ADVANCED DESIGN OF FLEXIBLE AIRCRAFT PAVEMENTS

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ABSTRACT

Road and airfield flexible pavement design methods are similar in that load-induced strains are estimated using layered elastic methods. Pavement life is predicted using materials performance relationships that relate the strains generated within pavement layers and the subgrade to the actual measured performance of full-scale pavements under full-scale loading.

The introduction of new generation aircraft such as the Boeing 777 and Airbus A380, both of which have 6-wheel configurations was the major impetus for new full-scale tests to improve the pavement design methods used to determine pavement thicknesses needed for such aircraft.

This paper details the recalibration of the computer program, APSDS 5.0 (Aircraft Pavement Structural Design System) to take account of the new test data. To accurately reflect the performance of the test pavements, separate calibrations have been developed for 1, 2, 4 and 6-wheel configurations. Correlation between design outputs and the calibration data is significantly better than achieved by previous calibrations that did not treat the different configurations separately.

Structural pavement thicknesses determined by APSDS 5.0 are significantly less than those obtained using the design software FAARFIELD developed in the USA. Possible reasons for the difference are discussed.

INTRODUCTION

The design of aircraft landing gears comprising various configurations of wheels affects aircraft cost efficiency as measured by the cost per passenger-kilometre, but also influences the amount of accumulated damage caused to the world's aircraft pavements. Higher tyre pressures, fewer wheels and smaller spacings between wheels improve aircraft flying efficiency but increase the cost of maintaining pavements. A reliable, widely accepted design method is needed to assess the effect of wheel loading, wheel spacing and tyre pressures on pavement damage so that both flying efficiency and pavement damage are taken into account.

Strains induced within layered pavement structures by aircraft multiwheel configurations can now be estimated using layered elastic analysis. However, prediction of pavement life in terms of load repetitions is empirically based; Strain-based design methods for determining the required pavement thickness must be calibrated against performance data from full-scale test pavements under full-scale aircraft trafficking.

APSDS 5.0 (Aircraft Pavement Structural Design System) is a computer software program based on layered elastic analysis. It has two unique features. The first is that subgrade strains are computed for all points across the pavement in order to capture all damage contributed by all the aircraft wheels. This contrasts with other pavement thickness design methods that compute only single maximum values of strain. The pattern of strains is then used to develop equations that relate load repetitions to pavement rut depth by calibrating against full-scale test data. The second unique feature is that, in order to adequately reflect the test data, different calibration parameters are used for each wheel configuration.

Using the new calibration described in this paper, APSDS 5.0 now produces pavement thickness designs that more accurately reflect the performance of the full-scale test pavements than was previously possible.

BACKGROUND TO AIRCRAFT PAVEMENT DESIGN

Road and airfield flexible pavement design methods are similar in that load-induced strains are estimated using layered elastic methods such as CIRCLY. Pavement life is predicted using materials performance relationships that relate the strains generated within pavement layers and the subgrade to the actual measured performance of full-scale pavements under full-scale loading.

Most empirical road performance data comes from roads that have been subjected to loading by a range of vehicles. The traffic consists of a mix of standard classes of road vehicles that have standardised axle configurations. The traffic loading is expressed in Equivalent Single Axles (ESAs) in an attempt to sum the damaging effects of the different axle groups.

By contrast, empirical aircraft pavement performance data is obtained from full-scale test pavements each of which has been loaded with an actual undercarriage of a particular aircraft. Mixed loadings are not used. This more direct and fundamental approach avoids the need to convert different axle configurations to an equivalent load such as an ESA.

The layered elastic method was introduced into regular aircraft pavement design practice in the mid-1990’s with the release of two computer programs; the U.S. Federal Aviation Administration’s LEDFAA (Layered Elastic Design, Federal Aviation Administration) and the Australian-developed program APSDS. FAA’s FAARFIELD has now replaced LEDFAA.

Prior to the introduction of the layered elastic method, flexible aircraft pavements were usually designed using the US Army Corps of Engineers CBR pavement design method detailed in Instruction Report S-77-1 (Pereira, 1977). Aircraft induced deflections at subgrade level were calculated using Boussinesq’s single layer equations. These were then correlated with the load repetitions observed to cause rutting failure in full-scale tests. The method had been adapted from highway design practice in 1942 then modified and extrapolated to cater for higher loads, multiple wheel undercarriages and aircraft wander.

