Improving safety of runway overrun through foamed concrete aircraft arresting system: an experimental study

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Aircraft may overrun the ends of runways, sometimes with disastrous consequences. Because of the capability of high energy absorption, a foamed concrete arresting system can be employed to safely decelerate and stop the overrunning aircraft. In order to evaluate the performance of the foamed concrete arrestor system, a full-scale arresting test with an instrumented Boeing 737-300 aircraft has been conducted. The test bed of 140 m long by 15 m wide and 0.32 m deep was constructed to demonstrate the effectiveness of safely stopping the Boeing 737 aircraft entering the bed at 40 knots. In the test, the deceleration experienced by the aircraft was recorded in addition to its instantaneous speed, dynamic responses of the landing gear, and rut depths. Then, the validity of the analytical prediction model developed in previous study was examined by means of the full-scale test data. The results of the full-scale test show that the foamed concrete arrestor could provide an effective deceleration without exceeding the design allowable stresses on the landing gear during arrest process. Using the analytical model, the sensitivity of aircraft stopping distance was evaluated as a function of arrestor material compressive strength, aircraft weight, and arrestor-bed thickness. Based on these investigations, it is recommended that the foamed concrete system can be used as an alternative civil aircraft arresting system to improve the runway safety.

Keywords: runway safety; foamed concrete; energy absorption; full-scale test; arrestor system

1. Introduction

Runway overruns present a threat to the safety of passengers, and it may also result in costly damage to aircraft. Improvement of the runway safety level to aircrafts has been the subject of research worldwide [2,31]. Regulations on this subject require obstacle-free areas beyond the runway threshold with particular characteristics and lengths. For example, the International Civil Aviation Organization requires a runway safety area with a longitudinal dimension of 300 m (984 ft), composed of runway strip and runway end safety area [1]. However, many airports, which were constructed before the safety area become a standard, are unable to adapt the size of these areas to obtain the required levels of safety: the presence of natural obstacles (rivers, basins) or manmade constructions (roads, railways, and buildings) do not allow the required extension. Consequently, it is necessary to develop means to stop an overrunning aircraft in less than the standard length of runway end safety area.

As we know, a limited number of methods are available for preventing such aircraft overruns. The methods include active systems, such as arresting cables and nets, and passive systems, such as soft ground arresting systems. In general, the active systems are commonly used on aircraft carriers and at military airfields. For the cable-based arrestors, the cables stretched laterally across the landing surface and attached to a high energy dissipation device through tapes are used to halt effectively the aircraft safely over a short distance [21]. Obviously, in the cable-based arresting systems, the necessary hook device to engage the cable is needed and the structural airframe strengthening is required. They are not economically practical for use on commercial civilian aircraft. Also, there are some issues that complicate the use of the net-based arrestors for civil aircraft. If an aircraft passes through the net-based arrestor, the nets tend to envelope the fuselage of the aircraft. This result is problematic for civil aircraft because it could hinder emergency egress of occupants. In addition, the net-based engagement of civil aircraft would subject the leading edge wing flaps to loads for which they were not designed. The flaps could either become entangled or suffer damage as a result. Consequently, both the cable-based arrestors and the net-based arrestors are not appropriated for civil aircrafts. In such case, installing a soft ground arresting system in the safety area of the runway can be a perfect solution [26].

The soft ground arresting system is a passive arrestor, employing soft materials to absorb the kinetic energy of the overrun aircraft. The retarding force for decelerating and stopping the aircraft is derived from the drag on the
aircraft wheels as they travel through the material. Effectiveness of one such soft ground arresting system has been first studied by British Royal Aircraft Establishment since the 1960s [3]. Then, the researchers investigated in detail the performance of soft ground arresters for aircraft [4,5,19,27]. They have studied the effectiveness of gravel, aerated concrete, sintered fuel ash pellets, and urea–formaldehyde as arresting materials, and also the design of arrestors for use with different types of aircraft. In the 1980s, civil arrestor research examined the materials, such as clay, sand, water, and gravel, to develop a soft ground, as studied by Cook [9]. He discussed the various reasons why these materials were not appropriate for arresting overrunning aircraft. For sand clay materials, the mechanical behaviour could not be consistently predicted due to their sensitivity to moisture content. Water could be shown to perform well mechanically at speed less than 50 knots, but with the additional disadvantages of attracting water fowl and freezing in the winter. For gravel beds, the sprayed particles caused by the aircraft tire were identified as a potential engine ingestion hazard. Subsequent research focused on crushable materials, such as phenolic foam and cellular cement. White and Agrawal [32] pointed out that the advantages of the crushable foam materials are the predictability of the drag force imparted on the landing gear and the stability of the mechanical properties over a broad range of temperature. Thus, cellular cement became the candidate material due to its negligible crushing-rebounding behaviour, durability, and chemically inert composition.

Except for the selection of arresting materials, the evaluation methods for the passive arresting systems are composed of (1) numerical analysis and (2) experimental verification. The numerical analysis focuses on determining the stopping capability of the arresting materials and predicting the dynamic response of overrunning aircraft. Initially, predictive codes were developed for modelling of taxi, takeoff, and landing on soil landing strips [13]. Based on the codes, ARRESTOR was developed by Cook et al. [11] for the Federal Aviation Agency (FAA) to estimate the stopping distances for different types of aircraft and characteristics of arrestor beds. Further, Heymsfield et al. [22–25] used the ARRESTOR code to perform sensitivity analyses for various parameters and optimise the low density concrete behaviour for soft ground arrestor systems. Recently, the authors [33] proposed an analytical aircraft model with the consideration of the interactions between the landing gear and the new foamed concrete arrestor and studied the influence of critical parameters including aircraft weight, material compressive strength, and arrestor system configuration on the optimal design of different foamed concrete arrestor systems. The analytical model coded using MATLAB is capable of predicting aircraft gear loads, deceleration, and stopping distance within the foamed arrestor system. The analytical result was compared for the stopping distance of aircraft B727 with that of the FAA’s arrestor model prediction showed very good agreement. However, no full-scale aircraft arresting test verifications were provided in the paper.

