The mechanics of flying debris and test criteria

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1. INTRODUCTION

The Shelter Building Program of the Department of Public Works of the state of Queensland, Australia is intended to identify and upgrade existing buildings in the tropical cyclone belt to provide shelter during the event of a severe tropical cyclone. Resistance to flying debris is an important consideration during severe cyclones. Penetration of the building envelope by flying missiles has a number of undesirable results : high internal pressures threatening the building structure, wind and rain penetration of the inside of the building, the generation of additional flying debris, and the possibility of flying missiles inside the building endangering the occupants.

This paper addresses the mechanics of flying debris and describes test criteria developed. Work in the U.K. on the initiation of missile flight is reviewed. A new analysis of flight times and distance travelled is given. The test criteria for missiles proposed and accepted for the Queensland Shelter Building Program are described. Finally the design of a protective missile screen produced by an industrial group in Australia is described briefly.

2. INITIATION OF MISSILE FLIGHT

Wills *et al* (1998), have provided a useful analysis of conditions for the initiation of missile flight during a wind storm. They considered ‘compact’ objects, sheet objects, and rods and poles, and established relationships between the body dimensions, and the wind speed, U_f, at which flight occurs and the objects become missiles. For each the three categories, these relationships are :

$$\ell = \frac{\frac{1}{2}\rho_a U_f^{\,2} C_F}{I\rho_m g} \qquad (1)$$

$$t = \frac{\frac{1}{2}\rho_a U_f^{\,2} C_F}{I\rho_m g} \qquad (2)$$

$$d = \frac{\frac{2}{\pi}\rho_a U_f^{\,2} C_F}{I\rho_m g} \qquad (3)$$

where,

ℓ is a characteristic dimension for ‘compact’ objects
t is the thickness of sheet objects
d is the effective diameter of rod-type objects
ρ_a is the density of air
C_F is an aerodynamic force coefficient
ρ_m is the density of the missile material
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 (for objects resting on the ground $I \cong 1$)
g is the gravitational constant

Equations (1), (2) and (3) illustrate the important point that the larger the value of the characteristic dimension, ℓ, t or d, the higher the wind speed at which flight occurs. These equations also show that the higher the value of the density, ρ_m, the higher is the wind speed for lift off. Thus as the wind speed in a cyclone, or typhoon, builds up, the smaller lighter, objects e.g. gravel, small loose objects in gardens and backyards, ‘fly’ first. At higher wind speeds appurtenances on buildings are dislodged as the wind forces exceed their fixing resistance, and they also commence flight. At even higher wind speeds, substantial pieces of building structure, such as roof sheeting and purlins, may be removed, and become airborne.

3. FLIGHT TIMES AND DISTANCES

A missile, once airborne, will continue to accelerate until its flight speed approaches the wind speed, or until its flight is terminated by impact with the ground or with an object such as a building.

The aerodynamic force on a flying object in a wind of speed, U, can be expressed as :

$$\text{Accelerating force} = \frac{1}{2}\rho_a (U - v_m)^2 C_D A$$

where v_m is the velocity of the missile with respect to the ground, and A is the reference area for the drag coefficient, C_D

Applying Newton's law, the instantaneous acceleration of a compact object (characteristic dimension, ℓ), is given by :

Acceleration =

$$\frac{\frac{1}{2}\rho_a (U - v_m)^2 C_D A}{\rho_m \ell^3} = \frac{\frac{1}{2}\rho_a (U - v_m)^2 C_D}{\rho_m \ell} \qquad (4)$$

taking A equal to ℓ^2.

The same equation applies to 'rod' type objects when ℓ is taken as the length (A is the cross-section area).

Equation (4) shows that heavier and larger objects have lower accelerations, and hence their flight speeds are likely to be lower than smaller or lighter objects. The equation also shows that the initial acceleration from rest (v_m=0) is high, but the acceleration rapidly reduces as the difference between the missile speed and the wind speed reduces, so that the wind speed is approached very slowly. Of course the missile speed cannot exceed the wind speed.

Equation (4) can be integrated to obtain the time taken to accelerate to a given speed, v_m, and the distance travelled in this time. These equations are as follows :

Time taken to accelerate from 0 to v_m,,

$$T = \frac{v_m}{kU(U - v_m)} \qquad (5)$$

Distance travelled,

$$s = U\left[T - \left(\frac{1}{kU}\right)\ln(1 + kUT)\right] \qquad (6)$$

where k = $(\rho_a C_D)/(2\rho_m \ell)$ with units of (1/m).

Using Equations (5) and (6), the flight times and distance travelled by a) a steel ball of 8 mm diameter and 2 gram mass, and b) a 4 Kg piece of timber of 100mm by 50 mm cross section, and length 1.6 metres, have been calculated, for a wind speed, U, of 32 m/s (a reasonable value of mean wind speed for a design cyclone in an urban area on the Queensland coast), and are given in Table I.

Table I shows the much longer flight times and distances for the larger object.

4. MISSILE TEST CRITERIA

When specifying appropriate test criteria for missile impact resistance, the following principles should be followed :

- The missiles should be representative of actual objects available.
- The criteria should be physically realistic, i.e. if the flight threshold speed is greater than the expected wind speed in the storm, then the object should not be regarded as a potential missile.
- Unrealistic flight times and distances should not be implied by the specified missile speed.

