Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

A new theoretical model of aircraft arresting system based on polymeric foam material

Xianfeng Yang, Zhiqiang Zhang, Yun Xing, Jialing Yang, Yuxin Sun *

Institute of Solid Mechanics, Beihang University, Beijing 100191, PR China

ARTICLE INFO

Article history:
Received 22 July 2016
Received in revised form 7 November 2016
Accepted 11 March 2017
Available online xxxx

Keywords:
Arresting system
Polyurethane foam
Energy absorption
Analytical model
Parametric investigation

ABSTRACT

The engineering material arresting system (EMAS) has been widely employed in airports around the world for purpose of stopping the overrun airplanes from damage. However, the foamed concrete, which is used as the EMAS core at present, has drawn increasing criticism from the public opinion for environmental issue and aging problem. In this paper, a new arresting system made of polyurethane foam with high energy absorption capacity was proposed to overcome the above problems. An analytical model based on the Avalle empirical model, which takes into account the coupling effect between the aircraft wheel and the foam material, was presented to estimate the horizontal resistances exerted on the aircraft wheel, including the crushing drag, the tearing drag, the adhesive drag and the friction drag. In addition, the stopping distance required to arrest the overrun aircraft was predicted. Furthermore, the accuracy of the theoretical results was validated through comparison with the results of FAA full-scale arresting tests. Besides, the influences of the arrestor height, material strength, aircraft weight and the radius of aircraft wheel on the arresting performance of polyurethane foam material were performed, indicating that a reasonable parametric selection is extremely crucial to obtain the optimal design for the aircraft arresting system.

1. Introduction

Aircraft seems likely to overrun the runway during an unsuccessful takeoff and landing, leading to an accidental damage to the aircraft structures and loss of life. Casualty statistics [1] in recent years have concluded that there is an increasing probability of the accident occurrence with the increase of the weights and numbers of aircrafts. Under this circumstances, runway safety areas, especially the engineering material arresting system (EMAS), designed at the terminal of the runways are recommended by the Federal Aviation Administration (FAA) to provide an auxiliary buffer zone for the overrun aircrafts [2].

Substantial work has been done for the development of the arrestor system. Bade [3] firstly conducted an investigation of soft-ground materials for the emergency arresting of the aircrafts which overrun a conventional runway for Royal Aircraft Establishment in 1968. Since then, many researchers were contributed to the selection of arresting materials [4–8].

Currently, foamed concrete, which is suggested by the FAA advisory circular [4], has been the preferred material for constructing the arresting system due to its special microstructure morphology and mechanical behaviors. The remarkable advantage of foamed concrete is the low plateau stress (usually 0.3–0.4 MPa) and the low initial peak load. In addition, the stress platform area is relatively long (about 70%) with low fluctuation of stress, which keeps the impact force exerted on the wheel below the damage threshold of the landing gear. Thus, the safety of the aircraft structure and passengers can be ensured. However, foamed concrete is prone to generate a huge cloud of dust after being crushed, leading to serious environment issue. What's more, the engine inlet is readily accessible to the dust particles, which poses a threat to the regular operation of the engine due to the impact and accumulation of the dust particles. Besides, the foamed concrete material is extremely sensitive to ambient humidity and is liable to aging, which leads to a significant reduction of material arresting performance as time passes. Furthermore, a large amount of foamed concrete is in demand to build the EMAS, and the wastewater and impurities generated during the manufacture process can pollute environment heavily. Therefore, researchers are trying to look for a new material to take place of foamed concrete material. They studied the mechanical and energy absorption behavior of some alternative materials, among which some polymers with cellular structures such as expanded polypropylene (EPP) and expanded polyurethane (PUR) foam have attracted many interests. By an ap-

---

* Corresponding author.
E-mail address: yxsun@buaa.edu.cn (Y.X. Sun).

http://dx.doi.org/10.1016/j.ast.2017.03.019
1270-9638/© 2017 Elsevier Masson SAS. All rights reserved.

Please cite this article in press as: X.F. Yang et al., A new theoretical model of aircraft arresting system based on polymeric foam material, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.03.019

propriate choice of porosity and microstructure, one can design the lightweight cellular material in order to get the mechanical characteristics similar to the foamed concrete and satisfy the demand of energy absorption performance [5]. In addition, they are not grind up into powder during the arresting process; instead, they are stuck on the ground in pieces. Therefore, they will not destroy the engine and is more environment friendly.

At present, the existing literatures are mainly focused on the theoretical analysis and experimental test about foamed concrete, there is hardly any literature or report about the usage of cellular polymers in the aircraft arresting system. The present work aims to study the capacity of polyurethane foam as material employed in EMAS.

The study of the arresting behavior of polyurethane foam material is based on its stress–strain behavior. Up to date, there have been several analytical models to describe the constitutive relationship of cellular materials. For example, the Gibson model is presented firstly to exhibit the three stages of stress–strain curve by three equations [6]. Rusch [7–9] established a phenomenological model with a simple formulation expressed by the summation of two power laws, which did not descript the densification stage reasonably. Liu and Subhash [10] built a phenomenological constitutive model for foam materials under large deformation. Recently, Avalle et al. [11] studied the energy absorption behavior of several types of foams, namely EPP, PUR (Bayfill EA), EPS and PPO/PS (Noryl GTX), and presented a new formulation aiming to include the dependency of the model parameters on the foam properties. The Avalle model is significant and convenient in studying the energy absorption capacity of cellular solids.

