

Phenomena of Foamed Concrete under Rolling of Aircraft Wheels

Chun-shui JIANG, Hong-yu YAO, Xian-bo XIAO¹, Xiang-jun KONG, Ya-jie SHI

China Academy of Civil Aviation Science and Technology,
Xibahe Beili #24, Chaoyang District, Beijing, 100028, China

Abstract. Engineered Material Arresting System (EMAS) is an effective technique to reduce hazards associated with aircraft overrunning runway. In order to ascertain phenomena of the foamed concrete used for EMAS under rolling of aircraft wheel, a specially designed experimental setup was built which employed Boeing 737 aircraft wheels bearing actual vertical loads to roll through the foamed concrete. A number of experiments were conducted upon this setup. It is discovered that the wheel rolls the concrete in a pure rolling manner and crushes the concrete downwards, instead of crushing it forward, as long as the concrete is not higher than the wheel axle. The concrete is compressed into powder in-situ by the wheel and then is brought to bottom of the wheel. The powder under the wheel is loose and thus is not able to sustain wheel braking. It is also found that after being rolled by the wheel the concrete exhibits either of two states, i.e. either ‘crushed through’ whole thickness of the concrete or ‘crushed halfway’, depending on combination of strength of the concrete, thickness of the concrete, vertical load the wheel carries, tire dimension and tire pressure. A new EMAS design concept is developed that if an EMAS design results in the ‘crushed through’ state for the main gears while the ‘crushed halfway’ state for the nose gear, the arresting bed would be optimal to accommodate the large difference in strength between the nose gear and the main gear of an aircraft.

1. Introduction

Aircraft overrunning runway is one of the major threats to aviation safety. Engineered Material Arresting System (hereinafter abbreviated as EMAS) has been proven to be an effective technique to address this issue [1]. EMAS comprises foamed concrete blocks with thicknesses of hundreds of millimeters that are arranged on the ground beyond runway end. Once an aircraft overruns runway and then runs into EMAS, the foamed concrete will get crushed as rolled by the aircraft wheels. In this way, drag forces are generated to the aircraft landing gears, and the aircraft is therefore slowed down gradually and eventually is stopped in the EMAS bed for safety. Studies on EMAS mainly focus on the analysis of the drag forces imposed on the aircraft landing gears as well as the dynamic simulation for arresting process. Wang et al. [2] and Cook et al. [3,4] assumed that the drag force landing gear subjected to is determined by the product of forward project area of the wheel portion immersed in the foam material and crush strength of the foam material, which is called ‘horizontal push model’ in this paper. Li et al. [5] assumed that the drag force suffered by wheel is similar to that when the wheel moves in dry snow. DeLoach et al. [6] have drawn a conclusion that the drag force is related to the

