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WINDBORNE DEBRIS IN THE URBAN ENVIRONMENT

ODŁAMKI KONSTRUKCJI UTWORZONE PRZEZ DZIAŁANIE WIATRU W ŚRODOWISKU MIEJSKIM

Abstract

This paper presents a comprehensive review of the research into windborne debris using. It introduces the components of the typical debris risk model - wind field model, debris generation model, debris trajectory model and debris impact model - and reviews the research that has been done in each of these constituent areas. The majority of this research has focussed on understanding the fundamental physics of debris flight, using both experimental and computational approaches to derive analytical and empirical models. This fundamental physics must be viewed, however, within a probabilistic framework that allows the risk to be assessed in a relevant manner. Much of the research relates to hurricane hazard in the USA, however windborne debris is clearly a threat to the urban environment during European wind storms. The way that FEMA's HAZUS®MH hazard assessment tool has brought natural hazard modelling into the engineering context is viewed as an approach that could be adapted for both mitigation and design in a European context.

Keywords: wind engineering, damage, windborne debris, CFD, hazard

Streszczenie

Niniejsza praca przedstawia kompleksowy przegląd badań dotyczących szczątków konstrukcji utworzonych i niesionych przez wiatr. Artykuł wprowadza elementy modelu ryzyka dla typowych odłamków – model pola wiatru, model tworzenia się odłamków, model trajektorii ruchu odłamków i model uderzenia odłamków – oraz przegląd badań, które zostały wykonane w obszarze tych zagadnień. Większość badań skupia się na zrozumieniu podstaw fizyki lotu odłamków, przy użyciu zarówno metod doświadczalnych jak i obliczeniowych, co pozwoliło na stworzenie modeli analitycznych i empirycznych. Należy rozpatrzyć podstawy fizyczne zjawiska, jednak w ramach zagadnień probabilistycznych, które pozwalają na odpowiednie oszacowanie ryzyka. Duża część badań odnosi się do zagrożenia huraganami w USA, jednak odłamki utworzone i niesione przez wiatr stanowią też istotne zagrożenie dla środowiska miejskiego w czasie burz występujących w Europie. Sposób, w jaki narzędzia do oceny ryzyka, utworzone przez FEMA i HAZUS®MH, pozwoliły na modelowanie ryzyka w ramach inżynierii, można postrzegać jako podejście, które może być dostosowane do ograniczania zjawiska i projektowania w kontekście europejskim

Słowa kluczowe: inżynieria wiatrowa, uszkodzenia, odłamki konstrukcji utworzone przez działanie wiatru, CFD, ryzyko

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1. Introduction

Reviews of damage caused to buildings and structures during strong winds have shown that windborne debris contributes greatly to the quantity and cost of damage [31, 32, 39]. Although the problem is most significant during the strongest winds associated with tropical storms and tornadoes, windborne debris also occurs in extra-tropical cyclonic storms such as those that occur in Northern Europe. The Federal Emergency Management Agency (FEMA) in the USA has published a number of reports on hurricane damage [2–4], which illustrate both the source of windborne debris and the damage caused by that debris. Examples of typical damage caused by windborne debris are shown in Fig. 1.

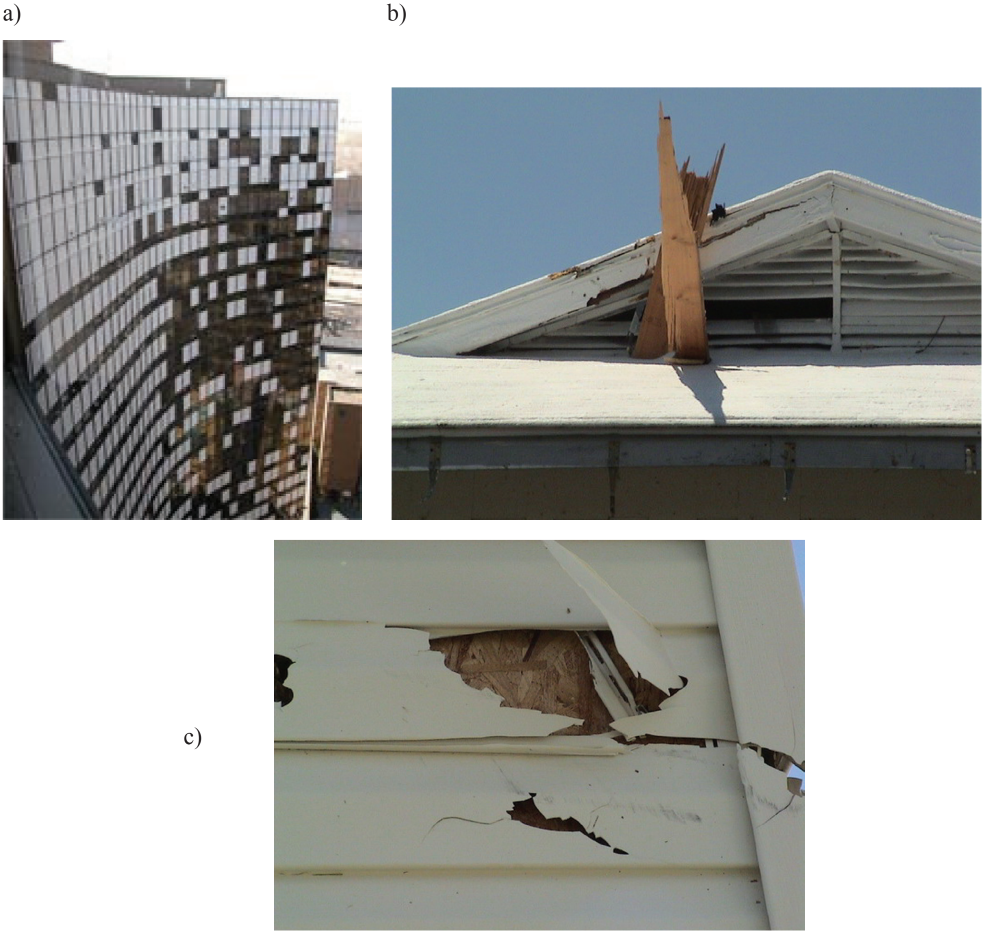


Fig. 1. Examples of damage caused by windborne debris, a) north façade of Hyatt Hotel, New Orleans damage by pea gravel from neighbouring roof (photo by K. Porter for MCEER), b) example of hazard due to missiles generated by failed structures (photo by T. Reinhold, AAWE gallery), c) example of cladding damage due to windborne missiles (photo by T. Reinhold, AAWE gallery)

Windborne debris arises from a variety of sources including building components where tiles, shingles or cladding sheets are torn from roofs. Items attached to buildings, such as signage or HVAC equipment, or loose construction material e.g. shingle and gravel on built up roof (BUR) structures, can also be torn free during high winds and become windborne debris. Other sources of debris include materials stored in the open at ground level, street furniture and tree branches. However, it is generally roofing materials that pose the greatest risk because their height and exposure make them more vulnerable to wind and more likely to fly further and faster.