In fact, actual experiments have played important roles throughout the development of these passive arresting technologies. The full-scale tests involving actual aircraft engagement with prototype arrestor installations must be conducted to evaluate the effectiveness of the arresting system prior to application. In an early study on urea–formaldehyde foamed arrestor, the Royal Aircraft Establishment conducted trials with a Comet 38 aircraft in test beds of various depth, length, and density [20]. The report indicates that the deceleration of aircraft in the arresting bed is independent of entry speed, in which both the leading and trailing wheels provide significant drag force that can be predicted. By the 1990s, the FAA, recognising the potential safety benefits of these passive arrestor systems, decided to conduct various tests [10,32]. Two full-scale tests at entry speeds of 92.6 and 111.12 km/h (50 and 60 knots) were performed: the aircraft was arrested, respectively, in 128 and 165 m. These results showed that an expected forward thrust with an increase of stopping distance was produced: 27.45 m more than their mathematical model predictions.

A type of civil aircraft arresting system, named Engineered Material Arresting System (EMAS), was eventually developed by the Engineered Arresting Systems Cooperative in collaboration with the FAA under a cooperative research and development agreement [6]. To date, a number of airports in the United States have installed EMAS. The effectiveness of the systems has been proven by safety stopping events of overrun aircraft, in some cases characterised by high maximum takeoff weight [14]. However, various issues and concerns regarding the current EMAS technology exit. One of the issues is that the costs associated with acquiring the EMAS are high [29]. In addition, the long-term durability of the system over time is unknown, and no tests are currently available that can verify that the installed EMAS maintain their original characteristics. A new arrestor material that offers better performance, lower cost, and higher durability is needed to be developed. With this goal, an alternative foamed concrete arrestor which could be used in a similar manner as the current cellular cement design but with potentially improved durability is presented in this study. To evaluate the arresting performance of the new foamed concrete arrestor system, a full-scale aircraft arresting test is carried out. Additionally, the validity of an analytical prediction model (APM) is examined by the full-scale test to predict arresting effectiveness for a wide range of aircraft. The research is organised as follows: first, the description of full-scale arrestor test program is given in Section 2; the experimental observations and results of the actual aircraft arresting trial are described in Section
3; then, the comparisons between testing results and APM simulations are reported in Section 4, followed by the discussions and the sensitivity analysis of aircraft stopping distance in Section 5; finally, concluding remarks are given in Section 6.

2. Full-scale arrestor test program

In order to evaluate the foamed concrete arresting system and the availability of APM for theoretically predicting the results of arresting event, an experimental verification using a full-scale test is needed. A full-scale arrestor test was conducted at Chinese Tangshan Airport, in October 2012. Figure 1 shows the test aircraft, a Boeing 737-300, on the test runway. The test programme includes the indentation tests on the arrestor material, design, and construction of testing arrestor bed, installation of instrumentation (e.g., the global positioning system (GPS), event synchronisers, and strain gauges) and data collection, and the manipulation of aircraft. Detailed descriptions of this test program are given in the following.

2.1. Arrestor material properties

To find a suitable arrestor material, several properties (e.g., compressive strength, maximum compression) must be considered on the basis of the EMAS design requirements in Advisory Circular 150/5220-22A [15]. Combining adequate compression resistance with higher durability, a kind of foamed concrete with nominal density of 305.2 kg/m³ was selected as the arrestor material in this study. This new foamed concrete was made from a mixture, which contained Portland cement, perlite, foaming agent, super-plasticizer, and water. The mixture proportions of the foaming concrete are listed in Table 1. For ease of installing the arrestor bed on the test runway, the physical dimensions of the foam panel were prepared with 1.0 by 1.0 m square in the surface and 0.32 m in its thickness. The 0.32 m depth arrestor bed was used to reduce the potential for damage to the aircraft in the event that the analytical results were erroneous. The produced foam panels were cured in a humid workshop for 28 days. After curing, laboratory tests were performed using cubical specimens (300 \( \times \) 300 \( \times \) 150 mm) originating from the foam panel to determine the compressive behaviour of the foamed concrete material. The testing effort for the specimens was quasi-static indentation tests using three flat-nose circular cylindrical indenters of different diameters of 60, 80, and 100 mm. For each indenter, three tests were carried out. The indenters were pushed to about 130 mm depth into the foamed concrete blocks, as shown in Figure 2. To minimise the friction effect, the indenters were lubricated with lubricant spray. Tests were performed on a standard 20 kN servo-hydraulic testing machine in displacement control at room temperature and a crosshead speed of 0.5 mm/min. The load–displacement curves were recorded.

