Modelling the launch and collision phases of wind-borne debris

David M. Hargreaves[1*] and John S. Owen[1]
[1]Faculty of Engineering, University of Nottingham, NG7 2RD, UK
[*] E-mail: david.hargreaves@nottingham.ac.uk

1 INTRODUCTION

It is well documented that debris impact is an important mechanism of damage during severe wind events [1, 2], often contributing significantly to the total losses sustained by the building stock. The investigation of the flight of wind-borne debris (WBD) can be traced back to the work of Tachikawa [3]. Indeed, the Tachikawa number (the ratio of aerodynamic and gravitational forces) is now used to characterise WDB flight [4]. As the study of WDB has developed over the years since, the conditions under which the various types of WDB would become airborne were studied [5], 2D analytical Lagrangian models 3DOF were developed [6], followed by the 3D, 6DOF models, which eventually were incorporated into CFD models [7]. Many of these studies have focussed on debris flight in steady, uniform wind fields, unconstrained by buildings, for example, with corresponding lack of turbulence or intermittency of flow. Experimentally, such work exists [8], but the inclusion of a launch building is something that has not, as yet, been modelled computationally, although Moghim and Caracoglia [9] did look at impact locations close to a tall building.

This paper is a proof-of-concept for the inclusion of the launch scenario in CFD models. One of the reasons this as not been possible until recently is that dynamic meshing techniques that were utilised by Kakimpa et al [7], made it difficult to model the debris close to the building envelope – cells would collapse as the gap became small. Advances in CFD technology, notably Chimera (or overset) meshes, now mean this limitation is no longer an issue. This paper details the modelling approach in 2D, laying the groundwork for the shift to 3D.

2 METHODOLOGY

2.1 Domain and Mesh

A domain, 40 m long and 20 m high was created in the xy-plane using DesignModeler. For the base case, a duo-pitch building of length 5 m, wall height 4 m and a roof angle 30° was created with walls of thickness 0.15 m. On the leeward side, an opening to mimic a failed window was created and on the leeward roof, an opening was created to accommodate the debris. To use the Fluent terminology, this domain was meshed to create the *background* mesh using triangular elements and quadrilateral element in the mesh boundary layers.

The plate debris has a separate domain and mesh, called the *overset* or *component* mesh. This again was built in DesignModeler, with a 0.2 m by 0.02 m plate surrounded by a 1 m by 1 m square domain. The debris was offset and rotated so that it would fit exactly in the roof gap in the background mesh. The initial background and overset meshes can be seen in Figure 1(a). A small gap either side of the plate was necessary to avoid meshing problems. In future work, this gap in the roof will be modelled as a porous region in the background mesh.

2.2 Governing Equations

ANSYS Fluent, version R2024r1 was used throughout. The 2D form of the Navier-Stokes equations were used with the Realisable $k-\varepsilon$ turbulence model with standard wall treatment, which was deemed appropriate for this proof-of-concept study.

2.3 Material Properties and Boundary Conditions

The fluid properties were the default values for air (dynamic viscosity, μ, is 1.79×10^{-5} Pa s and density is 1.225 kg/m^3). The density of the plate, in the base case, was 165 kg/m^3, which is low for a typical roof tile in the UK but was chosen to illustrate the range of flight modes seen in this paper. The mass and moment of inertia of the plate were set appropriately in the 6DOF solver available in Fluent. To reduce

DOI 10.5258/WES/P0010

the jetting effect from the windward window to the gap in the roof, an inertial resistance factor of 1.0×10^4 m^{-1} was applied in a horizontal band at the base of the roof.

A standard ABL boundary layer was applied at the upwind inlet, using the expression language available in Fluent with the u component, turbulent kinetic energy and dissipation rates all being functions of height above the ground. All walls were set to smooth no-slip, apart from the ground which was given a roughness height appropriate to a z_0 of 0.01 m. The reference wind speed was 20 m s^{-1} at 6 m reference height for the base case.