Debris picked up by the wind can rapidly accelerate to reach and even exceed the background wind speed. The debris can travel significant distances (ranges of over one hundred metres have been reported) and can have significant momentum when it impacts the ground or downwind buildings. Clearly, in an urban environment, the risk of damaging impact with other structures is much higher and there are also risks associated with cars and pedestrians in the streets. Several fatalities have been reported in the media with people or vehicles struck by debris.

Typical debris impact damage involves the penetration of the building envelope, usually through broken windows, though cladding can also be damaged. However, it is important to note that the damage is not usually limited to the building envelope. Once the building envelope is compromised water is able to enter the building, which could lead to damage to the contents. Furthermore, the subsequent internal pressurisation of the damaged building can also cause internal damage and makes it more likely that the building will suffer further structural damage, such as roof loss. This in turn produces more debris, including structural members, which can cause damage to property further downwind. This is the so-called debris damage chain Fig. 2 [43].

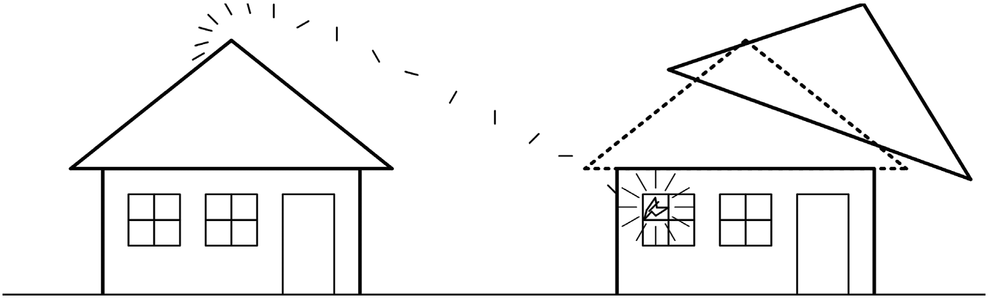


Fig. 2. The windborne debris damage chain (after [43]) Debris shed from the upwind building penetrates the downstream building causing internal pressurisation and subsequent major damage

Windborne debris is clearly a significant hazard and the associated risk is considerable. Design against windborne debris focuses on preventing debris generation by following guidance on appropriate fixings and fastenings and on dealing with the consequences of debris damage, such as internal pressurisation. However, field reconnaissance has shown that the generation of wind borne debris is not usually the result of poor design. When component failure generates debris, it is usually the result of the failure of the fasteners, either due to poor installation or to corrosion. Therefore, much of the responsibility for managing the risk of windborne debris lies with government authorities and building owners. Hence, in hurricane prone regions of the US, building codes such as the Florida Building Code provide guidance on the protection of vulnerable building envelopes using shutters etc. Inevitably, though, many of the losses fall on the insurance and re-insurance industries and it is these sectors that have driven the production of appropriate hazard loss models.

This paper will present a comprehensive review of the research into windborne debris using the general structure of the debris risk models as a template. It will introduce the components of the typical debris risk model and then review the research that has been done in each of the constituent areas. Although much of the research relates to hurricane hazard in the USA, windborne debris is clearly a threat to the urban environment during European wind storms. An aim of the paper is to highlight the progress made in US hazard modelling and hence identify future research opportunities in the European context.

2. Debris risk models

In his review paper, Holmes [10] identifies the four core components of a windborne debris damage model:

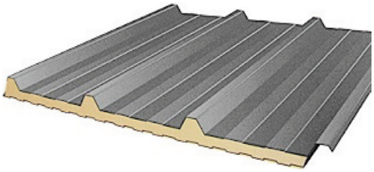
- Wind field model
- Debris generation model
- Debris trajectory model
- Debris impact model

There have been several models created with this outline structure. An early attempt to model damage caused by windborne debris [49] identified the maximum debris flight speed as a key parameter for predicting damage, which was assumed proportional to the debris kinetic energy. Three types of debris were defined in that study – compact, sheet and rod (Tab. 1). For a number of specimens of each type comparisons were made between wind tunnel test data and the predictions of flight speed, which was defined as the wind speed necessary to initiate flight. Although the comparisons were good, the model itself was very simple and limited in scope; the work's significant contribution being the debris classification.

A more detailed and comprehensive debris risk model has been incorporated into FEMA's HAZUS®MH hazard assessment tool. HAZUS®MH is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods and hurricanes [38]. The hurricane model of HAZUS®MH [44] includes not only the detailed wind field model, but also two separate windborne debris models: debris from residential buildings and roof top gravel debris. The former consist of shingles, tiles, roof-sheets etc. (sheet debris) and small roof timbers (rod debris). The latter are compact type debris and represent debris that has caused significant damage in historic hurricanes, such as Katrina (Fig. 1 and [3]). The model considers failure of individual component fixings under wind pressure and then predicts the subsequent debris trajectories. The trajectories are used to obtain energy and momentum risk curves that then form the input for a damage and loss estimation model [45] which is shown schematically in Figs. 3. and 4.

Table 1

Classification of debris types according to [49] with examples

Compact	 
Sheet	  
Rod	

The output from the HAZUS®MH hurricane model is a probabilistic estimate of the loss ratio, which compares well with insurance loss data for historic hurricanes. The purpose of the HAZUS®MH model is to allow users to quantify the cost effectiveness of mitigation techniques in different locations. It is therefore not a design tool as traditionally used in wind engineering, but a tool to be used by government bodies and building owners to estimate and then mitigate risk.

