IMPACT DYNAMICS OF ROD TYPE WINDBORNE DEBRIS

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ABSTRACT
The effect of rod orientation, rates of rotation and approach direction on impact forces from windborne debris is studied using a modified 6 degree-of-freedom trajectory model. In particular the impact of a 4 kg 100x50mm timber rod at 15m/s onto an elastic wooden weatherboard wall is modelled. It is shown that the forces are more sensitive to approach direction than to rod orientation or rotation. The main predictions of the model are verified using a simple experimental test rig, although some differences are noted. A set of random impacts is also investigated by using a 6 degree-of-freedom trajectory model and random release angles. The forces are calculated for impacts against a randomly oriented vertical wall at a distance of 10m during a 30 m/s wind. The results show that the expected peak impact force can be approximated by $F_{\text{peak}} = V_T(mk)^{1/2}\cos(\theta_w)$, where $V_T$ is the total impact velocity, $m$ the mass of the rod, $k$ the wall stiffness and $\theta_w$ the angle between the impact velocity vector and the wall normal.

KEYWORDS: WINDBORNE DEBRIS, IMPACT, ROD-TYPE

Introduction
The damaging effects of tropical cyclones and other extreme wind events on buildings and the need to protect vulnerable cladding components against windborne debris impacts is now well acknowledged, but this hasn’t always been the case. In assessing the failures of structures during windstorms, Minor et al. (1972) observed that windows were traditionally designed for wind pressures, but that breakage from impacts by windborne debris was the most common failure mechanism. In 1974 Tropical Cyclone Tracey devastated Darwin in northern Australia. Walker (1991) comments “It is clearly demonstrated in the investigation of Cyclone Tracey that two major factors contributing to the wide-scale damage to housing were internal pressurisation of buildings following failure of windward windows, generally due to windborne debris, and fatigue failure of cladding and metal connections under the fluctuating pressures”. Even two decades later such failures remained a problem, Minor (1994), referring to the damage done by Hurricane Andrew in 1992, comments “With few exceptions, glazing systems performed poorly, largely due to the impact of windborne debris, and damage to building contents was extensive”.

Twisdale et al. (1996) point out that windborne debris damage is influenced by four factors: (1) wind field, (2) debris generation, (3) debris trajectory and (4) debris impact. Holmes (2004) identified that since debris trajectories only last for a matter of a few seconds the relevant wind speed for debris’ flight is the peak gust wind, which for Hurricane Andrew has been reported to be as high as 77m/s. The relevant source and type of debris varies greatly, Minor et al. (1978) concluded that with tornadoes the most prevalent type of windborne debris in residential areas was timber from wood frame houses, whereas Minor (1994) discusses several situations where roof gravel caused extensive glass breakages on high rise
buildings but also notes that investigations in south Florida following Hurricane Andrew tended to point to roofing tiles as the most prevalent type of windborne debris. Wills et al. (2002) analysed the generation and damage potential of various type of windborne debris and showed how this was related to the initial fixing strength. They also provided a useful categorisation of wind-borne debris into the following types:

- Particles, such as roof gravels, where all dimensions are similar.
- Rods, such as timber structural members, with one dimension significantly greater than the other two dimensions.
- Plates or sheets, such as tiles and metal sheeting, where the thickness is significantly smaller than the length and width.

In recent years the trajectories of debris have received much attention, Holmes (2004) has studied the trajectories of particles, while sheet type debris has been considered by a number of authors including Tachikawa (1983,1988), Wang and Letchford (2003), Richards et al. (2005), Lin et al. (2006), Holmes et al. (2006), Baker (2007), Visscher and Kopp (2007). In addition Lin et al. (2007) and Richards et al. (2008) have recently considered the trajectories of rod-type debris. In contrast the impact of debris has received relatively little attention other than the development of impact testing methods.