Except for the selection and mechanical properties of arresting materials, the analytical models of the arresting process also have been conducted for many years. In 1986, Dole [12] presented a review of dynamic simulations for aircraft-surface interactions and revealed some computer programs to predict gear loads, structural response, and soil behavior when the aircraft traversed bomb-damage repaired runways or maneuvered on soil. Kraft and Philips [13] established an analytical model to evaluate the tire deflection, soil compression, drawbar pull or driving torque, surface slip and the nature of the soil when the tire contacted with the soft soil. Based on the above results, Cook et al. [14] developed the ARRESTOR code to calculate the arresting distance for different aircrafts on arrestor beds in 1995, which was intended for B707, B727 and B747. Later, Heymsfield et al. [15,16] conducted sensitivity analysis as well as optimizing the crushable foam concrete behavior according to the ARRESTOR code. Recently, Zhang et al. [17] presented an analytical model for foamed concrete arrestor to predict aircraft gear loads, deceleration, and stopping distance. Moreover, they also carried out a full-scale arresting test with an instrumented Boeing 737-300 aircraft to evaluate the performance of the arrestor system [18].

The present work aims to present a new theoretical model of EMAS arresting process based on the Avalle model to predict the performance of polyurethane foam arresting system. The content of the paper is organized as follows: in Section 2, a theoretical model based on the Avalle model is introduced, taking into account the coupling effect between the aircraft wheel and the foamed arresting material, to predict the horizontal resistance and stopping distance of the overrun aircrafts. The accuracy of the presented analytical model is validated through comparison with the FAA full-scale tests results in Section 3. Section 4 performs a series of parametric studies to investigate the influence of different material parameters and structural parameters on the arresting capacity for Boeing 727 aircraft. Finally, conclusions are drawn in Section 5.

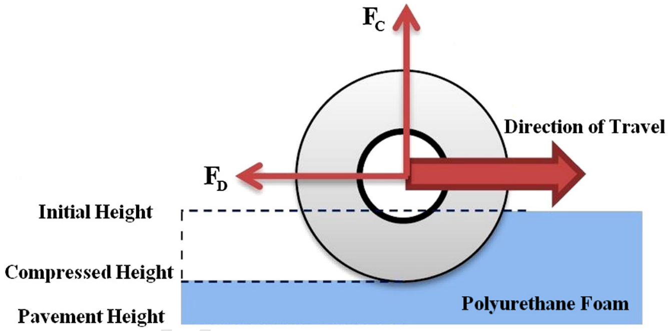

Fig. 1. Schematic illustration of aircraft arresting system.

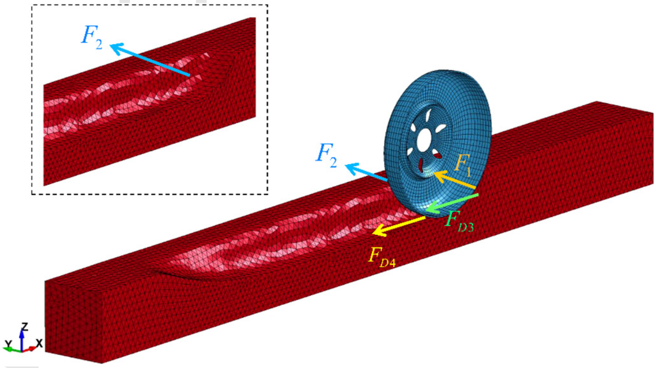

Fig. 2. Diagram of component forces for the resistance.

2. Analytical model of arresting problem

The aircraft arresting problem involves the coupling interaction between the arrestor bed and the aircraft wheel. When the aircraft enters the arrestor bed, the wheels sink into the polyurethane foam, and the foam material exerts resistance on the wheels in turn. As a result, the wheel decelerates to an eventual stop in security to protect the passengers and aircraft structures from damage.

To study the arresting performance of the polyurethane foam arresting system, an analytical model is presented, aiming at evaluating the loads exerted on the aircraft wheels by the arresting material, which can help to forecast the movement of the aircraft wheel. When an aircraft wheel crushes into the polyurethane foam, it compresses the arresting materials until a densification state comes into being, meaning that the interaction load reaches the compressive strength of the polyurethane foam. Fig. 1 illustrates the aircraft wheel rolling through the polyurethane foam, where F_C is the vertical force exerted on the aircraft wheel by the polyurethane foam; F_D is the total resistance opposite to the motion direction of the aircraft, consisting of the crushing force F_{D1}, the tearing force F_{D2}, the adhesive force F_{D3}, and the friction force F_{D4} as described in Fig. 2. It's worth noting that F_{D1} and F_{D2} are the horizontal component of F_1 and F_2, respectively.

2.1. Crushing force

When a wheel enters the polyurethane foam arresting system, it sinks into the arrestor bed under the action of gravity, and the foam will collapse, resulting in a rut with certain depth and width. It has been verified that deformation of the aircraft wheel is negligible comparing with that of the arresting material, hence it is reasonable to regard the tire as a rigid body. Fig. 3 shows the force diagram of an aircraft wheel rolling in polyurethane foam, where α is the corresponding central angle of the contact arc segment; h_0 is the initial depth of polyurethane foam; h_1 is eventual height of polyurethane foam after densification; R is the radius of the

Please cite this article in press as: X.F. Yang et al., A new theoretical model of aircraft arresting system based on polymeric foam material, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.03.019