A feature of the method was that pavement thickness reduction factors, called alpha factors, were needed because the tests showed that equal subgrade deflections did not indicate equal pavement life. Pavement life was longer when the deflection was produced by larger wheel groups. For example, for 10,000 repetitions the 4-wheel alpha factor was 0.825 and the 2-wheel alpha factor was 0.90; only 0.825 of the basic calculated pavement thickness was needed if a 4-wheel landing gear caused the deflection, but 0.90 of the basic thickness was required if the same deflection had been caused by a dual-wheeled landing gear.

The S-77-1 design method is computerised in the US Federal Aviation Administration’s software, COMFAA.

Pavement composition

Because they are based on Boussinesq single layer analysis, pavement thicknesses obtained using COMFAA are directly applicable only to pavements that have identical structures to those used in the full-scale test pavements that were used to produce the S77-1 design method. Therefore the actual thickness of any particular pavement structure must be converted to an ‘equivalent’ S77-1 thickness. This is done by taking account of the types, qualities and layer thicknesses of materials relative to those used in the Corps’ test pavements. The conversion is done using layer equivalency factors that reflect the load-spreading capabilities of the various pavement materials; asphalt, crushed rock base course, natural gravel sub-base, cement-treated crushed rock etc. When using APSDS to design aircraft pavements, the designer assigns a modulus value to each of the materials within the pavement to reflect its load-spreading characteristics. That is, the task of choosing layer equivalency factors has been replaced by the task of selecting elastic moduli. The calibration process described in this paper used only test pavement structures so did not involve the selection of layer equivalency factors or elastic moduli to convert to structures that contained different materials.

Relating strains to pavement performance

The S-77-1 design method used deflection as the indicator of pavement performance. Both APSDS and FAARFIELD use subgrade strain. (The Austroads flexible pavement design method also uses subgrade strain.) The performance relationships for both APSDS and FAARFIELD have been obtained by calibrating against the S-77-1 method , not by direct calibration against the Corps' full-scale trafficking tests. The calibration method entails developing equations that relate subgrade vertical strain to repetitions of that strain that would cause an unacceptable degree of surface rutting. The equations are termed "failure criteria" or "performance relationships" or "transfer functions".

In 2001 the authors published a calibration of APSDS 4.0 against S77-1 designs (Wardle, Rodway, and Rickards, 2001). This calibration is usually referred to as the Chicago calibration. The median correlation between the APSDS thicknesses and the COMFAA method thicknesses was approximately 60 mm.

Efforts were made to improve the 2001 calibration. White (2008) confirmed that better agreement between APSDS 4.0 and COMFAA pavement thicknesses could be obtained by using different calibration parameters for each wheel configuration. The introduction of new generation aircraft such as the Boeing 777 and the Airbus A380, both of which have 6-wheel configurations was the major impetus for FAA to conduct new full-scale tests to improve the accuracy of pavement thickness designs for such aircraft. These tests have been conducted at the US National Airport Pavement Test Facility (NAPTF). It is important to realize that there is only one body of full-scale test data available. This consists of 37 tests conducted by the US Army Corps of Engineers plus the results produced at the NAPTF since it commenced testing in 1998. Consequently, all of the current design methods use the same empirical data. However, various design tools produce different pavement thicknesses. These differences can be due to different methods used to interpret the data, different degrees of conservatism adopted, and possibly to errors of interpretation and design.

In December 2006, the International Civil Aviation Organization (ICAO) published updated alpha factors for the S77-1 method based on the new test data for 4 and 6-wheel configurations. COMFAA 2.0 incorporates the FAA's revised alpha factors and so now constitutes the FAA's best interpretation of all the available test data. This paper details the recalibration of APSDS against COMFAA 2.0. Note that a new version of COMFAA, version 3.0, with additional features, is now available. However, it uses the same alpha factors as 2.0 and therefore produces identical pavement thicknesses.

Using the new calibration data APSDS 5.0 now produces pavement thickness designs that more accurately reflect the performance of the full-scale test pavements than did the 2001 Chicago calibration. Correlation with the S77-1 designs has been improved by use of different calibration parameters for each wheel configuration. In addition, as described later in this paper, an improved method of determining the number of strain repetitions at subgrade level has been used.

DEVELOPMENT OF APSDS DESIGN PROCEDURES AND SOFTWARE

APSDS was developed from a road pavement design program, CIRCLY (Wardle, 1999), to include treatment of aircraft wander.