Typically, the load–displacement curves of three foamed concrete specimens with 60 mm indenter are shown in Figure 3. The figure shows that each tested foamed concrete specimen exhibits a characteristic crushable foam load history, i.e., it rises to a plateau (crushing) load value and then maintains almost a constant value until the foamed concrete is fully compacted, which is

<table>
<thead>
<tr>
<th>Component</th>
<th>Mix proportion (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>285</td>
</tr>
<tr>
<td>Expanded perlite</td>
<td>25</td>
</tr>
<tr>
<td>Foaming agent</td>
<td>16</td>
</tr>
<tr>
<td>Super-plasticiser</td>
<td>1.2</td>
</tr>
<tr>
<td>Water</td>
<td>165.8</td>
</tr>
</tbody>
</table>

Figure 1. Boeing 737-300 aircraft for full-scale test.
followed by a significant increase of the force representing the densification. It can also be observed that the three tested specimens exhibit slight variations in indentation responses due to the material heterogeneity. Similarly, the load-indentation characteristics for 80 and 100 mm indenters were obtained. It should be noted that the indentation load in Figure 3 is due to a combination of the crush stress of the material $\sigma_c$ (area under the indenters) and the tearing energy per unit area of the material $\gamma$ (circumferential edge of the indenters). Based on the method described in [17,33], the crush stress $\sigma_c$ and the tearing energy per unit area $\gamma = 4.627 \text{kJ/m}^2$ could be extracted from the indentation load. For convenience, the compressive-strength behaviour of a foamed concrete is represented by a power law relation without locking strain in this study. Therefore, this compressive-strength behaviour can be completely determined by the initial crushing stress $\sigma_0$, the power index $n$, and the coefficient $k$, i.e.,

$$\sigma_c = \sigma_0 + k \varepsilon^n$$

where $\varepsilon$ denotes the compressive strain of the foamed concrete. Using nonlinear fitting method, the mean compressive-strength behaviour for the three foamed concrete specimens is shown in Figure 4. From the figure, the three parameters in Equation (1) are easily identified: $\sigma_0 = 0.374 \text{ MPa}$, $n = 5.7$, and $k = 2.09 \text{ MPa}$. In addition, the mean compressive-strength behaviour is varied by $\pm 10\%$ to study the influence of the heterogeneity on material strength, as shown in Figure 4. In brief, the parameters for the foamed concrete would be used to calculate the aircraft landing gear loads in the arrestor bed by the APM in Section 4.

2.2. Arrestor bed

The full-scale test program was planned to taxi the instrumented Boeing 737-300 aircraft and bring the aircraft to a complete and safe stop within a foamed concrete bed. Based on the FAA’s survey of accidents, approximately 90% of the overruns involved an aircraft with a 70 knots runway exit velocity or less [15]. To ensure the safety of the full-scale test program, the moderate aircraft entry speed of 40 knots (20.58 m/s) was adopted in this study.

In design of test bed, the margin of safety for the bed length was sufficient to avoid the potential risk that the aircraft went beyond the length of test bed. With the material strength and the margin of safety as specified, the test arrestor bed was designed to be 140 m long and 15 m wide using the previously developed APM. The general layout of the arrestor bed configuration is shown in Figure 5(a). At the arrestor bed start, the bed started with a 0.05 m thickness and increased to 0.32 m over 3 m material length, forming an approach ramp. A constant bed
thickness with 0.32 m was used over the next 137 m. The approach ramp was constructed to assure that excessive gear loads would not be imposed on the aircraft. Consistent with the design of the bed size, the actual arrestor test bed was installed on a taxiway at Tangshan Airport in China. The foam panels were arranged in 15 row, 140 blocks long and one block in depth, for a total of 2100 blocks. These blocks were adhered to one another. Figure 5(b) shows that the test bed was assembled by multiple precast foamed concrete panels. The bottom layer of foam was bonded to the taxiway with epoxy adhesive JN-LX to prevent the panels from relative sliding between two contact surfaces during the test runs. Adjacent panels were also fastened together with latex adhesive. Upon completion of construction of the test bed, it was covered by plastic sheeting for protection from damage until testing was initiated.

2.3. Testing aircraft and instrumentation

The full-scale test was carried out for a Boeing 737-300 with aircraft weight of approximately 38,500 kg. The 737 was instrumented with the measurement equipments consisting of a GPS, strain gauges, event synchronisers, signal processors, and a data collection system. The result of measurement provided by the instrumented aircraft was adopted to evaluate the arresting capacity of the foamed concrete bed, and validate or modify the APM which theoretically predicts the performance of the arrestor system. The details of the experimental set-up for full-scale test are described as follows.

The GPS was fitted axially on the floor of the passenger cabin above the centre of gravity (CG) position to obtain faithfully the transient aircraft ground speed in travelling direction. The adopted acquisition frequency of the GPS was 40 Hz. Based on the Kalman filter method, the GPS accuracy was 0.1 m/s. The acceleration at the CG was obtained by differentiating the velocity with respect to time.

Strain gauges were used to capture the dynamic response of landing gear during arrest. Based on the fundamentals of design and analysis of the landing gear [12] and the Federal Aviation Regulations Part 25 [16], several important locations were determined for the strain measurements: N1, N2, N3 for the nose gear, MR1, MR2, MR3 for the right main gear and ML1, ML2, ML3 for the left main gear, depicted in Figure 6. It is observed that the datum points of nose gear N1, N2 and N3 were located at the shock strut (Figure 6(a)), right drag strut, and left drag strut (Figure 6(b)), respectively. For the right main gear, the strain gauges at MR1, MR2, MR3 could be used to capture the dynamic strain of the shock strut, drag strut, and lower side strut, respectively, as illustrated in Figures 6(c) and 6(d). Similarly, the strain gauges at ML1, ML2, and ML3 for the left main gear could be obtained. After these datum points had been marked on the struts, the strain gauges of 16 mm were attached with a 100% epoxy solid adhesive, which, after the application of a suitable pressure, had to be cured inside an oven at approximately 70°C for about 2 h. Moreover, all strain gauges were positioned along length direction (long side of each strut). They were connected to the simultaneous bridge modules to form Wheatstone half bridges. Bridge modules are controlled by an embedded real-time controller, which was connected to a personal computer (PC). The data acquisition system in this measurement set-up was adopted 2000 Hz sampling rate per channel (under the condition of nine channels working simultaneously). Thus, the waveform of the dynamic response at the locations of landing gear could be recorded at the same time during the arrest.
In addition, a high speed camera with a resolution of 1024 × 1024 pixels (MS55K, Mega Speed Corp., Manitoba, Canada) was situated 80 m apart, on one lateral side of the test bed, as shown in Figure 5(a). Using this camera, the arrest was filmed at 300 frames per second. To better visualise the travelling characteristics of the testing aircraft, the white and black reference poles were placed on one side of the test bed, as shown in Figure 5(b). Points located at the first window in the aircraft (P₁), the end window in the aircraft (P₂), and the approximate centre of mass of the aircraft (P₀) were digitised using custom software written in Matlab (release 11). From this, the instantaneous position of P₀ was obtained. Meanwhile, we obtained the instantaneous angle θ' between the line linking P₁ and P₂ and the ground. Then, the instantaneous velocity (V), acceleration (a), and pitch angle (θ) at any time (t) were calculated as