In Australia a wind driven impact test is an optional test for envelope components of all buildings in cyclonic regions. However, the wind loading code (AS/NZS 1170.2) requires that in such areas the building must be designed to withstand the internal pressure resulting from a dominant opening unless the building envelope (windows, doors and cladding) can be shown to be capable of resisting impact loading equivalent to a 4 kg piece of timber 100mm x 50 mm cross-section (about 2.4m long) projected end on at 15 m/s. This design missile first appeared in a building code in the Darwin Area Building Manual in 1976 and is now not only used in Australia but a very similar 9 lb (4.1 kg) ‘2 by 4’ (102x51mm) roofing member at 50 ft/s (15.2 m/s) has been adopted by the South Florida Building Code. Minor (1994) points out that initially the Dade County Building Code Committee chose a roofing tile as the design missile but it recognised that it would be difficult to define a representative tile and almost impossible to propel a tile repeatedly with the same orientation and at the same speed as part of a standard test, and so ultimately the committee chose the ‘2 x 4’ timber instead. While such impact tests are perfectly valid methods of determining the strength of cladding elements, it might be questioned whether they are representative of real situations where even rod type projectiles are likely to approach a building from any direction and with random orientation. In real life an end on impact with the velocity perpendicular to a wall, which is the normal testing orientation, will be the exception rather than the rule.

In the present study the impact force of rod type missiles with various orientations and various approach directions are considered in order to assess what influence these have on the impact forces.

**Standard Missile Impact Modelling**

The 6 degree-of-freedom trajectory model developed by Richards et al. (2008) has been modified in order to deal with impact situations. For simplicity the rod is assumed to be a rigid body and the wall a uniformly elastic plane. The rod used is the 2.4m long, 4kg piece of 100x50mm timber discussed above. The stiffness of the wall has been chosen to approximately match that of wooden weather boards typically used on houses in Australasia, the particular value used was $k = 173 \text{kN/m}$. Although impact damage is of ultimate interest, many cladding materials, including wood, behave in an elastic manner up to the point of brittle failure and so elastic modelling is valid up to the point of failure, which will only occur if the maximum strength of the structure is exceeded. The interactive forces are modelled as the combination of the elastic normal force and a friction force that is limited by the
coefficient of friction, which has been estimated to be of the order of 0.5. During an impact the friction may vary between static and slipping states and so the instantaneous friction force is determined at each time step by calculating the force required to bring the contact point to rest, or keep it at rest, during the immediate time interval, and then limiting this if it exceeds the coefficient of friction times the current normal force.

Figure 1: Peak impact forces for (a) the velocity normal to the wall and the rod angled away from normal and (b) the velocity at oblique angles and the rod aligned with the velocity.

Two test cases have been considered, one where the velocity of the rod is 15 m/s in a direction normal to the wall, but the rods are at different angles to the velocity vector and a second case where the approach velocity is at an oblique angle and with the rod aligned with this velocity. The resulting peak normal forces for the two cases are shown in Figure 1(a) and (b) respectively. In both cases the highest normal force corresponds to complete conversion of the initial kinetic energy $E_k = \frac{1}{2}mv^2$ into strain energy $E_s = \frac{1}{2}kd^2$, where $d$ is the deflection of the elastic wall. It therefore follows that the expected maximum normal force

$$F_{\text{max}} = kd = V(\sqrt{mk})^{1/2} = 12.5 \text{ kN} \quad (1)$$

From Figure 1(a) it may be observed that the peak force is not too sensitive to angling the rod and that if the rod is within about 30° from normal then the peak force is greater than 90% of that which occurs with an end on impact. If the rod’s angle is greater than 60° then the peak force during the initial contact may be as low as 50% of the maximum, however in such cases the initial contact transfers much of the linear kinetic energy into rotation and the second contact may result in a force which almost equals that for an end-on impact. It may also be observed that at 90° the initial impact force is as high as the end-on case, but in practice this slapping impact is unlikely to cause damage due to the higher contact area. The overall effect of the angle between the rod and the velocity vector does little to reduce the global peak force but does affect the details of the impact and the time during the process when the peak force occurs. However it may be a significant factor in the failure of a structure where an end on impact might punch a hole straight through a clapping element whereas a more angled secondary impact, although capable of producing equally high forces, might cause an indent which must increase in area as penetration proceeds and hence the amount of damage caused to a structure could be considerably lower. One further factor which would affect real impacts is the energy absorbed during the primary impact which isn’t included in the current elastic wall model. Simple tests, such as dropping a piece of wood onto the centre of a wooden beam, show that the coefficient of restitution is of the order of 0.5. Hence while the primary impact force may be similar to that calculated, the energy transferred into rotation
during more angled impacts is likely to be lower than calculated and hence the secondary impact weakened.