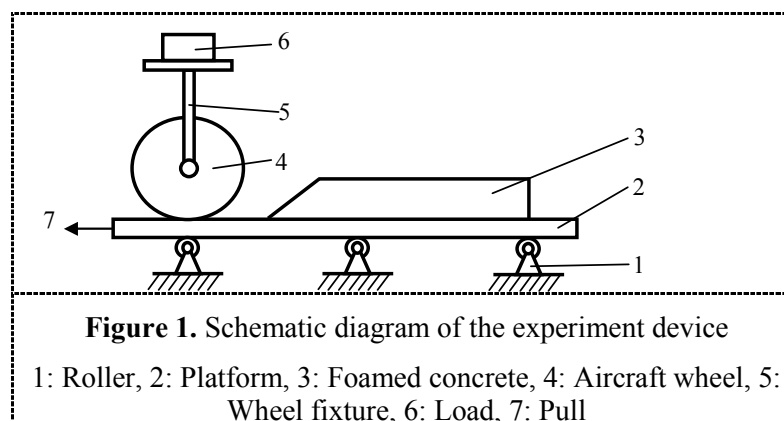
¹ Xianbo.xiao@gmail.com



speed of aircraft or the second power of the speed on assumption that the arresting process is similar to the movement of an object in a fluid. Heymsfield et al. [7] believed that after an aircraft's bogie landing gear runs into the arresting bed, the rear wheel advances in the rut created by the front wheel, thus no drag force is created on the rear wheel. Physical basis of these analysis and simulations mostly rely on the experimental results in terms of material mechanics, without experimental results under actual conditions, i.e. under rolling of aircraft wheels. In seeking for the experimental results under actual conditions, the greatest fidelity could be undoubtedly achieved by conducting a test of taxiing a real aircraft into an arresting bed, but the cost and the safety risks are great and few test parameters are adjustable. Simulated experiments in laboratory are of fidelity between the real aircraft test and the material mechanics experiment, while design and construction of the experimental device are still problems to be solved. A device for simulation was described [8]. To be exact, a small sized aluminum cylinder simulating aircraft wheel of reduced scales was hung up and then ploughed through foamed concrete in the way of pendulum. In this paper, this process is regarded distinct from the situation that an elastic pneumatic rubber tire rolls (might accompanied with sliding) in the foam. DeLoach et al [6] also launched an interesting EMAS experiment by using a runway friction coefficient measurement vehicle with a speed of up to tens of kilometers per hour, but the wheel in the experiment was not a real aircraft wheel. Furthermore, because of small size of the wheel, the wheel was managed to penetrate the foam by only about 100 mm so as to avoid the interference between the wheel fixture and the foam material to assure correct drag measurement. So, the experiment configuration made a considerable difference from the actual conditions. In order to clarify phenomena of the material under rolling of aircraft wheels and to provide a physical basis for mathematical simulation of the arresting process, a special experimental device was designed and built. A number of experiments were carried out upon the device and some interesting phenomena were observed.

2. Experimental Device and Methods

Aircraft Experimental device is shown in Figure 1 [9]. Platform (2) was free to move in its longitudinal direction on the support of rollers (1) and was constrained by lateral rollers from moving in its lateral direction. Foamed concrete blocks (3) were arranged in line on the platform and constrained with baffles on both sides in the rear end. Front of the concrete had been sawed into ramp to eliminate the impact when the wheel rushes into the material. Real aircraft wheel (4) can rotate freely on wheel fixture (5). Load (6) was stacked on top of wheel fixture to subject the wheel to a practical shared weight of an aircraft. The wheel fixture was free to move vertically while held laterally by lateral rollers.



Experiments started with pulling (7) the platform at a constant speed, which makes the wheel roll into the foam via the ramp. Sensors recorded with time forces in three-direction exerted on the wheel fixture, vertical displacement of the wheel fixture, rotation speed of the wheel, speed of the platform, pulling force to the platform and other parameters involved. The device employed main wheel and

nose wheel respectively, of a Boeing 737-300 aircraft and adopted static loads on each wheel of this type of aircraft under various payload conditions. Notably, deviation of the experiment conditions from the actual situation lies in lower wheel speed (250 mm/s), wheel fixture lacking damping mechanism of aircraft landing gear and the interference of the wheel fixture with foam material when the wheel penetrated the material deeply.

In order to clarify phenomena around rear wheel of a bogie landing gear rolling in arresting bed, rolling-twice experiment was designed. As the name implies, after wheel rolled arresting bed for the first time, the wheel was driven to roll the as-rolled bed once again. The same aircraft wheel advanced in the rut produced in the first rolling, which is equivalent to the effect that the rear wheel of bogie landing gear rolls the arresting bed.

Foamed concrete used in the experiments was made of mixture of cement, fly ash, fiber, vesicant and water. Thicknesses of the concrete ranged from 240 to 600mm. Most pores in the material are enclosed with diameters of 1 ~ 2 mm. Porosity of the material is around 75% and density 200 Kg/m³. The microstructures and mechanical properties of the material have been reported [10].

3. Experimental Results

3.1. Rolling or sliding

Under a variety of experimental conditions, it is recorded by the sensors that linear speed of the platform accords with rotational speed of the wheel, indicating that the wheel rolls material in a pure rolling manner.