Aviation traffic loads differ from road traffic loads in that aircraft wheels are more evenly distributed across the width of the pavement. This is partly due to a lower degree of channelization and partly due to the wide variation in spacing of wheels and groups of aircraft wheels compared with the standardised wheel spacings on road vehicles. Field observations have shown that successive passes of aircraft along a runway or taxiway pavement follow a bell-shaped distribution about the pavement centreline. This can be reasonably modelled by a normal distribution, so the degree of aircraft wander is characterized by the standard deviation. The standard deviation has been found to be significantly different for runways, taxiways and aircraft docking bays. This affects the pavement thickness required at each of these locations.

Prior to the introduction of APSDS, the lateral distribution of aircraft loads was treated in an approximate fashion using the Pass-to-Coverage Ratio (PCR) concept. The PCR is defined as the number of passes required by an aircraft to cause the most frequently ‘covered’ point on the pavement to be covered by any part of a tyre’s contact area. The PCR depends upon wheel configuration, tyre width and the degree of aircraft wander. For example, the PCR for a Boeing 747 on a taxiway is 1.75 whereas that of a Boeing 737, which is a smaller aircraft with fewer, narrower wheels, is 3.5. This means that the most frequently loaded point on the taxiway surface is twice as likely to receive a wheel load when a B747 passes as it is when a B737 passes along the taxiway The PCR concept solely addresses the statistics of load distribution at the pavement surface and, therefore, incorrectly implies that the reduction in pavement damage due to aircraft wander is the same for all pavement types and thicknesses. APSDS corrects this error.

As explained in the introduction, APSDS computes subgrade strains for all points across the pavement in order to capture all damage contributed by all the aircraft wheels. This contrasts with other pavement thickness design methods, including S-77-1, Austroads and FAARFIELD that compute only single maximum values of strain. The pattern of strains is then used to develop equations that relate load repetitions to pavement rut depth. This method has long been recognized as desirable by a number of pavement specialists. For example, the concept was described by Monismith et al. (1987). However, it involves computations that could not be performed quickly enough for regular design use until personal computers with adequate computing speed became available. The method eliminates the need for the use of the pass-to-coverage concept and allows the designer to calculate pavement thicknesses for any degree of aircraft wander.

APSDS uses a special version of the CIRCLY layered elastic numerical engine to compute strains, which are then related to pavement life (strain repetitions). The strains are converted to damage using performance relationships of the form:

$$N = \left[\frac{k}{\varepsilon}\right]^{b} \qquad (1)$$

Where: N is the predicted strain repetitions to cause failure

k is a material constant determined by calibration.

b is the damage exponent for the material, determined by calibration.

ε is the static load-induced strain

The pattern of strains at subgrade level experienced during the passage of a multiple axle wheel configuration primarily depends on the pavement thickness. The two extremes are:

- multiple distinct short pulses beneath each axle, for thinner pavements.
- a single longer pulse that reflects the overall loading on the wheel configuration, for thicker pavements.

Between these two extremes the pulses resulting from each axle overlap making the calculation of damage problematic. Recently the ‘reservoir’ method, as used in bridge design to handle complex loadings was implemented in APSDS to overcome this problem and to ensure a smooth transition between these two extremes.

The Damage Factor for the i-th loading is defined as the number of repetitions (n_i) of a given damage indicator divided by the ‘allowable’ repetitions (N_i) of the damage indicator that would cause failure.

The Cumulative Damage Factor (CDF) is given by summing the damage factors for all loadings in the traffic spectrum using Miner’s hypothesis:

$$\text{Cumulative Damage Factor} = \sum \frac{n_i}{N_i} \qquad (2)$$

For example, if 1,000 repetitions of a particular strain would cause failure, then 300 repetitions produces a Damage Factor of 0.30. If 50,000 repetitions of a smaller strain would cause failure then 10,000 repetitions produces a Damage factor of 0.20. The two loadings produce a CDF of 0.50 so half of the pavement's life has been consumed.

APSDS 5.0 calculates the CDF as a function of lateral position across the pavement. The pavement is presumed to have reached its design life when the cumulative damage at any point reaches 1.0.

Figure 1 is a sample graph showing the CDF variation across the pavement. In addition to the Total CDF the contribution from each aircraft model is shown.