Figure 1(b) shows that if the rod approaches the wall at an oblique angle this has a more significant influence on the peak forces and that at angles close to parallel with the wall the initial glancing blow and any secondary impact are both quite weak. Here also, if the approach angle is within $30°$ from normal then the peak force is greater than 85% of the maximum. With the more oblique impacts some of the initial kinetic energy is associated with the rod’s velocity parallel with the wall, which is less likely to be reduced by the impact. For simple analysis purposes it is suggested that the expected peak impact force can be modelled by a simple function such as:

$$F_{\text{Peak}} \approx F_{\text{max}} \cos(\theta)$$

(2)

where $\theta$ is the angle between the rod’s velocity vector and the wall normal. This function is also shown in Figure 1(b) where it forms an approximate upper bound to the calculated forces.

**Experimental Verification**

In order to verify the basic concepts discussed above a small 0.41m long, 0.85 kg 100x50 rod was dropped from a height of 1.0m onto an instrumented target and the normal forces measured. The same two cases were tested. The error bars in Figure 2 show the range of results obtained from more than 15 repeated tests at each angle. While the experimental results confirm many of the features predicted by the model it does appear that in both cases the forces drop off slightly more rapidly than predicted once the angle increases beyond about $15°$ from normal. The reason for this discrepancy is unknown.

**The Effects of Rotation**

The aerodynamics of rods are such that they are statically unstable with the major axis aligned with the relative wind vector and hence they will tend to tumble in flight. Tachikawa (1983) found that during wind tunnel tests of various shaft mounted plates the steady tumbling had typical tip speed to wind speed ratios ranging from 30% to 50%. Numerical experiments have hence been carried out with the 2.4m long, 4kg piece of 100x50mm timber rotating at a speed of $\pm 4$ rad/s with an impact velocity of 15m/s. This means the tangential tip speed due to rotation is 32% of the impact velocity. The resulting peak impact forces for the same test cases considered in Figure 1, but with the addition of rotation, are shown in Figure 3. It can be observed that while the total energy of the rod has increased slightly this only has a very small effect on the overall maximum impact forces. For an end on impact the rotation has no significant effect at all; however as the impact angle increases then rotation which drives the
leading tip into the wall \((p < 0)\) helps to keep the impact force at a level similar to the end on impact. On the other hand rotation which draws the leading tip away from the wall \((p > 0)\) reduces the force during the initial impact but does enhance the forces during any secondary impact.

**Figure 3**: The effect of rotation on the peak normal force for the first and second impact with \(p = 4\) rad/s (leading tip rotating away from the wall) and \(p = -4\) rad/s.

### Random Impact Modelling

The test cases considered in the previous sections represent somewhat idealised versions of real impacts, where not only the velocities but the orientations and rates of rotation will vary rather more randomly. In order to investigate more realistic conditions the trajectory model developed by Richards *et al.* (2008) was used to generate a random set of impact conditions. 50 sets of conditions were generated by considering the trajectories of the 2.4m long, 4kg piece of 100x50mm timber when released from the ground fixed origin with no velocity and zero rates of rotation in a uniform 30m/s \(X_e\)-direction wind. The trajectories were randomised by selecting the initial orientation as defined by the angles \(\alpha\), \(\beta\) and \(\phi\), as depicted in Figure 4(c). All possible orientations of a rectangular rod can be created by varying each of these angles over the range \(-90^\circ\) to \(90^\circ\) and so uniform random number generators were used to select each of these angles within these ranges. The initial condition statistics are given in the first few cells of Table 1, where for each angle the mean value is near zero, the standard deviation close to the \(52^\circ\) value expected for a uniform random distribution and the maximum and minimum values covering most of the range \(-90^\circ\) to \(90^\circ\).

**Figure 4**: Trajectory model axes: (a) The principal axes of a rectangular object, (b) the ground fixed and translating axes and (c) the angles defining the orientation of the object.
Data was then extracted from the trajectory calculations at a point where the downwind distance $x_e$ was 10m. This distance was selected because at this point the mean velocity in the direction of the wind is of the order of 15m/s, the speed used in many impact tests. This distance is also of the order of typical spacing of structures in a suburban environment. The general statistics at this range are also given in Table 1.