A later debris risk assessment model [24] uses Poisson random measure theory to predict damage during a hurricane due to debris from building sources. The approach includes a probabilistic model of debris trajectories that are used to predict impact and damage locations on neighbouring structures. Predictions of simulated debris transport distance and velocity are compared with field observations [25] and the model used to assess the vulnerability of residential developments using a Monte Carlo simulation [26, 50].

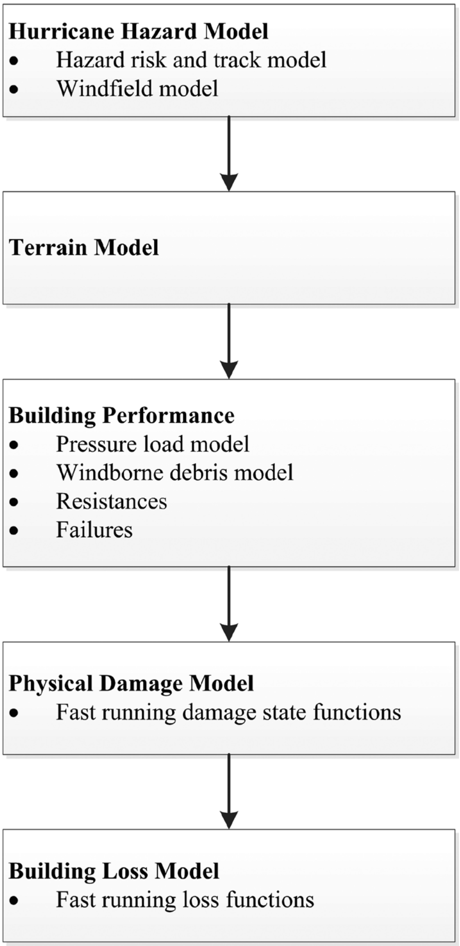


Fig. 3. HAZUS overview of damage and loss function calculation approach [45]

3. Wind field models

The purpose of the wind field model is to estimate the likely occurrence of damaging winds at a given location and to relate wind storm parameters to local mean and gust wind speeds at, say, rooftop height. These can then be used in conjunction with the debris generation model to predict the likely occurrence of wind borne debris.

The hurricane model in HAZUS®MH is based on an extensive study [46, 47] that considered historical hurricane data, including hurricane tracks, to create a model that could be used to generate simulations of future hurricanes. The simulations compared well with historical data in terms of both wind speed and central pressure. The model also includes a terrain model so that the simulation data can be used to predict wind speed and pressure data for specific locations. Similar studies on historic storms in North West Europe have been performed, but these have been in the context of catastrophe modelling for the insurance industry or meteorology; there is, as yet, not effective transfer into the engineering context. How and whether the traditional wind speed data from design codes such as EC1 can be applied to analysis of the risk from windborne debris has also still to be fully addressed.

One important aspect of the wind field model that requires further development is the local flow around buildings. It is known that the gust wind speed is most critical for debris generation. However, within the urban environment, this is likely to be determined by large scale turbulence and flow separation around buildings. These flow features will also have a significant influence on the debris trajectory and hence the risk of impact. It is therefore important that the local wind features are properly considered in the wind field model, both for the analysis of the debris generation process and modelling debris flight.

4. Debris generation model

The purpose of the debris generation model is to predict the type and source location of debris during a wind storm and the likelihood that the debris will take off. Field observations on typical debris indicate that residential roofing materials (e.g. tiles, shingles and roof sheets) are the most common components. Debris from roofs is particularly significant because it will be subject to higher wind speeds and so is more likely to be torn off. It is also likely to fly further because it is launched from height and is of the sheet type.

Damage surveys report that failure of roofing elements is most likely to result from failure of the fasteners, either because of poor installation practices or through mechanical failure of inadequate or corroded fasteners. These factors have been the focus of full scale investigations of residential buildings [16, 40]. Although local failure of roof coverings is important, in some cases the underlying roof structure can also become the source of debris. This usually occurs because the structural design did not take into account the consequences of internal pressurisation following perforation of the building envelope.

Future research to refine the debris generation model is limited by the wide variability of debris form and fixing capacity. It must therefore focus on an appropriate probabilistic representation of these factors based on historical damage surveys.

5. Debris trajectory model

The purpose of the debris trajectory model is to predict the flight path of wind borne debris, and in particular to determine the distance and direction travelled and the impact speed. The former is required to assess the likelihood of impact on surrounding buildings and assets. The latter is required to assess the likelihood of damage being caused by that impact. The debris trajectory model must take account of the uncertainty of the processes involved including aerodynamics, flow field and launch conditions. Hence, the debris damage loss models outlined above include a probabilistic approach to modelling debris flight.