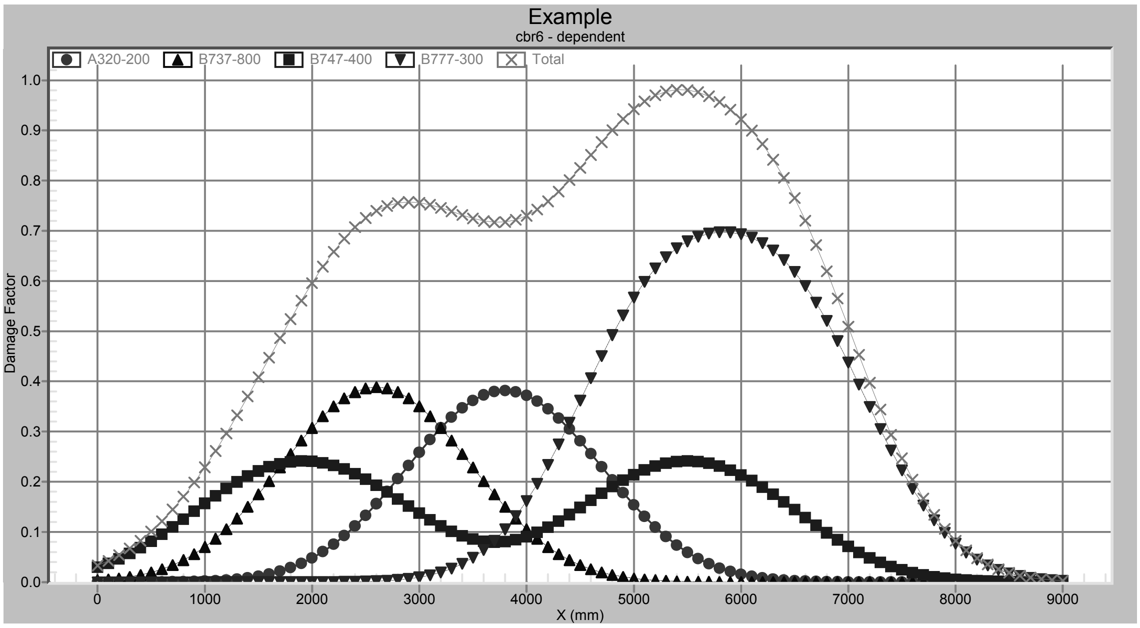

Figure 1: Sample APSDS 5.0 CDF Graph showing CDF variation across a pavement

THE CALIBRATION METHOD

Aircraft used for calibration

The commercial aircraft used in the calibration are listed in Table 1. Aircraft masses ranged from 74 to 560 tonnes. The numbers of aircraft passes considered were 10,000, 100,000 and 1,000,000 to cover a reasonable range of aircraft usage levels.

The calibration process was based on individual aircraft rather than aircraft traffic mixes. The aircraft specifications are given in Table 1.

The A380 was considered both in the Dual-tridem and Dual-tandem calibrations.

The single wheel loadings were considered to have loads of 20 tonnes and 30 tonnes per wheel with tyre pressures of 1.02 MPa and 1.54 MPa respectively.

Table 1: Characteristics of aircraft used in calibration

Aircraft Model	Take-off mass (tonnes)	Gear Configuration	Tyre pressure (MPa)	pass to coverage ratio
A380-800	560	Dual-tridem	1.50	1.42
		Dual-tandem	1.50	1.91
B747-400	398	Dual-tandem	1.38	1.73
B777-300	300	Dual-tridem	1.48	1.38
A340-300	276	Dual-tandem	1.42	1.90
A300-600	172	Dual-tandem	1.34	1.69
B767-200	144	Dual-tandem	1.31	1.98
B757-200	116	Dual-tandem	1.26	1.93
B737-800	79	Dual	1.41	3.53
A320-200	74	Dual	1.38	3.70

Pavement structures

As stated earlier, the pavement thicknesses obtained using COMFAA are only directly applicable to pavement structures identical to those used in the full-scale test pavements used to develop the S-77-1 design method. Consequently, the same pavement structures as shown in Table 2 were used for the APSDS calibration.

Table 2: Pavement structures used for the calibration

Material	Thickness
Asphaltic concrete E (Elastic Modulus) = 1400 MPa, Poisson's Ratio (ν) = 0.4	75.0 mm
Fine Crushed Rock (Unbound base course) ν = 0.35	150.0 mm
P154 (Unbound sub-base) ν = 0.35	variable
Subgrade E (MPa) = 10.0 x CBR, ν = 0.4	

The unbound base course is a standard crushed rock material commonly specified for aircraft pavements. It is designated by the FAA as P209; a high quality graded material with a minimum California Bearing Ratio (CBR) of 80%. The unbound sub-base is a standard, crushed or non-crushed material designated by the FAA as P154, with a minimum CBR of 20%. Typically P154 is natural gravel, sand or ripped rock.