Table 1: Trajectory and Impact Statistics for 50 Random Cases

<table>
<thead>
<tr>
<th>Mean</th>
<th>St Dev</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>St Dev</th>
<th>Max</th>
<th>Min</th>
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<tbody>
<tr>
<td>$\alpha_0$ (°)</td>
<td>0.43</td>
<td>46.11</td>
<td>84.94</td>
<td>-89.92</td>
<td>Wall Angle $\gamma$ (°)</td>
<td>4.10</td>
<td>34.93</td>
</tr>
<tr>
<td>$\beta_0$ (°)</td>
<td>-2.04</td>
<td>50.04</td>
<td>89.39</td>
<td>-86.38</td>
<td>$V_{xw}$</td>
<td>12.18</td>
<td>2.91</td>
</tr>
<tr>
<td>$\phi_0$ (°)</td>
<td>-4.79</td>
<td>56.18</td>
<td>78.41</td>
<td>-83.68</td>
<td>$V_{yv}$</td>
<td>-8.10</td>
<td>2.36</td>
</tr>
<tr>
<td>$t$ (s)</td>
<td>1.17</td>
<td>0.28</td>
<td>2.07</td>
<td>0.89</td>
<td>$V_{zw}$</td>
<td>1.10</td>
<td>0.89</td>
</tr>
<tr>
<td>$x$ (m)</td>
<td>10.0</td>
<td>0.0</td>
<td>10.0</td>
<td>10.0</td>
<td>$V_{xw}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$y$ (m)</td>
<td>-5.48</td>
<td>3.48</td>
<td>-0.49</td>
<td>-17.86</td>
<td>$V_{yw}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z$ (m)</td>
<td>0.32</td>
<td>2.48</td>
<td>5.92</td>
<td>-5.82</td>
<td>$V_{zw}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{xe}$ (m/s)</td>
<td>14.71</td>
<td>1.50</td>
<td>17.93</td>
<td>11.21</td>
<td>$F_{max} = V_{r}(mk)^{1/2}$ (N)</td>
<td>14183</td>
<td>1244</td>
</tr>
<tr>
<td>$V_{ye}$ (m/s)</td>
<td>-8.10</td>
<td>2.36</td>
<td>-4.37</td>
<td>-16.48</td>
<td>$\theta_w$</td>
<td>42.38</td>
<td>14.16</td>
</tr>
<tr>
<td>$V_{ze}$ (m/s)</td>
<td>0.02</td>
<td>1.86</td>
<td>4.39</td>
<td>-4.13</td>
<td>$V_T$</td>
<td>17.06</td>
<td>1.50</td>
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<tr>
<td>$\alpha_{10m}$ (°)</td>
<td>15.45</td>
<td>41.57</td>
<td>77.34</td>
<td>-71.40</td>
<td>$\theta_{1}$</td>
<td>14.183</td>
<td>13217</td>
</tr>
<tr>
<td>$\beta_{10m}$ (°)</td>
<td>-1.47</td>
<td>55.78</td>
<td>88.74</td>
<td>-84.94</td>
<td>$2^nd$ Peak (N)</td>
<td>8011</td>
<td>3064</td>
</tr>
<tr>
<td>$\phi_{10m}$ (°)</td>
<td>5.25</td>
<td>45.95</td>
<td>87.85</td>
<td>-88.72</td>
<td>$F_{Peak}$</td>
<td>8684</td>
<td>2544</td>
</tr>
<tr>
<td>$p$ (rad/s)</td>
<td>0.18</td>
<td>1.40</td>
<td>4.09</td>
<td>-3.20</td>
<td>Force Ratio</td>
<td>0.61</td>
<td>0.17</td>
</tr>
<tr>
<td>$q$ (rad/s)</td>
<td>-0.16</td>
<td>1.45</td>
<td>3.50</td>
<td>-3.49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r$ (rad/s)</td>
<td>-0.45</td>
<td>8.88</td>
<td>16.96</td>
<td>-15.79</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It may be noted that typically the rod takes 1.2s to cover the 10m distance although values as low as 0.9 s and as high as 2 s also occur. At the end of this time the X-direction velocity is on average 14.7 m/s but ranges from 11.2 to nearly 18 m/s. In addition there is a significant vertical velocity ($V_{ye}$) of up to 16.5 m/s and horizontal cross-wind velocities up to 4.4 m/s. Typically the rod has fallen by about 5.5 m, but it may have hardly fallen at all or dropped up to nearly 18m. In general the orientation angles at 10m are quite different from the initial values but are similarly distributed. The transverse rates of rotation $p$ and $q$ can be seen to generally lie in the range ±4 rad/s, which are similar to the values considered in the previous section, however the rates of rotation about the longest axis of the rod can be much higher.

