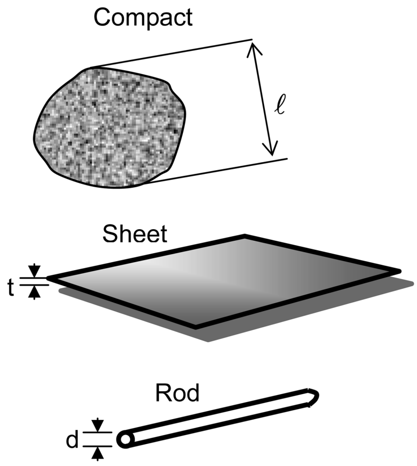


Fig. 2 Three generic debris types (Wills, *et al.* 2002)

3. Components of a windborne debris damage model

The main features required for an engineering windborne debris damage model are summarized as follows (Twisdale, *et al.* 1996):

a) A wind field model. A wind-field model for large scale events such as hurricanes and typhoons is required to determine the gust wind speed within a region, and with appropriate corrections to the site level. It is required to determine threshold wind speeds for generation of windborne debris from buildings or other sources, such as trees and vegetation. Examples of hurricane wind field models are those described by Vickery and Twisdale (1995), and Vickery, *et al.* (2000).

A regional cyclone windfield model will normally output upper level mean wind speeds. Using an assumed velocity profile, this is usually converted to a mean wind speed near ground level, for example at a standard reference height of 10 metres in open country terrain. Studies of debris trajectories, (e.g. Holmes 2004) have suggested that the relevant windspeed for a debris flight, which typically only lasts a second or two, is a peak gust. For debris removed from a roof this would be the gust speed at roof level in an urban area.

b) A debris generation model. A model is required to establish the source, numbers and generic shapes of debris items. The missiles can be assumed to originate primarily from roofs of low-rise buildings, and hence will consist of roof cladding and structural members.

For a piece of roofing material to become airborne, the wind loads must exceed the structural resistance. Hence the model should include a wind loading component which converts wind speeds generated by the wind field model into wind pressures and forces on the building surfaces. A model of structural resistance is also required. For housing it cannot be assumed that the resistance is that required by current design standards, and the lower resistance of older buildings, mistakes during construction, and effects of long-term deterioration such corrosion of steel, need to be included. This part of the model would, of course, have similar features of a prediction model for building damage to direct wind forces.

To correctly model the sources of debris, this model would also need to include information on the density of buildings. Clearly this would be much greater in urban than in rural areas.

c) Debris trajectory model. A model of debris trajectories, once they become airborne, is required to predict consequent damage due to impact on downwind buildings. The principal quantity of interest in the trajectory is the horizontal velocity. This together with the mass of the debris affects the kinetic energy and momentum at impact, and hence the damage produced on a downwind structure. Vertical displacements and velocities are mainly of interest with regard to whether a debris item hits the ground downwind before it hits a downwind building.

d) Debris impact model. The magnitude of damage produced by an impacting windborne missile would be represented in a debris impact model. Clearly this model should include a catalogue of the impact resistance of various commonly-used building materials: brick and concrete masonry, glass, timber, fibre-cement, sheet steel etc.

4. Debris generation model

Twisdale, *et al.* (1996) surveyed observed missiles after the 1995 Hurricanes 'Erin' and 'Opal' in the United States, and found the clearly dominant contributors were roofing tiles, shingles, sheathing, and structural members from roof trusses, with lesser contributions from wall cladding, miscellaneous house materials like guttering, vents, and yard items and accessories. This led to the development of a windborne debris damage model, with the generation part focused on the generation of windborne roofing elements.

Twisdale, *et al.* (1996) then describe a debris generation model which is essentially a wind load failure model for roofing elements of low-rise buildings. It is based on simulating wind loads on elements of a simple representative gable-roof building, and checking whether these exceed the resistance of roof sheeting and roof truss elements. The resistance is based on the pull-out strength of nails, and an assessment of errors in construction – i.e. an assessment of the number of nails attaching plywood roof sheathing to the underlying roof trusses.