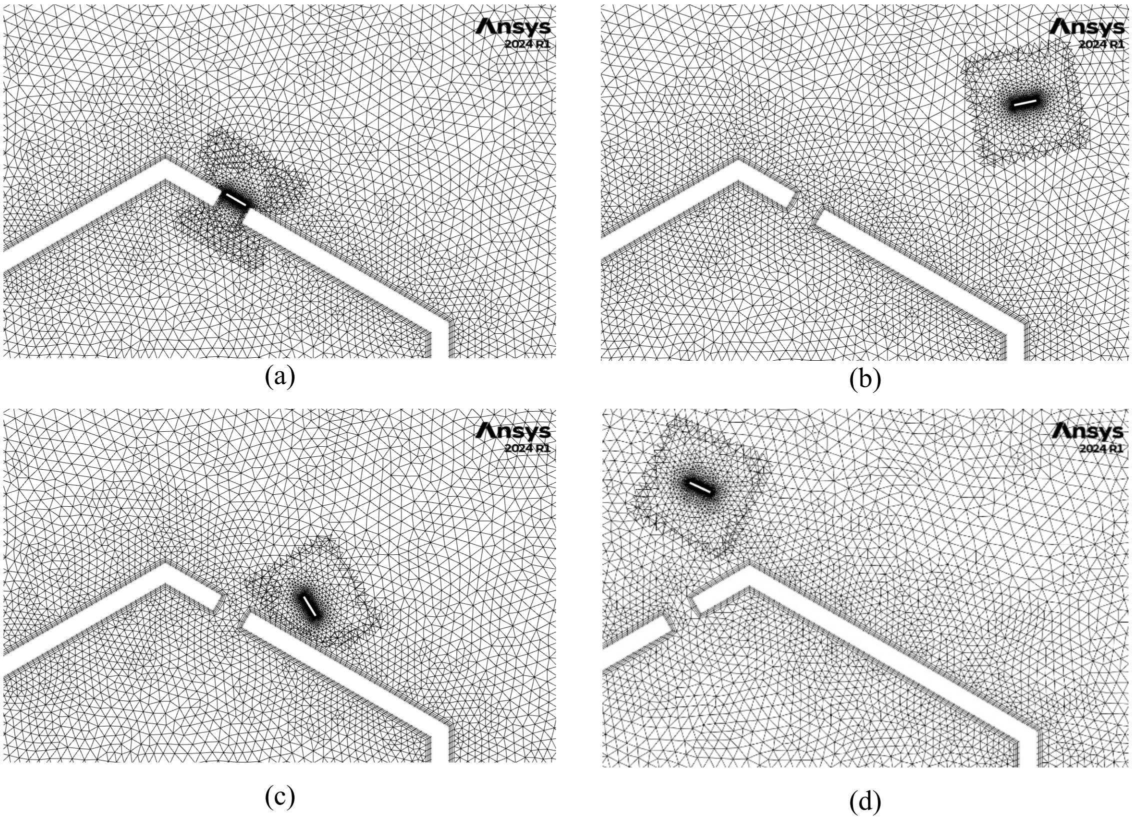

Figure 1: Background and overset meshes: (a) for the base case at release (t=0 s), (b) the base case at t=0.5 s, (c) with an increased internal resistance in the building at t=0.5 s and (d) with a windward face release position at time t=0.15 s.

2.4 Solution

For each case, the flow field for a fixed plate was solved using the transient solver with a time step of 1 ms. Once the lift and drag coefficients on the plate reached stationary values, the simulation was saved. Dynamic meshing was then enabled, and the simulation run on from this release time ($t = 0$ s). A User-Defined Function was written that would terminate the simulation if the plate came withing 1 cm of a wall. In fact, the overset mesh can model the plate going through a wall (and out of the domain) but this was not thought appropriate here. The simulation was saved at this impact point.

3 RESULTS AND DISCUSSION

Rather than attempt to explore the entire parameter space, three scenarios will be addressed, which highlight the breadth of the flight regimes that occur when debris is launched from a building. For context, Figure 2 shows a contour plot of the velocity magnitude from one of the cases prior to launch. Most notable are the flow separation on the windward roof, the larger separation above the leeward roof and the large recirculation zone in the wake of the building, characterised by reverse flow near the ground, travelling back towards the building.

3.1 Wake Flight

The base case set up, with a low internal resistance in the building, causing a positive pressure on the underside of the plate, results in the plate launching into the wake - Figure 1(a) shows the mesh after 0.5 s of this flight. As can be seen in Figure 3(a), initially it behaves similarly to a plate in a free stream. However, on entry to the wake, it begins to stall and then is swept back towards the building in the trapped vortex of the wake. Figure 3 also shows the velocity, angular velocity and forces acting on the plate.