\[ V(t) = \frac{P₀(t + \Delta t) - P₀(t - \Delta t)}{2\Delta t} \]  
\[ a(t) = \frac{P₀(t + \Delta t) - 2P₀(t) + P₀(t - \Delta t)}{\Delta t^2} \]  
\[ \theta(t) = \tan^{-1} \left( \frac{P₁(t) - P₂(t)}{P₁(0) - P₂(0)} \right) \]

where \( \Delta t = 1/300 \) s is the sampling time step.

2.4. Full-scale test procedure

The procedure for conducting the full-scale test may be briefly divided into three phases, i.e., (1) testing preparation period which included the discussion of testing plan, the construction of testing bed, and the installation of instrumentation, (2) fulfilment of the full-scale test, and (3) post-test stage composed of final cleanup and other tasks.

Once all pre-tasks were accomplished, the aircraft was then taxied to the pre-designated starting point. The aircraft was accelerated to the test speed. No flaps or spoilers were deployed for this test. The aircraft was steered along the centreline of the arrestor bed. Just prior to the aircraft invading the arrestor bed, the power of engine was shut down that the influence of thrust on the longitudinal acceleration would be minimised. The data collection system was activated at the beginning of the run and remained on while the aircraft was brought to a halt in the foamed concrete bed.

After the aircraft was completely arrested, the foamed concrete bed was inspected, photographs were taken, and the rut depths for each wheel track were measured and recorded. The aircraft was then inspected for possible damage to the landing gear based on the values of measured maximum strain. Finally, all crushing foam materials and the residual foamed concrete bed were removed from the test runway.

3. Full-scale arresting test results

3.1. General observations

The aircraft was accelerated with all engines to approximately 40 knots and the power was cut-off just before entering the test bed. Figure 7 shows the sequence of images for the full-scale test obtained with a high speed camera. Figure 7(a) depicts the time when testing aircraft was taxiing to the starting point of the test bed, set to be 0 s. At this point, the aircraft entered into the test bed with 39.4 knots (20.27 m/s), measured by the GPS. At the beginning of the arrest, only the wheels of nose landing gear sank into the foamed concrete bed due to the distance between the nose gear and main gear. After 0.384 s, the
wheels of main gear began to roll through the foam bed, as shown in Figure 7(b). When the main gear completely entered into the test bed, a significant arresting effectiveness increase occurred. During this phase, a great number of crushing foam concrete particles emerged from the test bed, as illustrated in Figures 7(d) and 7(e). It is suggested that the phenomenon was caused by the adhesive resistance of arrestor material, based on our previous paper [33]. Finally, the aircraft came to a complete stop at 60.91 m into the foam bed after 5.427 s, as shown in Figure 7(f). Overall, the aircraft successfully stopped after travelling 60.91 m in the test bed with a recorded entry speed of 39.4 knots. Figure 8 shows a photograph of the arrested Boeing 737 aircraft. After completely arrested, the aircraft was inspected. The visual inspection indicated no visible damage to the aircraft engines and airframe.

The test bed was then inspected, and it was evident that deep rutting had occurred. The rut depths (percentage full depth) were measured along the aircraft travelling direction at 5 m intervals and the results are given in Figure 9. It is observed that the rut depths of nose gear and main gear exhibit an oscillating behaviour due to the aircraft’s pitch rotation. Additionally, we noted that the nose landing gear shows greater variability in rut depth than that of landing main gear, as shown in Figure 9. It is believed that the effect was caused by the larger distance from the nose gear strut to the aircraft CG. Consequently, the forward pitching motion of the travelling Boeing 737 increased the vertical load on the nose gear when overrun through the foamed concrete arrestor bed. This in turn drove the nose wheels deeper into the foamed test bed.

3.2. Dynamic strain of the landing gear

The dynamic strains at the pre-determined locations of the landing gear were recorded during arrest. Figure 10 shows their strain—time graph, including the nose gear (a, b, c), right main gear (d, e, f), and the left main gear (g, h, i). In this figure, the grey bars indicate the duration of dynamic response at every location for the landing gear. It is found that the duration of dynamic strain response for nose gear is 0.384 s longer than the duration for main gear because of the distance between them. Combining the strain—time graph with the layouts of strain measurements (Figure 6), it is observed from Figure 10 that the strain at locations of the shock strut (N1, MR1, ML1), drag strut (N2, N3, MR2, ML2), and the lower side strut (MR3, ML3) are negative, positive, and alternating, respectively. This means that the stress at locations of the shock strut, drag strut, and lower side strut were in compression state, stretched state, and alternating state during arrest, respectively. Considering the strain—time curves of the right (Figures 10(d)–10(f)) and left main gears (Figures 10(g)–10(h)), it indicates that the profiles of these curves exhibit perfectly symmetrical characteristics for the right and left main gears.

