Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 16. Introduction of stone deflector in the design of the Airbus A400M Aircraft

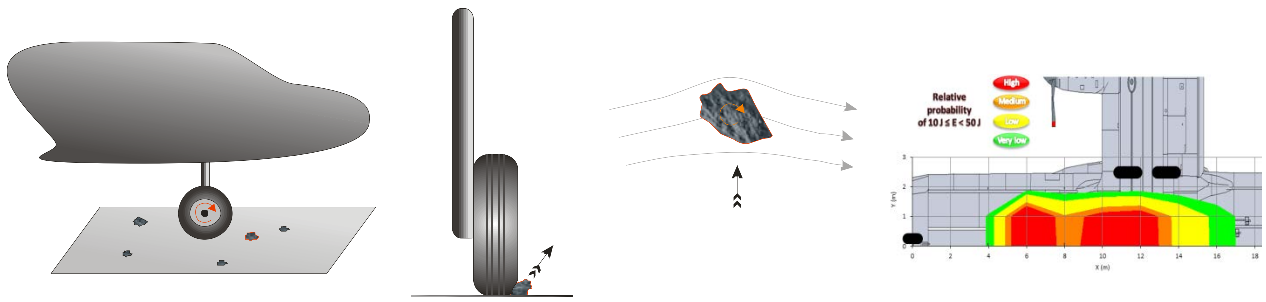
1. Summary of the impact (indicative maximum 100 words)

Runway stones thrown up by aircraft undercarriage wheels can cause considerable damage to the aircraft structure. A model of runway debris lofting developed at Imperial College has been used for the new A400M military transport aircraft, which Airbus reported was ‘absolutely needed’ during the successful development of a nose wheel debris deflector [5. A]. This deflector dramatically reduces the incidence and severity of the runway debris impacts and the associated maintenance costs and downtime of the new aircraft. Airbus has received 174 orders to date for the A400M. An indication of the cost savings comes from the Hercules C130K, the predecessor of the A400M, which incurred costs of up to £1M for each aircraft on active service in Afghanistan for the repair of runway debris damage. This cost is now eliminated for the Airbus A400M aircraft.

2. Underpinning research (indicative maximum 500 words)

The underpinning research responsible for this impact was led by Dr Greenhalgh from October 2006 to 2010 at the Aeronautics Department of Imperial College London. It was funded through a DSTL EPSRC CASE studentship. Before work started, there had been no realistic, reliable means of predicting the impact threat from runway stones hitting the undercarriage of the aircraft. Using information on runway debris characteristics, aircraft and tyre geometry for take-off and landing profiles, a model was devised to predict the likelihood of a tyre/debris encounter. This model was published as part of Reference 1. The next stage in the research was to model the mechanisms by which the debris, tyre and runway surface interacted to cause lofting and to determine the initial direction and speed of the projected debris. Initially, finite element (FE) models using contact mechanics were developed which captured the physics of the interactions between the hard stone, the ground and the compliant rubber tyre. The first models assumed solid, cylindrical tyres [2, 3], and these were extended to more realistic configurations, which, using data from indentation testing on aircraft tyres [4], included the inflation pressure and detailed tyre geometries [1]. All these models were validated against bespoke drop-weight experiments, monitored with high speed video, which reproduced key aspects of the contact conditions between the stones, tyres and ground. The understanding gained during the FE and experimental investigations, enabled the development of a physically-based analytical model [5] which was the first to provide an insight into the critical parameters which dictated the severity of the stone lofting processes, such as tyre geometry, stone mass and shape, and aircraft speed, and predicted the direction and initial speed, which included a significant spin component [1]. The kinetic energy associated with spin could be as much as 50% of the translational component. During a second research project funded directly by Airbus the models were further refined to incorporate the effect of the multiple interactions that occur when a wheel encounters a group of runway stones and to include the geometry of the tyres used on the Airbus A400M. Sang Nguyen received his PhD from the department of Aeronautics Imperial College for this work.