3.2. Movement of the foamed material

Figure 2 presents appearance of the foamed material after the experiment. Almost all affected foam material was compressed in-situ into the rut with little scattered, at least under conditions of this experiment (aircraft wheel speed of 250 mm/s and material thickness of 310 mm). As the material thickness increases, the pushing-forward effect of wheel on the material increases, so a small amount of material was pushed aside, even though the proportion was still small (see below).

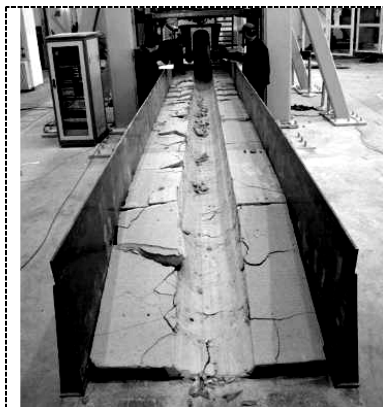


Figure 2. Foamed concrete appearance after the experiment

3.3. Pushing forward to the foam material by aircraft wheel

Figure 3 shows the appearance of foam material in front of wheel in experiment. The material was not pushed away, but instead, was compressed into the bottom of the wheel. Cracking of material in front of wheel and deformation of the wood board used as stopper indicate the presence of a forward pushing exerted by the wheel. Longitudinal section of this part of material is shown in Figure 4. The left part is uncrushed foam material while the right part presents indentation contour of wheel, and the

middle is material powder made by compression. Crushing of material is characterized by severe localization. The material powder in front of wheel gets thicker and thicker from top down, and basically non-existence at the top. This feature does not correspond to the 'horizontal push model' [2-4] where the crushed material amount in front of wheel (i.e. the thickness of powder) should be independent of the height. This indicates that the material crushing is mainly attributed to vertical or diagonal compression. Since the wheel front is in form of arc, the reaction force of the material compression could be decomposed into a component of horizontal drag force.

The increased material thickness will strengthen the pushing forward effect of aircraft wheel to the material. When the material thickness (600 mm) slightly surpasses the height of wheel axle (the test main wheel radius is 515 mm), surface layer of material was pushed away in the rolling (Figure 5). After the experiment, longitudinal section of the material in front of wheel (Figure 6) showed that the bulk of material was still compressed into powder by the wheel. Hence, under conditions that material is slightly higher than the wheel axle, the compression process is essentially that materials get crushed into powders by rotating wheel, and only material portion above the wheel axle is appropriate for the horizontal push model. Additionally, appearance of rut after wheel rolling shows that, for the material slightly higher than the wheel axle, two shallow grooves beside the deep wheel rut, on the top surface of the material, were created by the wheel fixture's scratching across the material, and the cross section of the shallow grooves corresponds to the projection of the wheel fixture.



Figure 3. Foamed concrete in front of the wheel

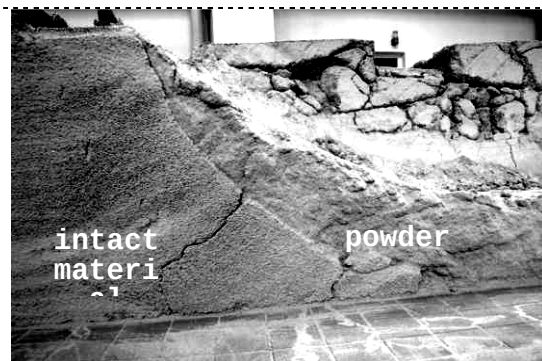


Figure 4. Longitudinal section of foamed concrete in Fig. 3



Figure 5. Surface material portion was pushed away when the material is higher than wheel axle

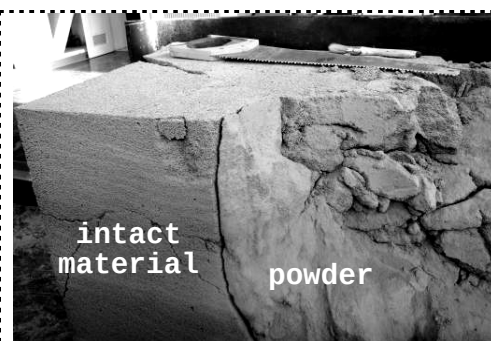


Figure 6. Longitudinal section of foamed concrete in Fig. 5

3.4. 'Crushed through' and 'crushed halfway'