Furthermore, significant differences are seen in the strain amplitude among the measuring locations of landing gear during the arrest, as shown in Figure 10. As we know, larger loading will produce higher strain amplitude and may cause more damage. The strain amplitude of the landing gear is highly dependent on the drag force acting on the landing gear. Therefore, the strain amplitude should be a main factor to evaluate the performance of the landing gear of arrested aircraft. Hence, the maximum strain amplitudes of test locations are listed in Table 2. It is found that the highest strain amplitude could reach 0.008152, at the drag strut of the nose gear (N2). Generally, the drag strut is made of alloy steel with high strength [30]. The maximum strain of the drag strut was well below the allowable strain of the alloy steel, indicating that the drag loads produced by the arrestor materials remain below the design limits of landing gear.

Overall, the foamed concrete test bed can effectively decelerate the overrunning Boeing 737-300 aircraft to a
safe stop with no significant damage to the aircraft structure, i.e., landing gear, turbine engines, based on results and observations of the full-scale test. Thus, the foamed concrete arrestor presented by us can be used as an aircraft alternative arresting system. However, a primary limitation of this full-scale arresting experiment is the fact that only one type aircraft was tested in this study. Other aircraft parameters (weight, speed, etc.) may pose unique arresting behaviours that were not identified in this study. To extend the applications of the foamed concrete arresting system to other aircraft with the same landing gear configuration, it is necessary to investigate the validity of the analytical arrestor predictive model developed by the authors [33], based on the full-scale test.

4. Investigation on the validity of APM

In this section, the validity of the analytical predictive model is investigated using on the above full-scale arresting test data. The procedure for examining the mathematical model involves the predictive results pertinent to the measurements of the actual arresting test.

4.1. Analytical prediction model overview

In the following, a brief overview of the APM for a foamed concrete aircraft arresting system is given. In order to characterise the arresting capability of the foamed concrete, an interactive model between wheel and foamed concrete was developed by the authors [33]. When an aircraft wheel enters the foamed concrete bed, the wheel sinks into the arrestor materials and creates a rut of certain depth and width depending on the width of wheel and the supporting force on the wheel. For a given travelling direction, the wheel/foam interface illustrated in Figure 11 is one example of the model. In this figure, $F_D$ is the total drag force (in horizontal direction) between the tire of an aircraft and the arrestor materials, leading to the deceleration of the aircraft. $F_C$ is the overall vertical reaction force
applied by the foamed concrete on the aircraft tire. In detail, the total drag force consists of the horizontal component of the crush force \( F_{D1} \), the horizontal component of the tearing force \( F_{D2} \), the adhesive-resistant force \( F_{D3} \), and the equivalent friction force \( F_{D4} \). Similarly, the total vertical reaction force consists of the vertical component of the crush force \( F_{C1} \) and the vertical component of the tearing force \( F_{C2} \). Ignoring the strain-rate effect, the analytical formulæ for the four drag force are given as follows:

\[
F_{D1} = B R \sigma_0 [\cos \beta - \cos(\beta + \alpha)] + \frac{BkR^{n+1}}{(n+1)h_0^2} [\cos \beta - \cos(\beta + \alpha)]^{n+1},
\]

\[
F_{D2} = 2 \int_0^\alpha yR\sin(\beta + \phi)d\phi = 2yR[\cos \beta - \cos(\beta + \alpha)],
\]

\[
F_{D3} = \rho_0 BRV^2 \left( \frac{3}{8} + \frac{1}{8}h_0^2 [\sin(\beta + \alpha) - \sin(\beta) - \sin(\beta + \alpha)]^{n+1} \right),
\]

\[
F_{D4} = \mu F_C,
\]

\[
F_{C1} = B R \sigma_0 [\sin(\beta + \alpha) - \sin(\beta) + 2BR\sin(\beta)]
\]

\[
+ 2\frac{BkR^{n+1}}{h_0^n} - \int_0^\alpha [\cos(\beta + \phi) - \cos(\beta + \alpha)]^n \cos(\beta + \phi)d\phi,
\]

\[
F_{C2} = 2 \int_0^\alpha yR\cos(\beta + \phi)d\phi = 2yR[\sin(\beta + \alpha) - \sin(\beta)].
\]

In the above analytical formulæ (5)–(10), \( B \) is the width of aircraft tire, \( R \) is the radius of aircraft wheel, \( V \) is the aircraft instantaneous velocity, \( \rho_0 \) is the apparent density of the foamed concrete, \( h_0 \) is the initial depth of the arrestor bed, \( \mu \) is the equivalent friction coefficient, \( \alpha \) and \( \beta \) are shown in Figure 12. In the figure, the interface between the aircraft tire and the foamed concrete bed is divided into two segments, i.e., the arc segment and the tire footprint segment. The angle of the arc segment is \( \alpha \) and the footprint length is \( l \). According to the geometry of a tire rolling in foamed concrete arresting, the angle \( \beta \) is expressed as

\[
\beta = \arccos \left( \frac{R - \delta}{R} \right)
\]

where \( \delta \) is the vertical deflection of the aircraft tire, determined by tire-load–deflection curves shown in Figure 15.