5. Debris trajectories

5.1. General features

Twisdale, *et al.* (1996) reviewed various 'missile transport' models that had been developed from the 1970s (originally developed for modelling tornado-induced debris impacts for design of nuclear facilities) to the mid 1990s and discussed their advantages and disadvantages. For efficient simulations Twisdale, *et al.* used a 'random orientation 6-degree model' (RO 6-D). For debris of the 'rod and 'sheet' types (Fig. 2), this model considers motion in three dimensions with six degrees of freedom and drag, lift and side forces; however, the angles of pitch, yaw and roll are randomly generated at each time step, and the corresponding moments are not simulated.

Horizontal distances travelled for roof sheathing, tiles and structural members calculated and observed values from Hurricanes 'Erin' and 'Opal' were compared by Twisdale, *et al.* (1996). Mean distances travelled agreed quite well; however, the variance of transport distances were over-estimated by the model – probably because of the random orientation feature of the trajectory model.

Subsequently, extensive experimental and numerical studies of the trajectories of generic debris shapes in horizontal winds have been carried out (e.g. Holmes 2004, Lin, *et al.* 2006, Holmes, *et al.* 2006b, Baker 2007, Visscher and Kopp 2007). The three generic debris shapes earlier defined by Wills, *et al.* (2002) as 'compact', 'rod' and 'sheet' types can be used to define trajectories in qualitative terms, and were used in recent studies.

Compact types have no aerodynamic lift forces and have trajectories that monotonically travel vertically towards the ground, under the action of gravity forces and the vertical component of air resistance (i.e. drag forces acting parallel to the relative wind with respect to the moving body).

Sheet types, on the other hand, develop lift forces (i.e. normal to the relative air flow around the body and their vertical components give vertical displacements and velocities which cause a body to 'fly' to a greater height than its origin. The main effect of this, as far as wind damage is concerned, is to keep a body in the air for longer and enable it to be accelerated to a greater horizontal speed (mainly under drag forces), and hence impact on a downwind building with a greater damage potential. Studies on 1/20 scale models of a building with removable roof sheathing in turbulent boundary-layer flow in a wind tunnel, were described by Visscher and Kopp (2007); these tests indicated two types of trajectory of the sheathing: 'translational' and 'auto-rotational'. The latter type of motion generated greater lift forces, and the flying sheathing travelled significantly greater distances downwind before impacting on the ground downwind, (further developments of this modelling technique are described in this Special Issue by Kordi, *et al.* 2010).

Rod types appear to have similar trajectories to sheet types, although the lift forces are generally lower due to the reduced surface areas.

5.2. Horizontal impact velocities, momenta and kinetic energy

The horizontal velocities attained by all three types are mainly determined by the mass of the debris object, and product of the average drag coefficient and the exposed area, during the trajectories.

It was shown, numerically and experimentally (Baker 2007, Lin, *et al*. 2007), that the *horizontal* velocity component of a windborne missile can be well represented by the following function:

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

where u_m is the horizontal missile velocity

V_s is the local (gust) wind speed

x is the horizontal distance traveled (this can be related to average building spacing)

b is a dimensional parameter depending on the shape of the missile and its drag coefficient, and its mass (Eq. (2)).

$$b = \sqrt{\frac{\rho_a C_{D,av} A}{m}} \tag{2}$$

In Eq. (2), $C_{D,av}$ is an average drag coefficient, averaged over the rotations of the body with respect to the relative wind. It has been shown that for prismatic bodies, including rods with rectangular cross-sections, and cubes, $C_{D,av}$ is about 0.8 (Lin, *et al.* 2007).

Note that the right-hand side of Eq. (1) does not include the wind speed, and is only a function of horizontal distance travelled (or building spacing in the case of an impact), and the missile properties in Eq. (2).