The data collected from the trajectory model was then used as the initial conditions in the impact model. However one additional piece of randomised information was also included. The velocities and angles calculated by the trajectory model are relative to the wind direction, however in real situations the vertical walls of buildings are likely to have random orientations relative to the wind. In addition it should be noted that if debris is equally likely to occur at all locations across a wind front then the chances of an impact occurring on a particular wall is proportional to the area of a wall projected normal to the wind. Hence if the angle between the wind direction and a wall normal is $\gamma$ then the chance of an impact occurring is proportional to $\cos(\gamma)$. As a result wall angles have been randomly chosen within the range $-90^\circ$ to $90^\circ$ but with a probability distribution proportional to $\cos(\gamma)$. The trajectory velocities were then resolved onto an axis system with the $X_w$ axis normal to the wall through
V_{xw} = V_{xe} \cos(\gamma) + V_{ze} \sin(\gamma) \tag{3} \\
V_{zw} = -V_{xe} \sin(\gamma) + V_{ze} \cos(\gamma) \tag{4}

and the rod orientation angles modified by simply changing the horizontal angle to

\beta_w = \beta - \gamma \tag{5}

The total velocity magnitude and the angle between the velocity vector and the wall normal were then be calculated through

V_T = (V_{xw}^2 + V_{yw}^2 + V_{zw}^2)^{1/2} \tag{6} \\
\theta_w = \sin^{-1}\left(\frac{V_{yw}^2 + V_{zw}^2}{V_T}\right) \tag{7}

These calculations show that the total velocities have a mean value of 17 m/s and range from just over 14 m/s up to almost 22 m/s, while the impact angles have a mean of 42° and a range from 17° to 78°. Even when the wind is normal to the wall there is usually some angle due to the vertical velocity of the rod.

Figure 5(a) shows the calculated primary and secondary peak forces for these 50 random runs plotted against the wall angle $\gamma$. While the results are quite scattered it can be observed that the highest impact forces are only of the same order as those expected from this projectile impacting end on with a velocity of 15 m/s normal to the wall, which is given by Eq. (1) as 12.5 kN. Although some cases have higher velocities the impact is always slightly angled and hence the impact force reduced. Figure 5(a) also shows that as the wall becomes more oblique the peak forces decrease significantly.

Figure 5(b) shows the same data, but for each run the highest peak force is ratioed to the potential peak force, $F_{\text{max}}$, calculated using Eq. (1) and the total velocity, $V_T$, for that particular run. This has been plotted against the impact angle, $\theta_w$. The results show that the simple formula Eq. (2) is a reasonable upper bound for the data although there are a few points which slightly exceed this curve.

Figure 5: (a) The primary and secondary peak impact forces for the 50 random cases plotted against the wall angle $\gamma$ and (b) the highest peak force ratioed to the expected maximum force, based on total impact velocity, plotted against the impact angle.

Conclusions

The effect of rod orientation and approach direction on impact forces from windborne debris has been studied using a modified 6 degree-of-freedom trajectory model. In particular the impact of a 4 kg 100x50mm timber rod at 15 m/s onto a wooden weatherboard wall has been modelled. The results show that the forces are more sensitive to approach direction than
to rod orientation. However if both the rod angle and the approach direction are within 30° of normal then the peak force is of the same order as the end-on normal-approach case, which is commonly used in test procedures. The main predictions of the model have been verified using a simple experimental test rig, although some differences have been noted. The affect of rod rotation has also investigated numerically and was shown to have little affect on the overall peak force although it did modify values during angled impacts. Finally a set of random impacts has been studied by using a 6 degree-of-freedom trajectory model and random release angles. The forces have been calculated for impacts against a randomly oriented vertical wall at a distance of 10m during a 30 m/s wind. The results show that the expected peak impact force can be reasonably modelled by $F_{\text{peak}} = V_T(\frac{mk}{2})\cos(\theta_w)$, where $V_T$ is the total impact velocity of the rod, $m$ the mass of the rod, $k$ the wall stiffness and $\theta_w$ the angle between the impact velocity vector and the wall normal.

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