Based on the above analysis, the interactive model reveals that the drag and vertical reaction forces induced by foam are function of the mechanical parameters of foamed concrete (i.e., the compressive strength and the tearing energy), the tire—load—deflection curve, and the aircraft speed. More detailed descriptions of these can be found in the reference [33]. Consequently, the drag force and vertical supporting force acting on each landing gear can be obtained. For a given aircraft tire, the overall vertical supporting force applied by the arrestor material can be calculated by

\[
F_C = F_{C1} + F_{C2}.
\]

It is suggested that the vertical supporting force on the area of the tire footprint segment of the arrestor material is associated with the angle \( \beta \) by the relation of the tire deflection curves in Figure 15 and the compressive stress—strain relation, Equation (1), from material tests. Then the densification strain in the compacted foamed concrete underneath the tire can be determined. Similarly, the total drag on an aircraft tire by the foamed concrete can be given by

\[
F_D = F_{D1} + F_{D2} + F_{D3} + F_{D4}.
\]
The Boeing 737-300 aircraft is dual wheel landing gear. For Figure 13. It is noted that the configuration of tires on the aircraft has six tires, two on each of the two main landing gears and two on the nose landing gear, as shown in Figure 13. Aircraft landing gear (Boeing 737-300). For the nose landing gear, the drag force and the vertical supporting force acting on it can be obtained by

\[
F_{ND} = 2F_D \quad (14-a)
\]

\[
F_{NC} = 2F_C \quad (14-b)
\]

where \(F_{ND}\) and \(F_{NC}\) are the drag force and the vertical supporting force of foamed concrete acting on the nose landing gear, respectively. Similarly, we can obtain the drag force \(F_{MD}\) and the vertical supporting force \(F_{MC}\) acting on each of the main landing gears. For another multiple-tire configuration (dual tandem and dual tridem), the vertical supporting force on the strut is also divided among all the tires. However, only the leading tires are responsible for producing the drag load when interacting with the foamed material, while the trailing tires do not participate in crushing the foamed concrete. Consequently, the trailing wheels, as ‘shadowed wheels’, are assumed not to contribute drag force except for the equivalent friction. These efficiency reductions would typically only apply to calculate the drag force on the main struts. In the following aircraft dynamic model, the total drag force and total vertical supporting force on landing gears from arrestor material will be determined by the above method.

At the core of APM is a multiple rigid-body aircraft model that calculates the dynamic loads and motion of an aircraft as it rolls through a foamed concrete bed [33]. The arrestor bed exerts loads on both the nose and main gears, and the aircraft responds by pitching forward, sinking into the bed, and decelerating to an eventual stop. Once the formulae of drag and vertical reaction forces are determined, the dynamic behaviour of the aircraft could be represented mathematically using the multiple rigid-body model illustrated in Figure 14. In the model, the landing gear struts are oleo-pneumatic energy absorbing devices, which can be represented by linear springs due to low loading rates and minimal strut travel, and low viscosity dampers according to the load-stroke behaviour of the strut [8,18] where the gear damping force is proportional to the square of the stroke velocity. The multiple rigid-body aircraft model has five degrees of freedom, which are aircraft horizontal travelling distance \(x\), aircraft vertical displacement \(y\), aircraft pitch angle \(\theta\), main gear stroke change \(y_M\), and nose gear stroke change \(y_N\). Based on Hamilton’s principle, the dynamic governing equations of the aircraft motion within the arresting system area can be derived by

\[
M_T \ddot{x} = -F_{ND} - 2F_{MD} \quad (15-a)
\]

\[
M_F \ddot{y} = k_{NG}(\Delta y_{N0} + y_N - L_N \theta - y) + 2k_{MG}(\Delta y_{M0} + y_M + L_M \theta - y) - M_F g + c_{NG}(\dot{y}_N - \dot{y} - L_N \dot{\theta}) | \dot{y}_N - \dot{y} - L_N \dot{\theta} | + 2c_{MG}(\dot{y}_M - \dot{y} + L_M \dot{\theta}) | \dot{y}_M - \dot{y} + L_M \dot{\theta} | \quad (15-b)
\]

\[
I \ddot{\theta} = k_{NG}(\Delta y_{N0} + y_N - L_N \theta - y) L_N - 2k_{MG}(\Delta y_{M0} + y_M + L_M \theta - y) L_M + c_{NG}(\dot{y}_N - \dot{y} - L_N \dot{\theta}) | \dot{y}_N - \dot{y} - L_N \dot{\theta} | L_N - 2c_{MG}(\dot{y}_M - \dot{y} + L_M \dot{\theta}) | \dot{y}_M - \dot{y} + L_M \dot{\theta} | L_M - F_{ND} H_N - 2F_{MD} H_M \quad (15-c)
\]

\[
M_{NG} \ddot{y}_N = F_{NC} - M_{NG} g - k_{NG}(\Delta y_{N0} + y_N - L_N \theta - y) - c_{NG}(\dot{y}_N - \dot{y} - L_N \dot{\theta}) | \dot{y}_N - \dot{y} - L_N \dot{\theta} | \quad (15-d)
\]

\[
M_{MG} \ddot{y}_M = F_{MC} - M_{MG} g - k_{MG}(\Delta y_{M0} + y_M + L_M \theta - y) - c_{MG}(\dot{y}_M - \dot{y} + L_M \dot{\theta}) | \dot{y}_M - \dot{y} + L_M \dot{\theta} | \quad (15-e)
\]
where $M_T$ is the total aircraft mass, $M_F$ is the mass of the fuselage and wings, $g$ is the gravitational acceleration, $I$ is the aircraft mass moment of inertia about the pitch axis, excluding the bogies, $M_{NG}$ is the mass of the aircraft nose gear, $M_{MG}$ is the mass of the aircraft main gear, $k_{NG}$ is the equivalent stiffness of the nose gear, $k_{MG}$ is the equivalent stiffness of the main gear, $c_{NG}$ is the damping coefficient of the nose gear, $c_{MG}$ is the damping coefficient of the main gear, $L_N$ is the distances from the CG to nose gear, $L_M$ is the distances from the CG to main gear, $H_N$ is the height from the base of the un-deformed tire of the nose gear to CG, $H_M$ is the height from the base of the undeformed tire of the main gear to CG, $\Delta y_{NO}$ is the static extension of the nose gear strut, $\Delta y_{MO}$ is the static extension of the main gear strut.