The form of Eq. (1) in a non-dimensional form for rod-type objects is shown in Fig. 3 based on experimental data from small models in a wind tunnel (Lin, *et al.* 2007). Also shown in Fig. 3 are the results of numerical simulations. In this figure, $\bar{u}$ is the non-dimensional ratio of missile speed to wind speed, $\bar{x}$ is a non-dimensional horizontal displacement given by (gx/U^2), and K is the Tachikawa Number (Holmes, *et al.* 2006a). Eq. (3) was fitted to the data in Fig. 3.

$$\bar{u} = 1 - \exp[-\sqrt{1.6K\bar{x}}] \tag{3}$$

Note that rapid acceleration occurs in the early part of the missile flight, when the relative wind speed to the missile is greatest. Subsequently, the aerodynamic forces, and hence missile acceleration, progressively reduce as the missile speed increases.

Thus Eq.(1) shows that for a given missile in a given storm event, the impact velocity on a downwind building wall is directly related to the distance downwind from the source of the missile. This equation could be used in a damage simulation model to represent the horizontal missile impact velocity for a given wind gust speed and missile properties.

Following from Eq. (1), the momentum and kinetic energy at impact can be represented by Eqs. (4) and (5) respectively.

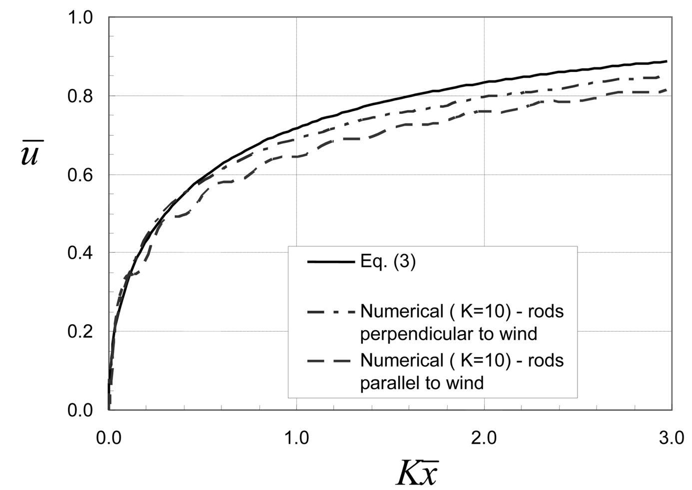


Fig. 3 Non dimensional horizontal missile velocity versus non dimensional distance traveled for rod-type objects (from Lin, *et al.* 2007)

$$m.u_m \cong mV_S\{1-\exp[-b\sqrt{x}]\} \quad (4)$$

$$E = \frac{1}{2}m.u_m^{\ 2} \cong \frac{1}{2}mV_s^{\ 2}\{1-\exp[-b\sqrt{x}]\}^2 \quad (5)$$

where m is the mass of the missile

The previous discussion has indicated that the horizontal velocities (and hence impact momenta and kinetic energy) of windborne debris are relatively simple functions of wind gust speeds and distance travelled - and hence of building separation.

6. Impact damage definition

The damage produced by an impacting missile on a building surface is dependent on the component of momentum normal to the surface and/or its kinetic energy at impact. These quantities were defined in Eqs. (4) and (5).

The change of momentum at impact is direct related to the force applied to a surface – it is equal to the impulse applied – the integral of force with respect to time. A perfectly elastic surface (i.e. with a coefficient of restitution at impact of 1.0) would not absorb any of the kinetic energy of the missile; it would be retained as kinetic energy of the missile moving away from the surface.

The total energy at impact must be conserved, and for many building materials suffering plastic deformation most of the kinetic energy of the debris item will be dissipated through deformation of the material.