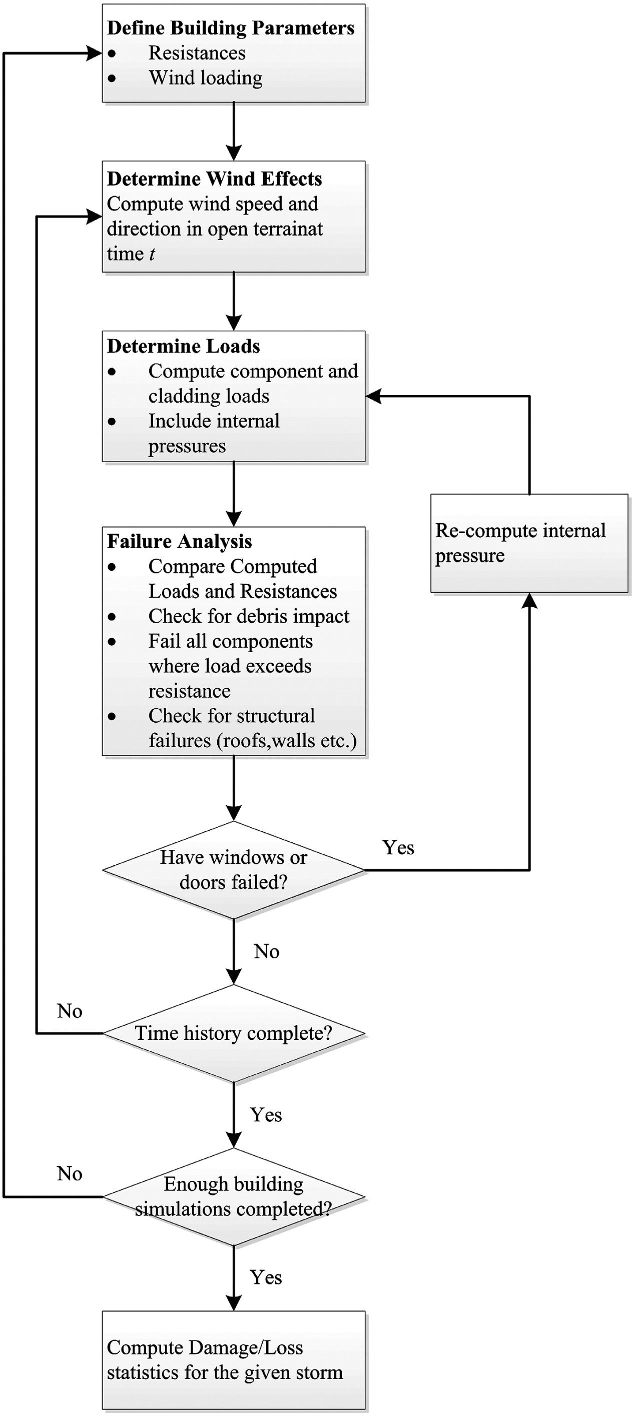


Fig. 4. HAZUS hurricane damage estimation methodology (after [45])

The ground breaking work on debris flight was carried out by Professor Tachikawa, who studied the flight of plate like debris in the wind tunnel [41] and subsequently developed a first debris trajectory model [42]. The wind tunnel studies revealed a number of different "flight modes" including translation, flutter and auto-rotation. As different flight modes have different aerodynamic characteristics this increases the spread in simulation results. The flight model included the effect of auto-rotation on the aerodynamic forces, which are analogous to the Magnus effect and generate additional aerodynamic lift and moment. These in turn influence the flight trajectory. The contribution of Professor Tachikawa to the development of the field by identifying the fundamental parameters affecting the flight of plate like debris was recognised by the designation of the Tachikawa number to describe the key non-dimensional ratio between aerodynamic and gravity forces [11].

5.1. Analytical Models

A very simple model of debris flight is included within [49]. Although this does not attempt to predict trajectories, it does propose a condition for debris launch in terms of the ratio of aerodynamic to gravity and restraining forces. The resultant debris flight speed is described as a proportion of the mean wind speed and comparisons made between predicted and wind tunnel results for the three debris types (compact, sheet and rod). A more detailed model for compact debris was developed by Holmes [9] who considered the 2D equation of motion ignoring rotational effects. The influence of atmospheric turbulence on the debris trajectories was investigated by modulating the background wind speed. The model was used to predict flight distances and velocities at impact for two spheres with different diameters and materials (8mm stone and 80mm wood).

Baker [1] presented a more complete version of the 2D debris flight equations, which included the rotation of the particle and the aerodynamic forces associated with autorotation. Baker proposed a different non-dimensionalisation of the equations to Tachikawa, but identified the same non-dimensional ratio of aerodynamic to gravity forces as the governing parameter. He presented solutions for both compact and plate-like debris including the effects of turbulence, and compared his predictions with the wind tunnel results presented by Wills [49]. An interesting result from this model was that, for auto-rotating flight modes, sheet like debris could achieve a flight speed greater than the mean wind speed because of the influence of the auto-rotational force coefficients. This indicates that accurate prediction of the flight of wind borne plate like debris requires an accurate model of the auto-rotational behaviour of the debris. This is fundamental to predicting the correct flight mode and determining the correct aerodynamic forces. A subsequent re-working of Baker's analysis using an improved definition of auto-rotational force coefficients illustrates the effects [17]. This later work was subsequently extended to a full three dimensional quasi steady model for plate like debris flight [18], which was evaluated by comparison with wind tunnel data. The results compared well when there is a dominant wind (as in debris flight). A further comparison of the models developed by Baker [1] and Holmes [12] is presented by Scarabino [37], who considers the stability of sheet type debris flight and the asymptotic solution of the debris flight equations.

A full six degree of freedom, 3D model of wind-borne debris trajectories was presented in [6]. Here, a Monte Carlo simulation approach is taken to address some of the uncertainties in the initial conditions and wind regime. The results are predicted probability distributions of debris impact locations and impact velocities, which match data from small scale wind tunnel tests.

5.2. Wind Tunnel Studies

Wind tunnel tests for debris trajectory models can loosely be classified into two different types. The first are aimed at understanding the aerodynamic performance of individual items of debris, usually in terms of measuring the aerodynamic and auto rotational force coefficients needed for the analytical models described above. The second are aimed at measuring debris trajectories to provide data for the validation of simulate trajectories predicted by those analytical models. These studies also consider the effect of local flow conditions (e.g. flow round buildings) on debris launch and flight.

The earlier models of debris trajectory made use of standard data sources such as ESDU to obtain aerodynamic parameters, although these sources don't provide the full range of angles needed. The first debris specific tests [36] measured static force coefficients on plates and rods, while varying both the angle of attack and the angle of tilt. However, direct measurements of the important auto-rotational behaviour were not made, instead values of force coefficients were modified using an approximation to dynamic stall and apparent camber to account for auto-rotation.

A subsequent series of tests did measure pressures and forces on auto-rotating square plates in the wind tunnel [27]. Two different plate sizes were considered, 1m by 1m and 0.3m by 0.3m, with the plates restrained to rotate about a horizontal axis. In this case the situation was effectively 2D and the plates did exhibit stable auto-rotation for certain wind speeds. The values of lift, moment and drag coefficients measured during these tests were then compared with the values used in the analytical models described above [1, 12, 36]. Further processing of the experimental data was then performed to compare the tip speed ratio during auto-rotation with theoretical models [29] and to investigate the fluctuating pressure fields [28].

Apart from the pioneering work of Tachikawa [41], one of the earliest wind tunnel tests to validate debris trajectory models is presented by Wills [49] for cube and plate type debris. Measurements were made of initial flight speeds, i.e. the mean wind speed at which the debris first launched, which was then use to calibrate their model for the debris launch criterion. A more comprehensive wind tunnel study of plate like debris is presented in [23]. Here, wind speed, angle of attack, debris size and debris density are studied to determine the influence of each on the trajectory. The debris is held on a launch mechanism by an electro-magnet, which is turned off to trigger release (hence, failure of fixing components is not considered at debris launch) and then the debris flight tracked by camera. The results of the wind tunnel study are used to propose an empirical formula for non-dimensional trajectories in terms of the Tachikawa number, which is then compared with the results in a 2D analytical model [12]. The authors later extended their work to include rod and compact debris types [22]. Their empirical trajectory models for different types of debris are compared in Fig. 5, which shows sheet type debris achieving the highest speed, yet not reaching the background wind speed.