It was found that under certain combinations of material strength, material thickness, wheel size, tire pressure and vertical load, either 'crushed through' whole thickness of the concrete or just 'crushed halfway' may occur in the rolled foam material. Figure 7 shows cross-sections of two ruts, corresponding to 'crushed through' (left) and 'crushed halfway' (right) respectively, after rolling. The latter state is correlated to a small drag force and low material utilization efficiency. Drag force can be enhanced by increasing vertical load rather than thickening the material. Whereas the 'crushed through' state is just in the opposite rules.

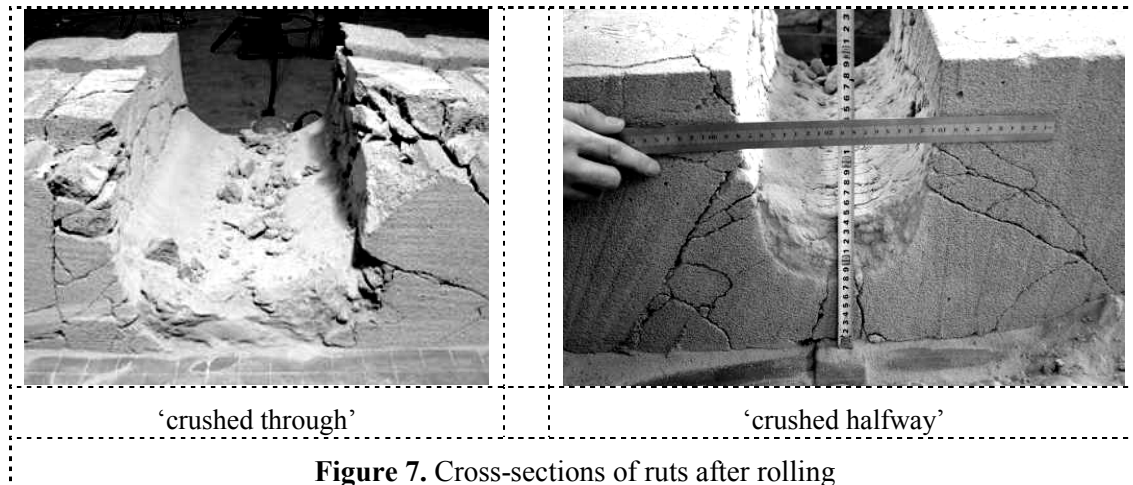


Figure 7. Cross-sections of ruts after rolling

3.5. Phenomena in the rolling-twice experiments

Compared with the first rolling, sinkage of wheel axle in the second rolling was increased by 26 mm, and the rut depth was increased by 18 mm, indicating that the material powder at bottom of the rut had been further compressed.

4. Discussions

The experiments showed that the wheels move in the foam materials in the form of pure rolling. Deposit of crushed material powder was observed beneath the wheel after experiment. It is impossible for the powder to bear the shear force generated from wheel braking due to its extremely low shear strength. Thus, although the standard design conditions for EMAS regulated by the Federal Aviation Administration (FAA) of the United States of America describe that friction coefficient equals 0.25 [11] when aircraft is braked, braking effectiveness can be achieved only in the setback section in front of arresting bed rather than in the bed. It has been verified with real aircraft tests that braking in arresting bed has no effect on drag force [12].

Some researchers [4, 6] reckon that during the arresting process, foamed concrete material is driven by wheels at high speeds in motion, and thus drag force expression should comprise the contribution of material kinetic energy $\frac{1}{2} \rho v^2$, where ρ is specific weight of the material and v the aircraft speed. Experimental results presented this paper show that almost all the affected foam material was compressed in-situ into the rut, so the kinetic energy of the material could be ignored. Speed effect on the drag force should be relevant to the loading speed effect on compression resistance of the material. The rotation of wheel results in different speeds at which each point at tire front compresses the material, which complicates the analysis of speed effect on drag force.