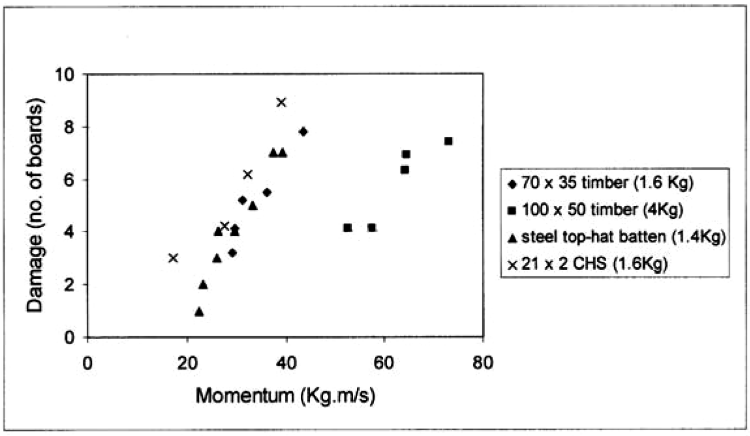
Generic impact tests at James Cook University (Reitano 2003) using a compressed air cannon with impacts of rod-type missiles on a series of spaced fibreboards indicated better correlation of damage (i.e. the number of boards penetrated) with impact kinetic energy than with the impact momentum, although there is a also a significant dependency on the shape of missile at the impact point. This is illustrated in Figs. 4(a) and 4(b) which show damage produced by several types of rod-type missiles plotted against momentum and kinetic energy respectively. For missiles of varying mass, better correlation was obtained with kinetic energy than with momentum in these tests, which were representative of impacts on building wall materials.

Thus both momentum and kinetic energy at impact are relevant quantities, with more emphasis on one rather than the other in particular cases. For damage to housing in hurricane regions, the HAZUS model in the U.S. adopts kinetic energy as the prime variable (FEMA 2007). The assumed probability distribution for the impact energy is the Weibull distribution. On the other hand, for simulation of impacts of roof gravel on glazing of commercial buildings the component of impact momentum normal to the surface has been adopted.

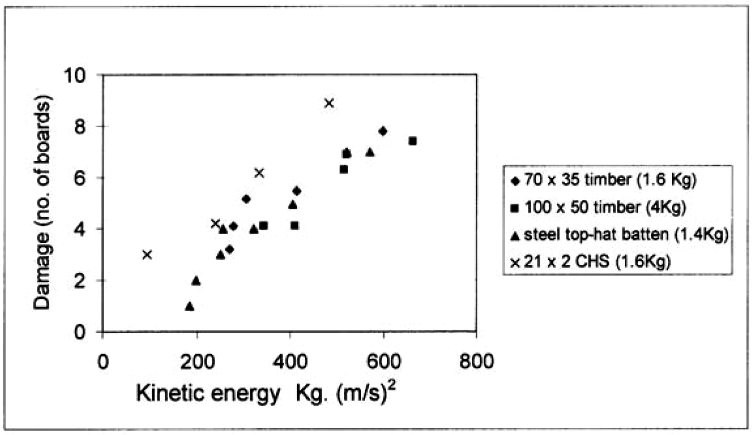
Although many standardized missile tests have been carried out for determination of the resistance of various surfaces to windborne debris damage, these are pass/fail tests and are usually commercial-in-confidence. However, in some cases tests have been carried out to determine the threshold of damage for impact by a defined missile. Table 2 gives the threshold momentum and kinetic energy for impact on 6mm glass (sheet size not given) of a 5 gram steel ball (Minor 1994).

Although both momentum and kinetic energy are listed in Table 2, it is likely that momentum is the more important parameter for impact on glass, for which deformation is approximately elastic.