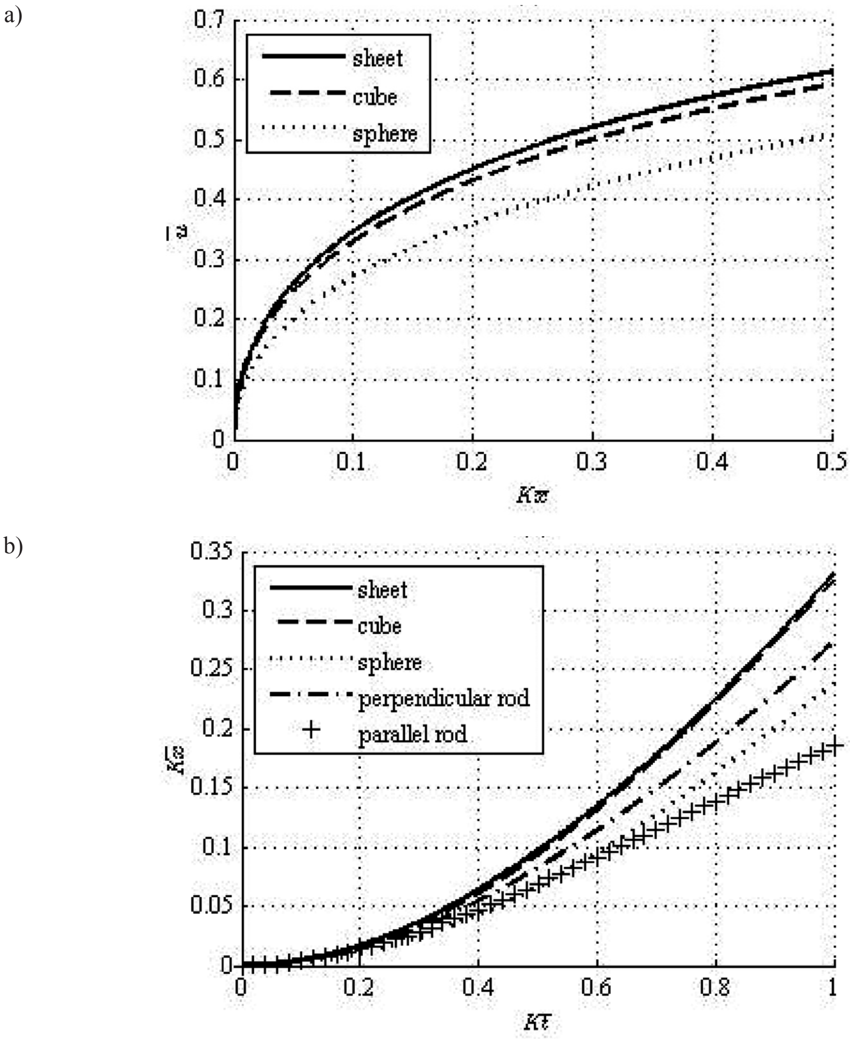


Fig. 5. Comparison of empirical trajectories for different debris types in terms of Tachikawa number (K) and non-dimensional time ($\overline{t}$) and distance ($\overline{x}$)

More recent wind tunnel studies have considered the performance of roof sheets on a 1:20 scale model of a typical house structure. In the first of these studies [48] the experimental design is described including the scaling of the fastener failure load, which is used to determine the hold down force for the electro-magnets. Only winds normal to the ridge line of the house were considered and the roof sheet was located immediately downwind of the ridge. The tests produced a probability distribution for the wind speed at panel failure and a set of trajectories that were recorded using high speed cameras. Significantly, both translational and auto-rotational flight modes were observed. Later tests on the same model considered the influence of wind direction [20] and panel location [19] on the debris flight.

Wind direction and the location of the panel on the roof both had an effect on the failure wind speed, the range of debris flight and the spread of debris. Another important observation was the influence of surrounding buildings. The presence of neighbouring buildings made a significant difference to the range and spread of debris, providing further evidence that the detailed local wind field is very important.

5.3. Numerical Simulations

Computational wind engineering is a rapidly developing field and recent work has applied Computational Fluid Dynamics (CFD) to the solution of the wind borne debris problem. As with wind tunnel testing, in the simplest cases CFD is just used to predict the aerodynamic and auto-rotational force coefficients for use in an analytic model. Measurements of auto-rotational force coefficients in the wind tunnel are especially sensitive to the experimental conditions including mass distribution, bearing friction and boundary effects. These factors can be identified and quantified by comparing the experimental results to computational simulations. A further advantage of the numerical simulations when studying the force coefficients is that they provide more details of the flow field and pressure distributions across the debris than can be obtained from wind tunnel testing. This in turn improves the conceptual understanding of the flow regime and flight dynamics.

The real advantages of using CFD, though, are seen when it is applied to the simulation of the debris flight itself. In this case, flight trajectories can be obtained for debris without the need to obtain force coefficients. Hence, irregular and non-standard debris can be simulated. Furthermore, the simulation of debris flight is effectively embedded within a simulation of the local flow field. It is therefore possible to study the effects of debris origin, local flow separation, building interference etc. on the debris trajectories. In effect simulations of debris trajectory are then not dependent on an assumed flow field as inherent in an analytical model, but on a simulated flow field that captures the key features of the flow.

However, the complexity of the physical problem means that the simulations are not trivial. First, it is necessary to simulate the local flow field around the debris. Because the debris is translating and rotating through the fluid, this has to be considered as a fluid structure interaction problem using an ALE formulation. The debris motion is calculated using a six degree of freedom rigid body solver in response to the flow induced forces. Motion of the debris then imposes a displacement on the mesh around the debris, which must be accounted for in the fluid solution. Second, unlike many FSI problems, the debris is in effect also translating through the domain, requiring regular re-meshing to avoid mesh distortions. Finally, the flow fields around buildings are notoriously difficult to simulate and so the mesh required may be very large and demand significant resource to solve it.