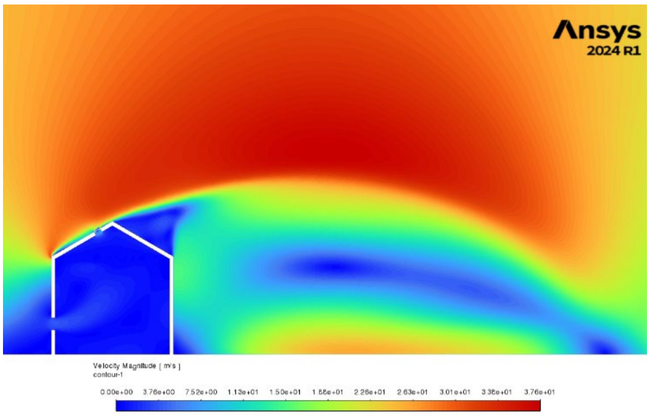

Figure 2: Contours of velocity magnitude in the vicinity of the duo-pitched building. Red corresponds to 37 m/s, with dark blue corresponding to 0.0 m/s.

3.2 Abrupt Flight

With a higher internal resistance in the building, the positive gauge pressure on the underside of the plate is lower and the forces acting on the plate in the early stage of its flight are insufficient for it to reach the high-speed flow above the building and it simply falls under gravity onto the leeward roof – see Figure 1(c).

3.3 Freestream Flight

A plate launched from the windward wall, Figure 1(d), immediately enters the accelerated flow above the ridge of the roof and rapidly flies off into the air. The combination of the rotation of the plate, the vertical component of the wind in this area and the initial launch velocity, causes the plate to rise as it exits the admittedly short domain being modelled here – see Figure 4(a). Figure 4(b), which shows the variation of velocity of the plate and is like that seen in previous work with freestream launches.

4 CONCLUSIONS

From these three simulations and a more comprehensive set of simulations that will be presented at the conference, it is clear that the launch of debris from a building presents a far greater range of flight modes than seen when the debris flies in the free stream. As a result, future work will focus on the move to 3D modelling with LES simulations. However, this brief study opens the possibility of gaining a better understanding of this complex phenomena and to feed into existing and new risk and reliability models.

REFERENCES

1. Grayson, J.M., W.C. Pang, and S. Schiff, *Building envelope failure assessment framework for residential communities subjected to hurricanes.* Engineering Structures, 2013. **51**: p. 245-258.
2. Kareem, A., *Structural Performance and Wind Speed-Damage Correlation in Hurricane Alicia.* Journal of Structural Engineering-Asce, 1985. **111**(12): p. 2596-2610.
3. Tachikawa, M., *Trajectories of Flat Plates in Uniform-Flow with Application to Wind-Generated Missiles.* Journal of Wind Engineering and Industrial Aerodynamics, 1983. **14**(1-3): p. 443-453.
4. Holmes, J.D., C.J. Baker, and Y. Tamura, *Tachikawa number: A proposal.* Journal of Wind Engineering and Industrial Aerodynamics, 2006. **94**(1): p. 41-47.
5. Wills, J.A.B., B.E. Lee, and T.A. Wyatt, *A model of wind-borne debris damage.* Journal of Wind Engineering and Industrial Aerodynamics, 2002. **90**(4): p. 555-565.

DOI 10.5258/WES/P0010

6. Scarabino, A. and P. Giacopinelli, *Analysis of the two dimensional sheet debris flight equations: Initial and final state.* Wind and Structures, An International Journal, 2010. **13**(2): p. 109-125.
7. Kakimpa, B., D.M. Hargreaves, and J.S. Owen, *An investigation of plate-type windborne debris flight using coupled CFD-RBD models. Part I: Model development and validation.* Journal of Wind Engineering and Industrial Aerodynamics, 2012. **111**: p. 95-103.
8. Kordi, B. and G.A. Kopp, *Effects of initial conditions on the flight of windborne plate debris.* Journal of Wind Engineering and Industrial Aerodynamics, 2011. **99**(5): p. 601-614.
9. Moghim, F. and L. Caracoglia, *A numerical model for wind-borne compact debris trajectory estimation: Part 1-Probabilistic analysis of trajectory in the proximity of tall buildings.* Engineering Structures, 2012. **38**: p. 153-162.