Based on the wheel/foam interface model and the dynamic governing equations, the APM was developed to simulate aircraft arrestments for the new foamed concrete arrestor with MATLAB. The APM allows experimentation with various aircraft types, speeds, arrestor bed thickness, and material strengths. Within a generalised framework, many aircraft arrestments could be simulated with the APM. It has four principal inputs as follow: (1) the mechanical parameters of foamed concrete; (2) arrestor bed thickness; (3) aircraft tire load-deflection curves; and (4) aircraft properties including aircraft dimensions, weight, speed, and landing gear design data. Using these four inputs, the APM runs a time-marching simulation to predict the dynamic loads on the aircraft, the arresting distance, and so on.

4.2. Comparisons between measured and predicted results

Since the results of the full-scale test with Boeing 737-300 aircraft have been recorded and the APM is capable of simulating the aircraft arrestments, the testing results measured by GPS and high speed video (HSV) and the results predicted by APM are then compared. Inputting the testing aircraft parameters for Boeing 737-300 given in Table 3 from the data summarised by Gerardi [18] and the Boeing Airplane Characteristics [7], aircraft tire load-deflection curves as shown in Figure 15, the equivalent friction coefficient (no braking) $\mu \approx 0.023$, test bed configuration (bed thickness), and the foamed concrete materials parameters into the APM, the prediction of aircraft deceleration and the stopping distance for the actual arrest could be obtained.

Figures 16(a) and 16(b) show the measured and simulated aircraft deceleration-time curves, and aircraft deceleration-travelling distance curves, respectively. In the figures, the two results measured by GPS and HSV are similar, although the curve measured by HSV shows ‘noise.’ Clearly, the ‘noise’ does not contribute to the aircraft deceleration because it is both positive and negative about a value, giving a net effect of zero. It is suggested that both the GPS and the HSV can capture the aircraft motions during the testing arrest. Comparing the measured and simulated curves, both the measured deceleration and the simulated deceleration first increase when nose tires penetrate the test bed at zero metre, while the main gear tires are still on pavement. The decelerations then increase strongly when the main gear tires enter the bed, at a nose-tire location of 12.45 m. After the initial transition, the measured deceleration oscillates largely, while the simulated deceleration oscillates slightly. It is noted that the ‘large oscillation’ feature of the measured curves in Figures 16(a) and 16(b) was not simulated in APM, although the mean measured

Table 3. Boeing 737-300 aircraft parameters [7,18].

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>$M_T$ (kg)</th>
<th>$M_F$ (kg)</th>
<th>$I$ (kg·m$^2$)</th>
<th>$L$ (m)</th>
<th>$L_N$ (m)</th>
<th>$L_M$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>38,500</td>
<td>37,244</td>
<td>1,512,752</td>
<td>32.18</td>
<td>2.76</td>
<td>2.84</td>
</tr>
<tr>
<td>$M_{NG}$ (kg)</td>
<td>110</td>
<td>0.305</td>
<td>0.197</td>
<td>1144</td>
<td>519</td>
<td>20,506</td>
</tr>
<tr>
<td>MG</td>
<td>573</td>
<td>0.508</td>
<td>0.368</td>
<td>1241</td>
<td>1301</td>
<td>20,506</td>
</tr>
</tbody>
</table>

Note: NG = nose gear strut, MG = main landing gear strut.
deceleration of $-0.42$ g is very close to the prediction of $-0.4116$ g from the APM.

Certainly, these discrepancies between the measured deceleration and the simulated deceleration must cause the differences between the measured and predicted aircraft stopping distances. Figures 17(a) and 17(b) show a comparison of measured and simulated, aircraft speed-time curves and aircraft speed-travelling distance curves, respectively. It is observed from Figure 17(a) that at early time period from $t = 0$ to $t \approx 1$ s, the aircraft speeds and the corresponding distances based on the APM simulations and the present test results are in very good agreement. However, the test speeds are slightly higher than APM estimations before $t \approx 4$ s. It should be noted that from $t \approx 4 - 6$ s, the test curve goes down sharply while the speed curves predicted by the APM have no such feature observed. It is also found that our prediction of the stopping distance is 66.73 m, which is 5.82 m greater than the actual stopping distance of 60.91 m from the test as shown in Figure 17(b). The error between the predicted and the measured is 9.56%, within 10% of each other. Similarly, we find that predicted arresting-time is 6.06 s, which is longer than the duration of the actual test, as shown in Figure 17(a).

In addition, Figure 18 presents a time history plot of the Boeing 737-300 aircraft pitch angle in travelling direction obtained from the full-scale test. This plot also contains a time history plot of the pitch angle simulated by APM. In the figure, both the measured and simulated pitch angles sharply increase when the nose tires penetrate into the arrestor bed. After the main-gear tires have entered the bed, the measured and simulated pitch angles oscillate. Comparing the measured and simulated pitch angles, the testing aircraft pitches at greater angle than the simulated aircraft model. Substantially, the greater pitch angle must cause the landing gear tires to be pressed deeper into the foamed concrete, generating higher deceleration and larger oscillation, as shown in Figures 16(a) and 16(b). Obviously, the higher deceleration could cause potential human injuries during the arresting process. Fortunately, the maximum value (0.806 g) of the measured deceleration is less than 1 g, indicating that the actual arresting test is successful based on occupant injury criteria [28].
5. Discussions

From the above comparisons, we find that the measured parameters from the aircraft are within an acceptable level (about 10%) of the values predicted by the APM. However, it must be pointed out that there are some discrepancies between the measured parameters from the aircraft and the values predicted by the APM. These are mainly caused by the differences between the idealised models including aircraft sub-model and foamed concrete sub-model and the actual arresting test. Possible reasons are given as follows.