The first detailed presentation of the CFD simulation of plate like debris is given in [15] where the simulations are compared with experimental data obtained from the wind tunnel [27]. The propriety CFD code, ANSYS FLUENT, was used to simulate the flow field using an unsteady RANS approach with the realisable k-ε turbulence model. An inner spherical region of mesh was defined around the plate like debris, which translated and rotated with the plate without deforming. This spherical region was then allowed to translate through an outer region which was re-meshed on every time step, Fig. 6. Comparison of force coefficients for static and fixed axis rotating plates with values from the literature and wind tunnel gave good agreement. Importantly, discrepancies with the wind tunnel data identified problems with the experiment including mass eccentricity and bearing friction. Predictions of the debris flight also compared well, with different flight modes being predicted.

This model was later refined by adopting a singularity free rigid body solver to avoid the complications of gimbal lock and by improving the outer domain by using an unstructured mesh, Fig. 7, [13]. Using this model, different debris flight modes (flutter, transitional and auto-rotational) were observed that corresponded to those seen in wind tunnel tests. Fig. 8 shows a comparison of simulated trajectories using CFD with an empirical model obtained from wind tunnel testing [23]. The simulations predict that in the auto-rotational flight mode sheet type debris can exceed the background wind speed. This agrees with the results of analytical models, but wasn't observed in the wind tunnel.

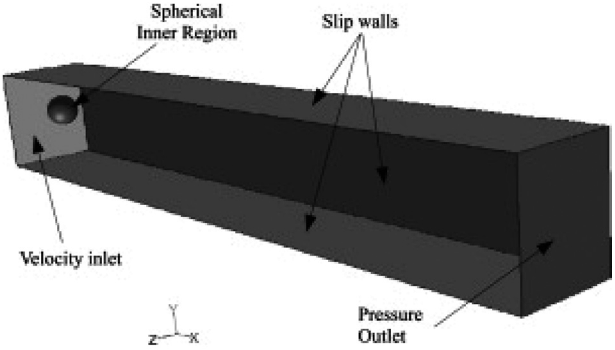


Fig. 6. Computational domain and boundaries for free-flight simulation of debris [13]

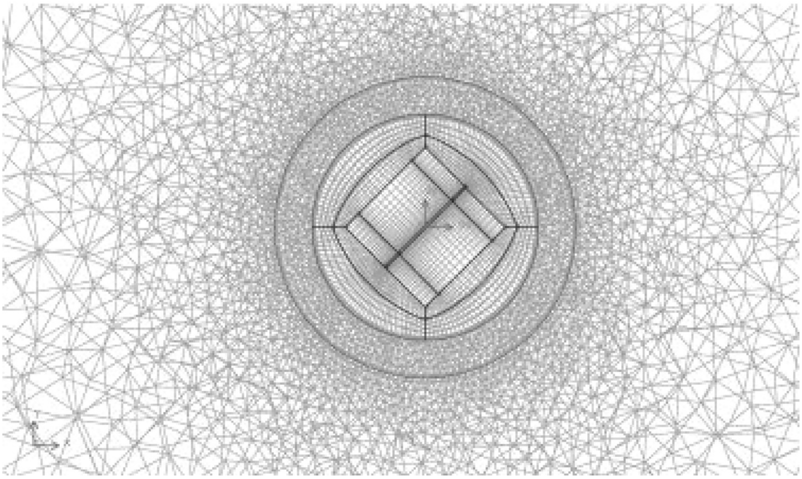


Fig. 7. Section through computational grid showing structured hexahedral mesh in the moving inner region surrounding the plate, together with an unstructured tetrahedral outer mesh that is re-meshed at each time step (after [13])

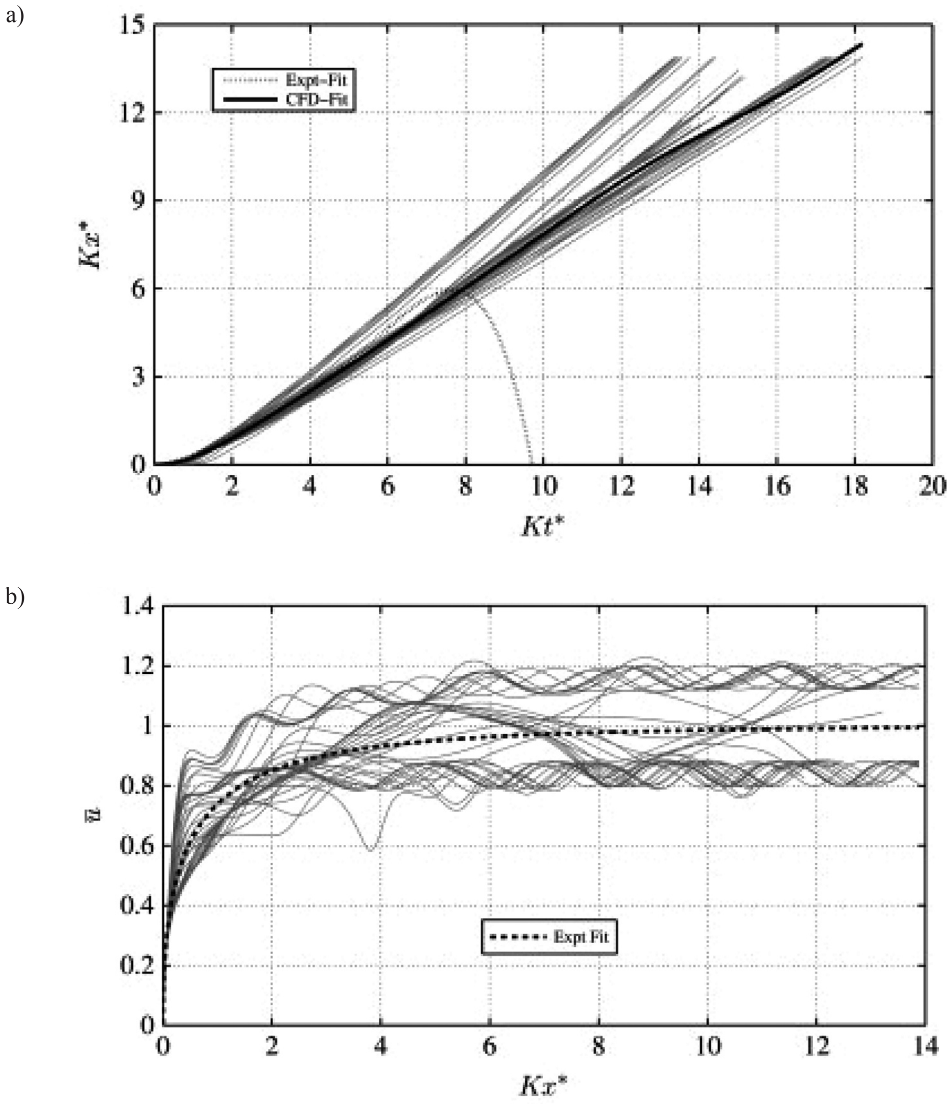


Fig. 8. CFD–RBD predicted trajectories for initial angles of attack of −85°≤α≤90°, showing (a) experimental (Lin et al., 2006) and CFD–RBD based fit expressions for non-dimensionalised horizontal distance, $K\overline{x}$, and (b) CFD–RBD predictions for non-dimensionalised horizontal speed (after [13]).