Having established a reliable model for the initial state of the lofted stone at the start of its projected motion, the next stage of research investigated the subsequent motion of the debris to enable prediction of the severity of any resulting impact on the aircraft. This work was funded directly by Airbus during 2011 and was led by Dr. Emile Greenhalgh with Dr. Nguyen as a postdoctoral researcher. Aerodynamic models were developed for the interaction between the spinning lofted stone and the airflow in the wake of the undercarriage wheels and beneath the fuselage [6]. The research focussed on the relative interaction between the different aerodynamic flows (such as tyre wake, aircraft boundary layer, ground effects and turbulence) and the rapidly spinning stones and culminated in the production of 'threat maps' which identify the sites on the aircraft lower fuselage that are exposed to the most severe impact conditions.



a. Likelihood of an encounter between the tyre and the debris

b. Debris lofting Mechanism

c. Trajectory of the spinning lofted debris

d. Impact threat map for medium energy range for C-130K fuselage

Figure 1: Overview of key research that led to impact

This is a unique capability that allows designers to optimise the damage tolerance of aerostructures exposed to such impact threats (i.e. undercarriage components and lower fuselage). The location and severity of debris damage predicted by the model has been shown to be in good agreement with that observed on aircraft such as C130K Hercules.

3. References to the research (indicative maximum of six references)

* References that best indicate quality of underpinning research.

[1] S.N. Nguyen, E.S. Greenhalgh, R. Olsson, L. Iannucci, P.T. Curtis, “Improved Models for Runway Debris Lofting Simulations”, The Aeronautical Journal, Vol 113, Issue 1148, pp. 669-681, (2009)
This paper was the first model to quantify stone encounters for realistic runway debris distributions which was an essential step towards accurate assessment of the threat posed by runway debris.

*[2] S.N. Nguyen, E.S. Greenhalgh, R. Olsson, L. Iannucci, P.T. Curtis, “Modelling the Lofting of Runway Debris by Aircraft Tyres”, AIAA International Journal of Aircraft, Vol 45, Issue 5, pp. 1701-1714, (2008) DOI: 10.2514/1.35564
This was the first instance of a computational model to simulate the stone lofting mechanism and, together with the experimental validation, produced vital information on the mechanism by which spin is imparted to the debris.

*[3] S.N. Nguyen, E.S. Greenhalgh, R. Olsson, L. Iannucci, P.T. Curtis, “Parametric Analysis of Runway Stone Lofting Mechanisms”, International Journal of Impact Engineering, Vol 37, Issue 5, pp. 502-514, (2010) DOI: 10.1016/j.ijimpeng.2009.11.006

*[4] S.N. Nguyen, E.S. Greenhalgh, R. Olsson, L. Iannucci, P.T. Curtis, S. Longstaff, “Experimental Characterisation of Tire Indentation by Simulated Runway Debris”, Strain: An International Journal for Experimental Mechanics, Vol 47, Issue 4, pp. 343-350, (2011) DOI: 10.1111/j.1475-1305.2009.00704.x

[5] S.N. Nguyen, E.S. Greenhalgh, R. Olsson, “Analytical Modelling of Runway Stone Lofting”, AIAA International Journal of Aircraft, Vol 48, Issue 4, pp. 1412-1421, (2011) DOI: 10.2514/1.C031306
This paper described a physically-based analytical model which was the first to provide an insight into the critical parameters which dictated the severity of the stone lofting processes, such as tyre geometry, stone mass and shape, and aircraft speed.

[6] S.N. Nguyen, E.S. Greenhalgh, J.M.R. Graham, A. Francis, R. Olsson, “Methodology for Predicting the Threat of Runway Debris Impact to Large Transport Aircraft” 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, 23-26, (April 2012) Paper no: AIAA 2012-1377.