Crushing of foamed concrete material is characterized by severe localization and discontinuity, corresponding to the experimental results of material mechanics [10]. Therefore, the application of

continuum mechanics to the analysis of drag force will meet great challenge, and in deed some finite element analyses obtained unsatisfactory results [13, 14]. Some researchers [7] discretized a tire into radial springs, and discretized the foam material into a series of sliding friction pairs.

As limited by the clearance above ground of engine that is hung below wing, the typical thickness of material for EMAS system is usually about 600 mm. Together with blocking up effect of crushed powder on the wheel and the possible ‘crushed halfway’ state, the material will not be substantially higher than the axle of aircraft main wheel (for example, radius of Boeing 737-300 main wheel is 508 mm). In summary, it can be concluded that the producing mechanism of drag force is that the material gets crushed into powder in situ vertically or diagonally, instead of the horizontal push model reported [2-4]. And the material strength is relevant to the strength when it is further compressed into powder, rather than the strength when the material commences cracking. Meanwhile, drag force produced by surface material portion higher than the wheel axle or interfered by structures beside wheel (such as axle, landing gear piston, etc.), can be calculated following horizontal push model.

On the other hand, Boeing 737-300 aircraft has nose wheels in radius of 340 mm, much smaller than the typical material thickness. So, the wheel axle and gear piston of the nose gear will definitely interfere with the material severely. No matter whether horizontal push model or other models is used, it would be difficult to accurately calculate the drag force nose gear subjected to. Because the size and amount of nose wheels are both smaller than those of main wheels, the inaccuracy of the drag force of nose wheels would not affect the stopping distance substantially, but is a challenge to the structure safety evaluation of nose gear of low load capacity. One of the solutions to address this issue is to reduce the material thickness, but this is always impeded by the demands for large drag force on main gear. Fortunately, it is worthy of trying to apply combination of the two states of ‘crushed through’ and ‘crushed halfway’ novelly discovered in this paper to solve the problem. If the ‘crushed halfway’ state occurs with nose gear while the ‘crushed through’ state occurs with main gear respectively through deliberate design, the structure safety and accuracy of drag force calculation of nose gear will be ensured due to the small immersion depth and resultant small drag force. Moreover, the main gear with a large load capacity will exert a large drag force adequately with the help of great immersion depth, and drag force calculation accuracy will be improved because of the high axle of aircraft wheel. In this way, an arresting bed can be optimized to accommodate different characteristics of nose and main gear.

The rolling-twice experiment results show that the rear wheel of bogie gear still compressed the material powder effectively to a small extent, which produces a small amount of drag force. Because rear wheel in the rut lacked supporting material at its front edge, and then entire vertical load was transferred to the material powder under bottom of wheel, the powder would be further compressed. It can be speculated that if the ‘crushed halfway’ state is with front wheel, the drag force rear wheel subjected to will increase.

5. Conclusions

Experiments of real aircraft wheel rolling through the foamed concrete were conducted upon a specially designed and built device. Some interesting phenomena of the material under rolling of the wheels were discovered, which can lend a physical basis for drag force analysis and mathematical simulation of the arresting process. The main conclusions can be summarized as follows:

- When the foam material is not higher than wheel axle, the wheel compresses the material in a pure rolling manner rather than compresses horizontally. The foam is compressed in-situ into powder and brought down to the bottom of wheel, with no kinetic energy endowed. Moreover, the shear strength of the powder pile is not enough to sustain wheel braking.
- Crushing of the foam material exhibits severe localization and discontinuity under compression of aircraft wheels.

- The material portion above the wheel axle and that interfered with structures besides the tire is pushed forward, appropriate for horizontal push model.
- Under certain combinations of material strength, material thickness, tire size, tire pressure and vertical load, either ‘crushed through’ whole thickness of the concrete or ‘crushed halfway’ may occur in the foam material after rolling. An optimized arresting bed could be designed by satisfying at the same time the distinct characteristics of both nose gear and main gear of an aircraft, with a reasonable exploitation of these two states.
- A small amount of drag force is generated on rear wheel of a bogie gear. And if ‘crushed halfway’ state is with front wheel of a bogie gear, the drag force exerted on the rear wheel would be further increased.

6. Acknowledgements

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