Figs. 9 and 10 present typical trajectories for different flight modes. Fluttering plates oscillate about an axis, but never rotate. Transitional plates oscillate at first, before developing stable auto-rotational behaviour. The auto-rotational plates enter stable autorotation from launch. For auto-rotating plates, the final flight speed depends on the direction of rotation. The key factor in determining the flight mode was the launch angle.

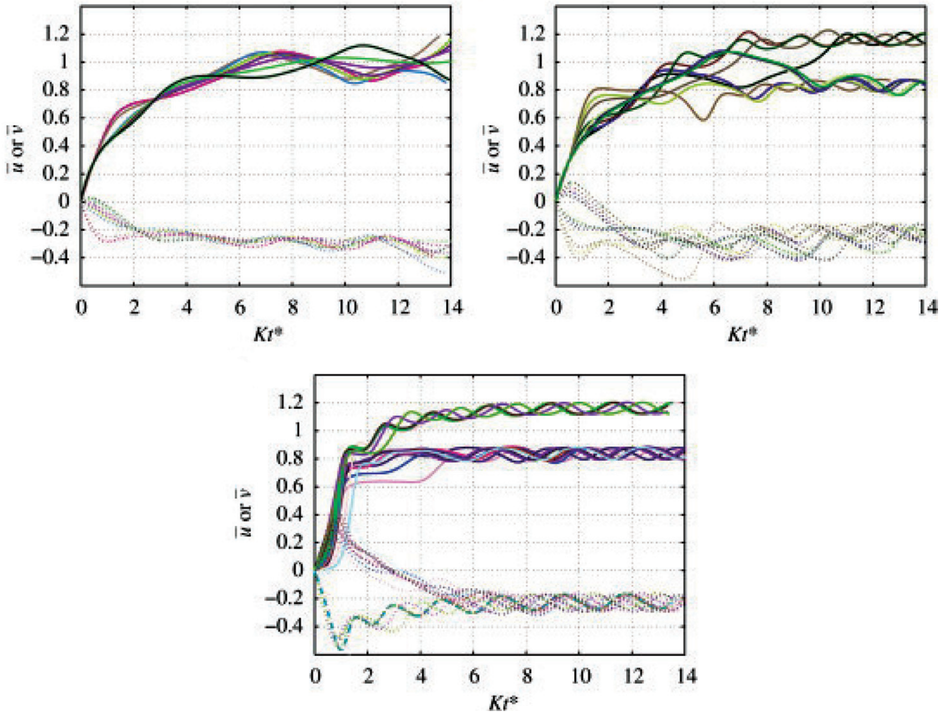


Fig. 9. Non-dimensionalised time-series of vertical (dashed lines) and horizontal (solid lines) plate speed for (a) flutter, (b) transitional and (c) auto-rotational flight modes (after [14])

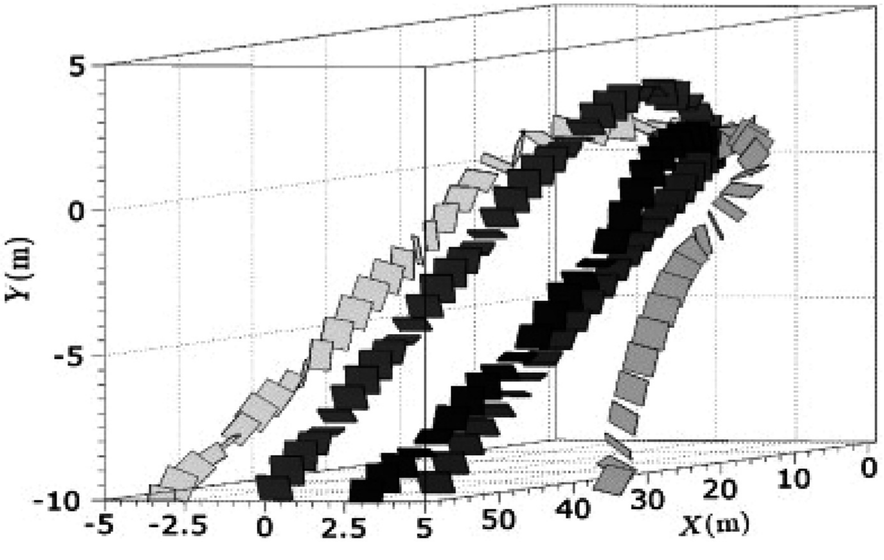


Fig. 10. Instantaneous orientations of plates in flutter (red), transitional (blue), autorotational (red) and complex 3D spinning (yellow and brown) modes of flight (after [14])

The CFD simulation was also used to propose equivalent empirical formulae for drag, moment and lift as a function of rotational speed. Trajectories for debris were predicted for a number of different debris types with different Tachikawa numbers and plate properties.

The influence of local environment was considered by including a representative building in the simulation; Fig. 11 presents typical and trajectories for roof debris [14]. The benefits of the CFD approach in terms of the improved understanding or the auto-rotation phenomenon is also clear [8].

The major limitation of the computational model described here is that it is deterministic, predicting the flight of specific debris in specific wind fields. Future work must address this by introducing an appropriate stochastic representation for both debris and wind field.