Impact tests on common U.S. building materials by Texas Tech University were described by



(a)



(b)

Fig. 4 Impact damage correlations with momentum and kinetic energy (from Reitano, 2003 - replotted)
(a) Damage versus momentum
(b) Damage versus kinetic energy

Table 2 Threshold of momentum and kinetic energy for failure of 6mm thick glazing (Minor 1994)

Type of glass	Impact velocity (m/s)	Impact momentum (Kg.-m/s)	Impact kinetic energy (Joules)
annealed	10	0.05	0.25
heat strengthened	12	0.06	0.36
fully tempered	20	0.10	1.00

McDonald (1990). A compressed air cannon was used to project a 6 Kg (approximately) 100 by 50 mm cross-section timber missile at various wall surfaces. The threshold speeds and kinetic energies for perforation – i.e. approximately the threshold for damage, for impact normal to the surface, on some of the materials tested, are summarized in Table 3.

Table 3 Threshold of kinetic energy for failure of common wall materials (McDonald 1990)

Material	Perforation velocity (m/s)	Impact kinetic energy (Joules)
12 mm thick plywood	23.2	1620
19 mm thick plywood	23.7	1680
Cement sheeting (‘stucco’)	23.7	1680
Lapboard	23.7	1680
masonite	24.1	1750
200m unreinforced concrete masonry	26.8	2160
Brick veneer	53.6	8630
200m fully reinforced concrete masonry	> 58 m/s	> 10,000

7. Windborne debris damage models

7.1. Model of Wills, et al.

A simple model of windborne debris damage was developed by Wills, *et al.* (1998, 2002), as part of the U.K. contribution to the International Decade of Natural Hazard Reduction (IDNDR) in the 1990s.

In this work, some useful simple mathematical relationships were developed concerning the threshold wind speed for debris generation, and the relationship between wind-induced damage and wind speeds. Three generic types of debris were defined (Fig. 2), and relationships for the threshold wind speeds for flight obtained, based on the balance between aerodynamic forces and gravity and structural resistance. Two types of potential windborne debris were considered: ‘loose’ items and ‘fixed’ items. In the latter case a fixing strength integrity parameter, I, was defined. In effect, this is the ratio of the structural resistance forces to aerodynamic forces as a proportion of gravity. Thus I is greater than one for a ‘fixed’ object and equal to, or less than one, for a ‘loose’ object. (I could be less than one if the horizontal force due to friction is the only force resisting an object being blown horizontally from a flat roof.)

The expression for the threshold wind speed at which various types of debris ‘fly’ depends on the type.

Thus for compact objects, the wind speed for threshold of flight, U_f is given by Eq. (6).

$$\ell = \frac{\frac{1}{2}\rho_a U_f^2 C_F}{I \rho_m g} \tag{6}$$

ℓ is a characteristic dimension for ‘compact’ objects

ρ_a is the density of air

ρ_m is the density of the object material

C_F is an aerodynamic force coefficient

U_f is the wind speed at which flight occurs

I is a fixing strength integrity parameter, i.e. the value of force required to dislodge the objects expressed as a multiple of their weight

g is the acceleration due to gravity

The nature of the aerodynamic force defined by C_F was not clearly stated by Wills, *et al*. However, since compact objects in general have negligible lift forces, C_F can be assumed to be a drag coefficient. The force then required to dislodge the object would therefore be approximately horizontal on a flat roof. In that case, for a 'loose' object, the parameter I would equal the coefficient of friction.

For sheet objects, Wills, *et al.* found that the wind speed for flight depends on the thickness of the sheet, but not on the length and width (Eq. (7)).

$$\rho_m t = \frac{\frac{1}{2}\rho_a U_f^2 C_F}{Ig} \tag{7}$$

where t is the thickness of the sheet object.

For rod objects a similar equation to Eq. (7) was derived, with t replaced by d, the effective diameter of the rod object.

Eqs. (6) and (7) indicate that lighter and smaller objects fly at lower wind speeds than heavier objects – a significant result when the damage potential is estimated.

When estimating damage producing by windborne debris, Wills, *et al.* incorporated a parameter J, representing the ratio of the flight speed to the wind speed. Although no value was given for J by Wills, *et al*, it is likely to be in the range of 0.4 to 0.9 on impact (e.g. Fig. 3).