Because granular pavement materials are stress-dependent (i.e. the modulus decreases with reducing stress), APSDS 5.0, like FAARFIELD, automatically sub-layers the zones of unbound materials and assigns a different modulus to each sub-layer. The sublayering method is described in detail by Barker and Brabston (1975).

Four subgrade CBR values were used in the calibration process. These were: 3%, 6%, 10% and 15%. These cover the normal range of CBR values assigned to various subgrade materials.

Results

For each subgrade CBR value, the pavement thickness required for each aircraft type for 10,000, 100,000 and 1,000,000 aircraft passes were calculated using both APSDS 5.0 and COMFAA 3.0. The S-77-1 method assumes that aircraft wander on a taxiway has a standard deviation of 773 mm so the same degree of wander was used in all the APSDS 5.0 computations. In common with COMFAA and FAARFIELD, the subgrade modulus in MPa was assumed to be 10 times the CBR.

The APSDS 5.0 computations for each CBR value were run as a batch using trial values of the performance parameters k and b. A least squares correlation measure for the pavement thickness was calculated for all the cases within the batch. The parameters k and b were varied by a simple manual bisection process to determine values that achieved the closest correlation with S-77-1. In addition to considering the case where all wheel configurations are combined together, results for individual wheel configurations comprising 1 wheel, 2 wheels, 4 wheels and 6 wheels were also analysed.

Table 3: Performance parameters obtained from calibration.

Subgrade CBR (%)	Wheel Configuration	Weighted Error (mm)	Weighted Error (%)	k	b
3	1 wheel	17.10	1.7%	0.00382	7.8
	2 wheels	20.14	1.9%	0.00254	12.4
	4 wheels	28.03	2.0%	0.00204	17.8
	6 wheels	35.67	2.3%	0.00200	27.1
	All wheel groups	143.14	11.0%	0.00180	25.3
6	1 wheel	9.66	1.6%	0.00382	9.3
	2 wheels	11.56	1.9%	0.00297	12.5
	4 wheels	31.72	4.2%	0.00216	18.7
	6 wheels	29.96	3.6%	0.00188	27.1
	All wheel groups	50.65	7.0%	0.00204	21.7
10	1 wheel	12.41	3.1%	0.00382	10.4
	2 wheels	7.46	2.0%	0.00300	13.1
	4 wheels	17.30	3.9%	0.00225	19.0
	6 wheels	9.85	2.0%	0.00192	27.1
	All wheel groups	25.14	5.8%	0.00254	16.2
15	1 wheel	8.71	3.2%	0.00382	11.0
	2 wheels	7.04	3.0%	0.00280	15.1
	4 wheels	16.58	6.1%	0.00252	18.3
	6 wheels	10.60	3.5%	0.00217	27.1
	All wheel groups	19.57	7.3%	0.00275	16.3

Table 3 shows the performance parameters that were obtained and gives the weighted error both in millimetres and as percentage of pavement thickness.

As can be seen from the table, the parameters k and b depend on the CBR of the subgrade. The Appendix provides regression equations that allow k and b to be calculated for any subgrade CBR.

The correlation between the APSDS thicknesses and the pavement thicknesses determined by the S-77-1 design procedure is 12.0 mm (2.4%) for a single wheel configuration, 11.6 mm (2.2%) for 2 wheel configuration, 23.4 mm (4.1%) for 4 wheel configuration and 21.5 mm (2.9%) for a 6 wheel configuration. This compares with the median correlation of 60 mm achieved in 2001.

As stated earlier, the S-77-1 method uses subgrade deflection rather than subgrade strain as the performance indicator. Deflections attenuate much more slowly than strains with horizontal distance from the loaded wheel. This results in greater wheel interaction being modelled by deflection-based design tools. This produces some inherent scatter when comparing results from deflection and strain-based tools.

To illustrate the degree to which the new APSDS 5.0 produces pavement thicknesses comparable to the S77-1 method, Figure 2 compares thicknesses for all nine aircraft for a subgrade CBR of 6% and combines the results for aircraft usage levels of 10,000, 100,000 and 1,000,000 passes.

The median difference obtained was 15.4 mm. Similar agreement is obtained for all subgrade CBR values.