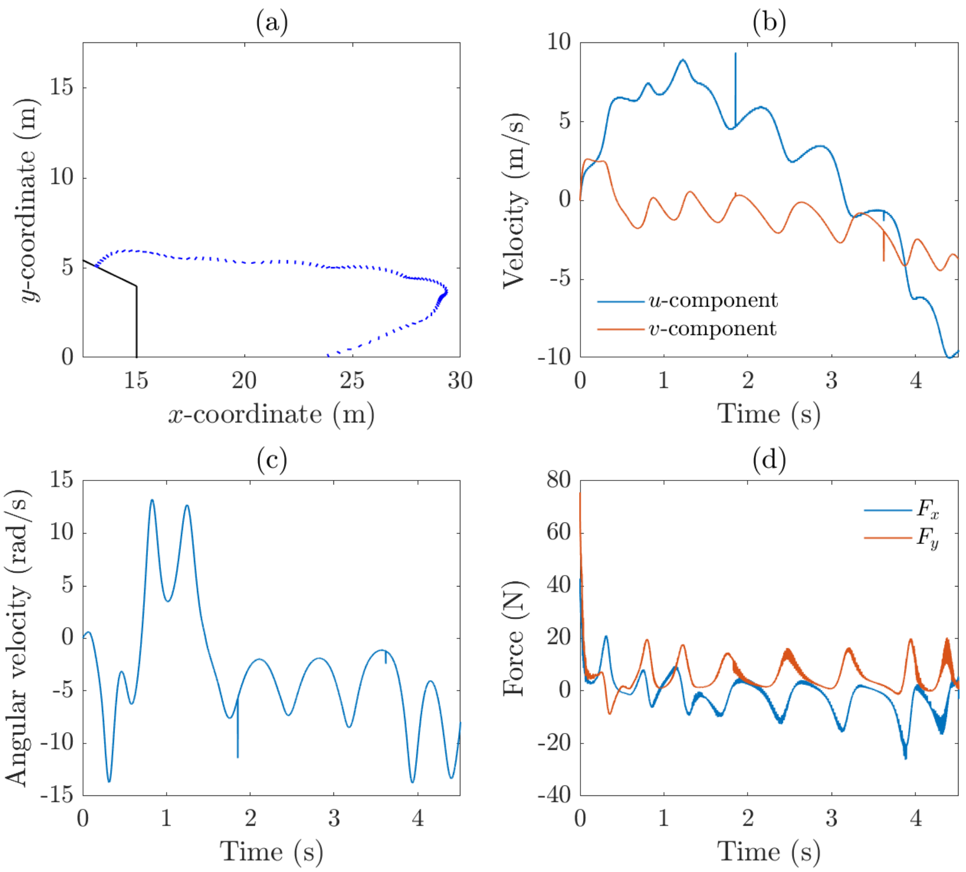

Figure 3: For the base case, (a) flight trajectory and plate inclination, (b) components of velocity, (c) angular velocity and (d) horizontal, F_x, and vertical, F_y, forces acting on the plate.

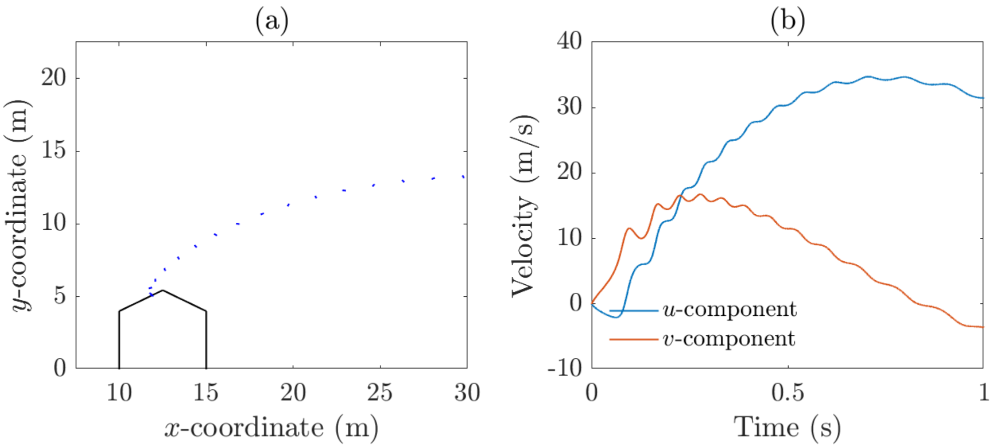

Figure 4: For a windward roof launch, (a) flight trajectory and plate inclination and (b) components of velocity of the plate.

DOI 10.5258/WES/P0010