Based on calculation of the kinetic energy at impact, Wills, *et al.* (1998) derived the following results for the three generic debris types.

For a compact type, damage $\propto \rho_m U^8$ (8)
(independent of body dimension; ρ_m is the body density)

For a sheet type, damage $\propto (LW)\, U^4$ (9)
(independent of body density; L, W are the principal dimensions)

For a rod type, damage $\propto (Ld)\, U^4$ (10)
(independent of body density; L, d are the length and effective diameter, respectively)

The dependence of damage on wind speed for the different debris types indicated by Eqs. (8), (9) and (10) is interesting. In fact, since both sheets and rods can develop lift, it is more likely that these types will have longer trajectories and become damaging debris. Compact objects on the other hand develop little or no lift and are more likely to hit the ground under the action of gravity. Hence, on the basis of relationships (9) and (10) it might be expected that for most damaging windborne debris items that actually impact on a vulnerable surface downwind, the damage would be proportional to the wind speed to a power of about 4.

Based on an assumed (and speculative) distribution of the number of compact debris items of various sizes, Wills, *et al.* (1998) derived a relationship for the total damage and wind speed, summed over all sizes of debris which in turn 'fly' over a range of wind speeds. For compact debris, this relationship suggested the total damage varying with wind speed with an exponent of five; there appears to be a mistake in the mathematics which, if corrected, would result in the exponent becoming six. However in the residential situation most damage is produced by the sheet and rod types, as indicated earlier. A simple power law relationship for these types cannot be readily derived used the Wills, *et al.* approach.

The Wills, *et al.* analysis also assumed that damage is linearly related to the impact kinetic energy. However, the relationship is probably quite non-linear since a greater amount of damage is generated once a threshold level of kinetic energy has been reached.

7.2. Models used by Twisdale, et al. and in HAZUS-MH

The model used for prediction of debris damage in hurricanes used in the HAZUS software, and described in the Technical Manual (FEMA 2007), is a somewhat simplified version of the earlier approach developed by Twisdale, *et al.* (1996). The simplifications are intended to make a 'fast-running' version of the program. The general approach was to run generic simulations of missile generation, trajectories and damage scenarios for groups of buildings at standard urban, or suburban, spacings, and then fit empirical functions to the results. There is a version for housing with missiles consisting of roofing elements, and a separate 'Commercial missile model' that simulates the effects of roof gravel (commonly used in the U.S. for insulation and/or ballast) on glazing. Glazing damage from roof gravel has emerged as a major problem in U.S. cities from damage investigations following hurricanes.

The basic equation used in HAZUS for estimating the risk of damage from missile damage is the following:

$$P_D = 1 - \exp\{-N.A.T[1 - F_\xi(\xi_D)]\} \tag{11}$$

where P_D is the risk of damage due to impacts on a given surface during a time period, T, in a given storm,

N is the average number of impacts per unit time, per unit surface area,

A is the area of the surface,

$F_\xi(\xi)$ is the cumulative distribution of energy or momentum,

ξ_D is the threshold of momentum or energy for damage of the material of that surface.

The average number of impacts is assumed to be the product of two functions :

$$N = n(V,d).f(d,h) \tag{12}$$

$n(V, d)$ is height-averaged number of impacts

$f(d, h)$ is a height factor

where, V = peak gust wind speed,

d = average building spacing,

h = height of the 'target element' above ground level.

Empirical expressions were developed for roof gravel in the 'Commercial missile model' based on multiple simulations of trajectories for various storm situations and building spacings.

In the residential missile model in HAZUS, the probability distribution $F_\xi(\xi)$, is modeled as a Weibull distribution with the parameters derived from fitting the distribution to data derived from multiple simulations of trajectories.