The first missile testing criteria in Australia was included in the Darwin Area Building Manual (Darwin Reconstruction Commission, 1976), following Cyclone 'Tracy' in 1974. This test specified that windows and doors should withstand impact at any angle of a piece of 100mm by 50mm timber weighing 4 Kilograms, travelling at 20m/s. A more severe test was specified for cyclone refuge shelters: 'end-on' impact of a piece of 100mm by 50mm timber weighing 8 Kilograms, travelling at 30m/s. As shown in Table I, to reach 30 m/s, a 4 Kg timber missile would need to travel for more than 10 minutes, and over 16 kilometres. Shortly after Cyclone 'Tracy' a larger (8 Kg) timber missile travelling at 30 m/s was originally specified for cyclone refuge shelters in Darwin. Fortunately such an unrealistic specification was dropped a year or two later.

Following a meeting of experts held at the Experimental Building Station, Sydney, in 1977, Technical Record 440 (Experimental Building Station, 1978) was issued. This reduced the test requirement for windows and doors of buildings to a piece of 100mm by 50mm timber weighing 4 Kg, travelling at 15 m/s. This test has since been adopted by the Darwin Area Building Code, and is also mentioned in the Australian Standard on Wind loads AS1170.2-1989 (Standards Australia, 1989), in relation to the prevention of dominant openings and resulting high internal pressures in cyclonic regions.

Following the above principles, the following procedures for the testing of debris screens and cladding for public shelter buildings in the Queensland coastal region (corresponding to Region C in AS1170.2), were proposed.

Debris Test Load A
End-on impact of a piece of timber 4 kilograms in mass, with cross-section dimensions of 100 mm by 50 mm impacting at 20 m/s
Debris Test load B
Series of five steel balls of 2 grams mass (8 mm diameter) impacting at 30 m/s successively

The first of these missiles is representative of a roof purlin and has previously been used in Australia as a test missile, as discussed earlier. The steel balls are representative of small hard compact objects, and have previously been adopted as test missiles for the hurricane-prone regions of Florida (Pantelides *et al*, 1992). The test specifications require these missiles to be projected at both 90 degrees and 30 degrees to the plane of the screen.

Both of these missile types have a flight threshold speed (estimated from the Equations (1) and (3)) about equal to the *mean* wind speed at the peak of the design ultimate cyclone. AS1170.2 gives this speed as 28-33 m/s in urban terrain, for heights up to 10 metres. Note that the *gust* speed is approximately twice the mean wind speed (i.e. 55-60 m/s in urban areas in the design event).

The missiles will have accelerated to about 95%, and 65% of the mean wind speed, for cases A and B respectively, at the peak of the design storm. Application of Equations (5) and (6) indicates that the missiles will have taken about 50 and 70 seconds of flight time, respectively, and travelled nearly a kilometre to reach these speeds. At the specified speeds, impacts by these missiles are clearly extreme events, but are considered comparable with the risk of the building receiving the extreme (ultimate limit states) wind load specified by the wind loads Standard (Standards Australia, 1989).

5. PROTECTIVE MISSILE SCREEN

The Shelter Program of the Department of Public Works of the Queensland Government has adopted the criteria, test procedures and specifications described in the previous section. The program is intended to identify and upgrade existing buildings in the region of Queensland affected by tropical cyclones, for use as public shelters during the event of a severe storm. It is not possible for many normal cladding materials, such as glazing, to resist the missiles as specified. A solution to this is to provide protective missile screens, which may be permanently in place, or are installed in the event of a storm warning.

The screen material may vary depending on the building owner's requirements. A louvre-type mesh can be used to provide protection from solar radiation, or a finer mesh used where see-through vision is required. To be able to resist the steel ball impacts (Debris Test Load B), the largest aperture in the screen should not exceed 8 mm. To ensure that the glazing, or other cladding, is not failed by the screen deflecting following the missile impact, the screen should be located at a distance of at least 1.25 times the maximum displacement under the impact test. The screen should envelop the glazed panel. This can be achieved by returning to the wall to completely envelope the opening, or overlapping the opening in the plane parallel to the wall.

BHP Building Products has constructed a test facility to project the missiles, and have developed *Stormgard Cyclonic Debris Screens* to meet the shelter requirements (Figure 1). The energy absorbing element of the screens consist of expanded steel mesh material. Two types of screen were used, and both were found to be capable of meeting the missile impact requirements.

6. CONCLUSIONS

A missile test protocol has been specified to satisfy the strict requirements of the Queensland Shelter Building Program for the coastal strip affected by tropical cyclones. After an analysis of the mechanics of flying debris, two missile types have been specified and accepted, with realistic speeds in relation to the wind speeds expected in the most severe storms affecting the region.

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Table I Flight times and distances for some missiles (wind speed = 32 m/s)

Object / speed	Time taken (secs)	Distance travelled (metres)
Steel ball to 20 m/s	5.4	71
Steel ball to 30 m/s	49	1270
Timber piece to 20 m/s	69	910
Timber piece to 30 m/s	625	16300

Figure 1. Installation of a Stormgard missile protection screen