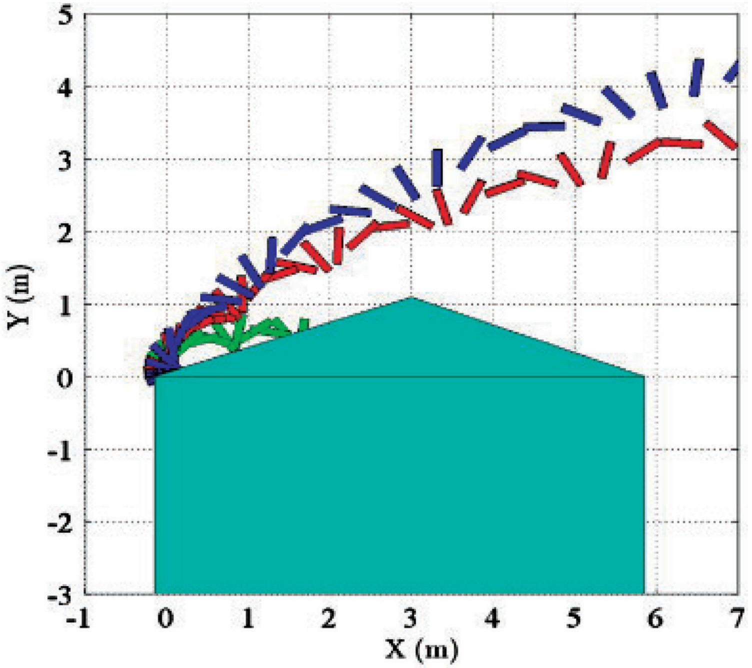


Fig. 11. Instantaneous snapshots of plate position and orientation during flight above the building for the 1 kg plate (blue), the 6.35 kg plate (red) and the 12 kg plate (green) (after [14])

6. Debris impact model

The purpose of the debris impact model is to predict the likelihood of damage due to debris impact during a storm. It therefore needs to consider the likely impact location and velocity of a debris particle, both of which can be obtained from the debris trajectory model. Typically a Monte Carlo analysis would be performed using the trajectory model to account for the uncertainties in the system; this highlights the benefits of having an efficient trajectory model. The debris impact model must also consider the likely damage caused by an impact, i.e. it needs to relate the kinetic energy and momentum of the debris at impact to the strength of the asset hit.

The earliest debris damage model [49] simply used the debris flight speed to provide an estimate of the energy at impact, assuming that this correlated with damage. Although simple, this damage function was able to provide helpful insight when used to compare the damage caused by Typhoon York in Hong Kong (Lee & Wills, 2002). The conclusions drawn are necessarily limited, but they do identify the debris damage chain seen in the field.

A more recent study considering the vulnerability of the facades on a representative tall building to wind-borne debris has taken the CAARC building as an example with a typical distribution of glazing (Moghim & Caracoglia, 2012a). A deterministic trajectory model was calibrated against the empirical equations given in [21] and then used to perform Monte-Carlo simulations in 2D and 3D. The influence of debris type (cubes and spheres) was considered together with the effect of the height and distance from the building of the debris source. 2D simulations showed a greater likelihood of damage, and should therefore be considered conservative or inaccurate.

When a simulation of a vertical gust is included [34] there is a noted increase in the likelihood of damage as the debris trajectory is longer. The vertical gust is a quite simplistic model in this context, but using a stochastic model to generate a turbulent wind field is more refined and has a marked influence on the debris flight and hence likelihood of damage [35]. Although both the turbulence and gust models require further validation, the results emphasise the importance of the local wind environment on the predictions of damage.

Grayson [7] has proposed an assessment framework for predicting building envelope failure during the passage of hurricane. The framework includes all the key elements of a debris damage model, including a generation model that reflects failure of fasteners under the action of wind pressure. The debris impact aspect of this model calculates both momentum and kinetic energy at impact and also considers the consequences of internal pressurisation on the integrity of the structure once the envelope has failed.

Considering the vulnerability of the building envelope to debris impact, ASTM specifies standard procedures for testing the impact resistance of cladding, glazing and hurricane shutters, but considers only spherical and rod like debris. Novel testing procedures have therefore been developed to determine the vulnerability of windows to lightweight sheet type debris such as shingles [30]. A range of mechanisms were used to project the debris, including an air cannon, catapult (shingles) and drop tests (rods) and tests considered different flight modes and impact angles. The vulnerability of the glazing was expressed in terms of the impact momentum of the projectile. A second study considered the vulnerability of hurricane shutters to impact from roof tiles [5]. In this case an air cannon was used to launch the projectiles whose flight was recorded using high speed video to determine impact speed and orientation.

7. Discussion and concluding comments

The literature reviewed in this paper has addressed an issue of real importance in the built environment; windborne debris does cause significant damage and considerable economic loss on an annual basis. It is also clear from the papers reviewed that a new and effective strategy has been proposed in the USA for mitigating this, and other natural hazards, and their associated risks. The HAZUS®MH model has provided an overarching framework within which detailed engineering research has contributed to the development of a workable model. It is important to note that through this framework engineering research has produced an impact that is accessible to a wider audience than the engineering community. Whereas previous research might have resulted in codes of practice for engineers, the HAZUS®MH model equips government agencies, property owners and insurance companies as well as engineers.

Although the direct outcome of this paper is to inform a specific audience about a specific hazard, the more valuable outcome is to ask questions about the overall methodology for managing natural hazards. FEMA has invested in a major programme of work, where is the equivalent in Europe? There is a significant body of research on wind hazard in Europe, but this is principally within the domain of meteorologists and catastrophe modellers in the insurance industry. It is on the periphery of engineering research.

The HAZUS®MH model is not a design tool, but the underlying concepts are core to the implementation of performance based design. Is there a need for a performance based design approach within wind engineering? Moreover, FEMA uses this tool to address other natural hazards: flooding and earthquake. However, the basic methodology could be adapted to address hazards relating environmental effects on buildings and people: pedestrian comfort and safety, pollution, heating and ventilation, fire, and terrorist actions such as dirty bombs.

Within such a model, there is also a need to identify the best protocol for simulating the risk. All the models reviewed here have relied on a deterministic analytical model of debris flight that is used as the basis of a Monte Carlo simulation to predict the likely trajectories. However, work has also been reviewed that presents an alternative computational framework. This approach has been shown to replicate work done in the wind tunnel, both to simulate trajectories and to determine aerodynamic and auto-rotational coefficients. There is great potential for developing CFD simulations of the urban built environment to provide not just more informed predictions of debris flight, but also better understanding of wind effects on the users of that environment.

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