4. Details of the impact (indicative maximum 750 words)

Military aircraft encounter a significant problem caused by damage from debris or stones lofted by the aircraft wheels onto the aircraft structure (see Figure 1 below). The conventional approach to designing against this threat is to essentially make an assumption about the worst impact energy (typically 50J) likely to occur during the lifetime of the aircraft. The structure would then be designed to tolerate any damage produced from such an impact when exposed to the most severe mechanical loading anticipated during its lifetime (i.e. design ultimate load). However, such an approach is not rigorous, and makes several assumptions regarding the type of impact conditions and the resulting damage. With weight being critical for aerospace design, overdesign of a structure imparts a considerable penalty; but if the perceived level of threat is underestimated, this could lead to parts of the aircraft being susceptible to damage during service, with potentially catastrophic or very costly implications. The latter is the case for the Lockheed C130K Hercules transport aircraft which the RAF have been using in the Gulf and Afghanistan and for which repair of runway debris damage is up to £1M per aircraft (source: verbal discussions with MoD and DSTL staff [A]).

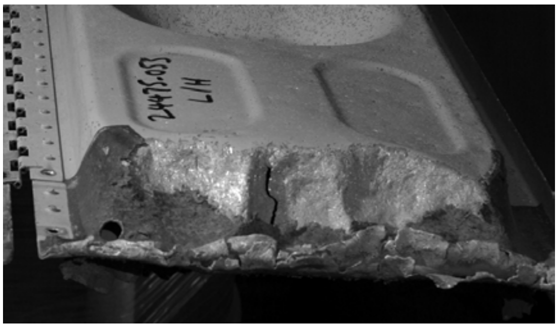


Fig 1 Runway debris damage to the leading edge of an undercarridge door of a transport aircraft

During initial work investigating the physics of the interactions between the hard stone, the ground and the compliant rubber tyre, the Head of Landing Gear Structures in Airbus Military (Spain) approached Dr Greenhalgh. He was interested in further developing the understanding of lofted debris and provided support for this work as outlined in section 2.

This research then had an immediate pathway for significant impact and has been relied upon by Airbus during the 2011 in designing the Airbus A400M Aircraft. The research allowed Airbus to quantify the severity of the threat to aircraft from runway debris and so enabled engineers to reliably design efficient aircraft structures to tolerate this threat [A]. The debris lofting model was able to predict the potential damage to the lower fuselage of the A400M aircraft from lofted runway debris. This was used in the design of a deflector plate for the nose landing gear (NLG) which would protect the lower fuselage from lofted stone damage. In particular, the models developed at Imperial were used to optimise the shape and exact position of the deflector plate [A].

In May 2012, The Head of Landing Gear Structures at Airbus commented that the research undertaken by Imperial College was “absolutely needed, because landing on unprepared runways was a new concept inside the Airbus Aircraft Family” and went on to state “The model identified the most critical parts on the fuselage, predicting in a reliable way the probable trajectories for a stone lofted by the NLG tyres and making it possible to start developing protections and devices that help to minimize the effect of such impacts during the operation on unprepared fields” The results of the Imperial model “confirmed the need of a stone deflector to help protect the belly of the A400M” and allowed Airbus “to improve the efficiency of such a stone deflector in the series design”. The results of the model developed have subsequently been shared inside the Airbus Community, and have raised interest from other areas as such as Power Plant and Dynamic Analysis [B].

As has been demonstrated above, the research has had a direct impact on the design of the new Airbus A400M. This has enabled one of the features of the plane to be reduced operational costs compared to its predecessor the Hercules C130K. The A400M has had successful test flights and is now being manufactured with over 174 orders in place as at 30th June 2013 [C]. The results of tests undertaken in the summer of 2013 on an unsurfaced runway covered with gravel of different sizes confirmed predictions made by the model and the efficacy of the deflector plate [B].

5. Sources to corroborate the impact (indicative maximum of 10 references.)

A. Flight lieutenant, Hercules IPT - Confirmation of the runway debris repair costs of £1M for a Hercules C130K

B. Head of Landing Gear Structures, Airbus Military - Corroboration of the impact of the research on Airbus design and results of subsequent full scale test landing on the prototype aircraft.

C. Airbus Military "Orders, Deliveries, In Operation aircraft by country- Worldwide" **pg. 3** (2013) http://www.airbusmilitary.com/Portals/0/Images/Aircraft/OrdersAndDeliveries/AMOrdersDeliveries.pdf Archived here on 17/09/2013.Corroboration of 174 orders for the Heavy Transport Aircraft Airbus A400M.