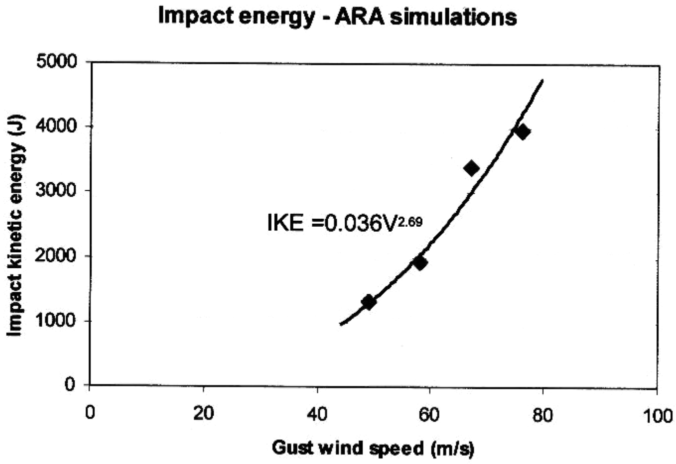


Fig. 5 Total impact kinetic energy as a function of maximum gust speed in a hurricane, from all windborne debris impacts in a representative U.S. subdivision (re-plotted from the results of Twisdale, *et al.* 1996)

The earlier report by Twisdale, *et al.* (1996), describes more details of the approach, and gives the results of some simulations for a residential housing subdivision. This was partly directed at determining the reliability (i.e. 1- risk) against windborne debris damage of missile protection strategies, including that adopted for low buildings in certain parts of coastal Florida.

If the total impacting kinetic energy from windborne missiles (i.e. sheathing, roofing members, tiles, outbuildings and accessories) in the Twisdale, *et al.* (1996) simulations is re-plotted against the maximum gust wind speed, the plot in Fig. 5 results. This indicates a power exponent of about 2.7 for the 'sheet' and 'rod' debris types - somewhat lower than the speculative values of five or greater for compact 'debris' suggested by the work of Wills, *et al.* (1998).

7.3. Model of Lin and Vanmarcke (2007, 2008)

Lin and Vanmarcke (2007 and 2008) proposed a debris risk model using basic probabilistic concepts. It was a based on the Poisson distribution for debris impacts, the missile velocity versus distance relationship of Eq.(1), and a matrix formulation for the interactions between all the buildings in a residential area. The Poisson Distribution was assumed for the number of debris items generated by a particular building, for the number of impacts on a given downwind building, and the number of damaging impacts on a given building.

The occurrence of a debris impact on a downwind building was assumed to happen when the 'landing position' intersected with the footprint of the target building. The landing position was modeled with a two-dimensional normal distribution centred at a mean flight distance (or at half the maximum flight distance in Lin and Vanmarcke 2007). The mean flight distance is based on experimental data (Lin, *et al.* 2006, 2007), and an assumed average flight time, taken empirically to be 2 seconds in Lin and Vanmarcke (2008). Damage is assumed to be proportional to impact momentum and impact missile velocities are based on variations of Eq. (1).

The Lin and Vanmarcke model was applied to a residential area in Florida for a defined gust speed of 49 m/s and a particular wind direction. The mean number of impacts and the probability of window damage were calculated for every house in the study area.

This model is further developed in two papers in this Special Issue (Lin and Vanmarcke 2010; Lin, *et al.* 2010).

8. Conclusions

This paper has reviewed a variety of work carried out in recent years relating to prediction of the damage caused by windborne debris in extreme wind events such as typhoons and hurricanes. Debris generation, trajectories and debris impact are important components of debris models and are discussed in some detail. The basis of previous windborne debris damage and risk models is reviewed.

There are conflicting conclusions on the relationship between debris damage and gust wind speed. A simplified approach by Wills, *et al.* (1998) has indicated a power relationship with an exponent of 5 to 6. However simulations by Twisdale, *et al.* (1996) would indicate a power exponent of less than 3.

Considering the significance of windborne debris in damage surveys after severe storm events, this topic is clearly one worthy of more attention.

Acknowledgements

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