In the foamed concrete sub-model, the uniform compressive strength of the foamed concrete is considered and only the mean compressive-strength behaviour of the foamed concrete obtained from indentation tests is used. However, the actual foam concrete blocks exhibit slight variations in compressive-strength behaviour due to the material heterogeneity, resulting from the production technology. Inevitably, the compressive strength of the installed blocks slightly fluctuated along the direction of the aircraft travel. The strength change created a corresponding variation in the loads on the landing gears when the aircraft entered the test bed. In this case, the penetration depth would change, providing a ‘rough runway effect’ to the entering test aircraft. This effect induced large oscillations of arresting aircraft after beginning forward motion. The oscillating behaviour further amplified by the aircraft mass moment of inertia about the pitch axis, and created significant fluctuations in the aircraft pitch angle, as displayed in Figure 18. Thus, this difference between the arrestor bed model used in the APM and the actual test bed may lead to the smaller measured stopping distance.

Again, it is supposed that these dissimilarities between the measured and simulated aircraft deceleration partially stem from the deviations between the actual and approximate load-stroke behaviour (landing gear stiffness). The deceleration frequency responses shown in Figure 19 can indicate that the actual aircraft landing gear stiffness may be greater than the approximate landing gear stiffness of the aircraft sub-model.

In order to evaluate the influences of the material heterogeneity and the landing gear stiffness on the aircraft arrest, the sensitivity of stopping distance to material compressive strength is examined by varying the material compressive strength by ±10%. Also, the sensitivity of stopping distance to aircraft landing gear stiffness is examined by increasing the landing gear stiffness by 3%, 8%, and 15%. In this sensitivity study, nominal values are used for the material strength and landing gear stiffness. The results for each case are shown in Figure 20 and Table 4, which imply that increasing the arrestor material compression strength results in decreasing the stopping distance. Additionally, increasing the landing gear
stiffness decreases stopping distance. For all 12 cases, the aircraft stopping distance for the case of C8% landing gear stiffness and 0% material strength is closest to the measured result. It may suggest that a greater correlation is identified between the actual aircraft and the aircraft sub-model with higher landing gear stiffness, even with some unknown aircraft parameter differences.

It is noted that only one arrestor bed geometry and aircraft weight are considered in the above studies. However, the aircraft stopping distance was found to be most sensitive to aircraft weight and arrestor-bed thickness by the authors in the earlier work [33]. For this reason, the sensitivity analysis is also conducted using the calibrated aircraft parameters to investigate stopping distance as a function of arrestor-bed thickness. In the analysis, two gross weight for the Boeing 737-300 aircraft are considered, the maximum landing weight (MLW; 51,710 kg) to evaluate an overrun during landing, and the maximum takeoff weight (MTW; 61,235 kg) for an overrun during an aborted takeoff. Also, three arrestor-bed thickness of 0.35, 0.5, and 0.7 m are considered. As specified in AC 150/5220-22A [15], the aircraft is assumed to enter the arrestor bed at 70 knots (36.01 m/s). The stopping distance ranges are shown in Figure 21 for comparison between the aircraft weight and to illustrate the significance of arrestor-bed thickness on stopping distance. In each range, the stopping distance for the case of ¡10% material strength represents an upper bound and the stopping distance for the case of C10% material strength represents a lower bound. In detail, the results of the aircraft stopping distances are summarised in Table 5. It is found that the aircraft stopping distance decreases as the arrestor-bed thickness increases. The stopping distance is smallest for the maximum arrestor-bed thickness, and largest for the minimum arrestor-bed thickness. Because stopping distance increases with aircraft weight, stopping distance is greater at MTW than at MLW. Overall, the parametric analysis identifies the ranges of stopping distance as function of arrestor material compressive strength, aircraft weight, arrestor-bed thickness for the Boeing 737-300 aircraft.

6. Conclusions
The experimental study presented in this paper focused on a foamed concrete aircraft arresting system which provides an economical and non-destructive means for decelerating aircraft that overshoot runway. A full-scale arresting test was conducted using an instrumented Boeing 737-300 aircraft to demonstrate the effectiveness of the arresting system and verify the APM.

Based on the results and observations of this foamed concrete arresting system testing effort, it can be concluded that the arrestor test bed can effectively decelerate an overrunning Boeing 737-300 aircraft to a safe stop with no significant damage to the aircraft landing gears. The foamed
concrete system can be used as an alternative civil aircraft arresting system to decelerate the overrunning aircraft, and commendably improve the runway safety. The accuracy of the APM in predicting Boeing 737-300 aircraft stopping distance, deceleration, and aircraft speed decay was successfully validated. Of the given aircraft parameters and arresting bed, the sensitivity of aircraft stopping distance to the arresting material heterogeneity, landing gear stiffness were investigated. All measured values were found to be within 10% of those predicted by the APM. Consequently, other aircraft with dual landing gear configuration arrestments can be reliably predicted using the APM.

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References
[28] W.K. San-Filippo, and H. Delong, Engineered materials arresting system: an alternative solution to runway...