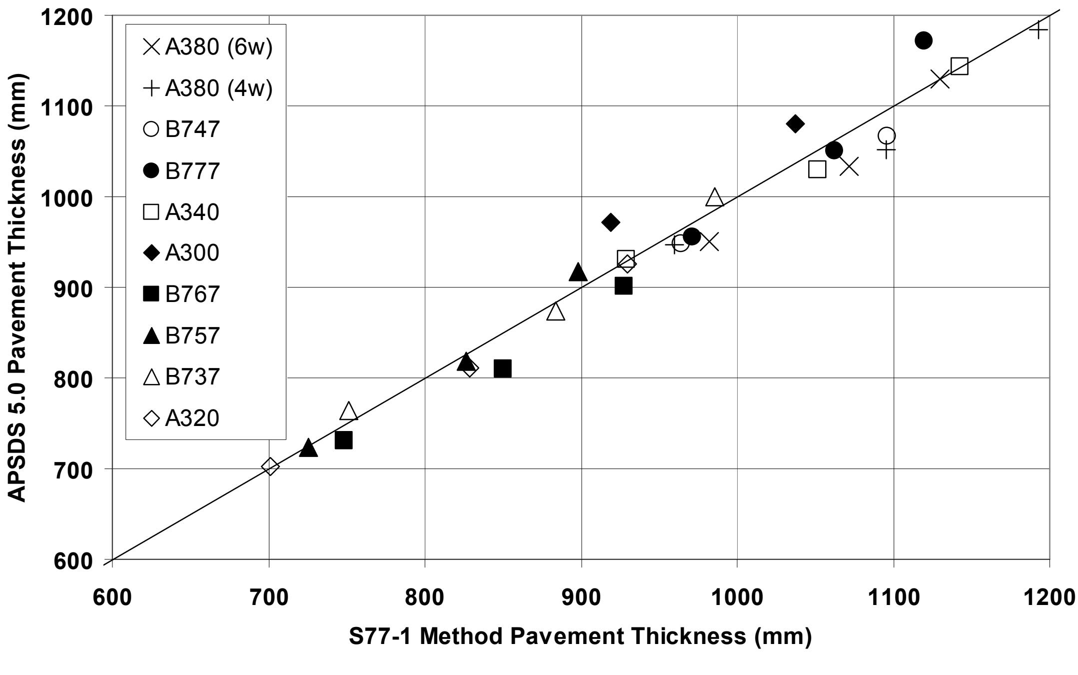

Figure 2: APSDS 5.0 pavement thickness vs. S77-1 method pavement thickness (subgrade CBR of 6%)

COMPARISON WITH OTHER DESIGN METHODS

Designs obtained with the new APSDS 5.0 calibration were compared with designs obtained using FAARFIELD, COMFAA 2.0 and the 2001 APSDS calibration. Figure 3 shows pavement designs for 100,000 passes of the B747-400 over a range of subgrade CBR strengths. The broad trends are similar for other aircraft models and usage levels. In the legend box, “APSDS

5.0 Dependent" indicates the new calibration that depends on the number of wheels in a wheel group. "APSDS 5.0 Chicago" refers to the 2001 calibration.

As stated earlier, APSDS thicknesses obtained using the new calibration are close to the COMFAA 2.0 design thicknesses. The FAARFIELD designs are significantly thicker than designs given by the new calibration and COMFAA 2.0. Possible reasons are:

1. The US Federal Aviation Administration (FAA) calibrated FAARFIELD to produce thicknesses that are similar to those that would be obtained for a typical mix of aircraft using the FAA's pre-computer manual design procedure. This was deemed to be necessary during the transition period commencing in 1995 when the layered elastic method was being introduced. During this period both the manual and layered elastic-based methods were being used by designers. The manual design method used the "design aircraft" concept that conservatively placed the wheel groups of all aircraft at the same distance from the pavement centerline rather than place them in their actual positions.

2. FAARFIELD uses all wheels of the aircraft to calculate the maximum subgrade strain. APSDS uses single wheel group loadings because there is not yet any evidence that interaction between groups of wheels increases or decreases pavement life.

3. FAARFIELD was calibrated in 2003, before the new reduced alpha factors were introduced.

4. FAA now requires thicker asphalt surfacing and thicker basecourse than those used in the earlier full-scale tests. The treatment of these layers in the FAARFIELD calibration process appear to have introduced an additional degree of conservatism.

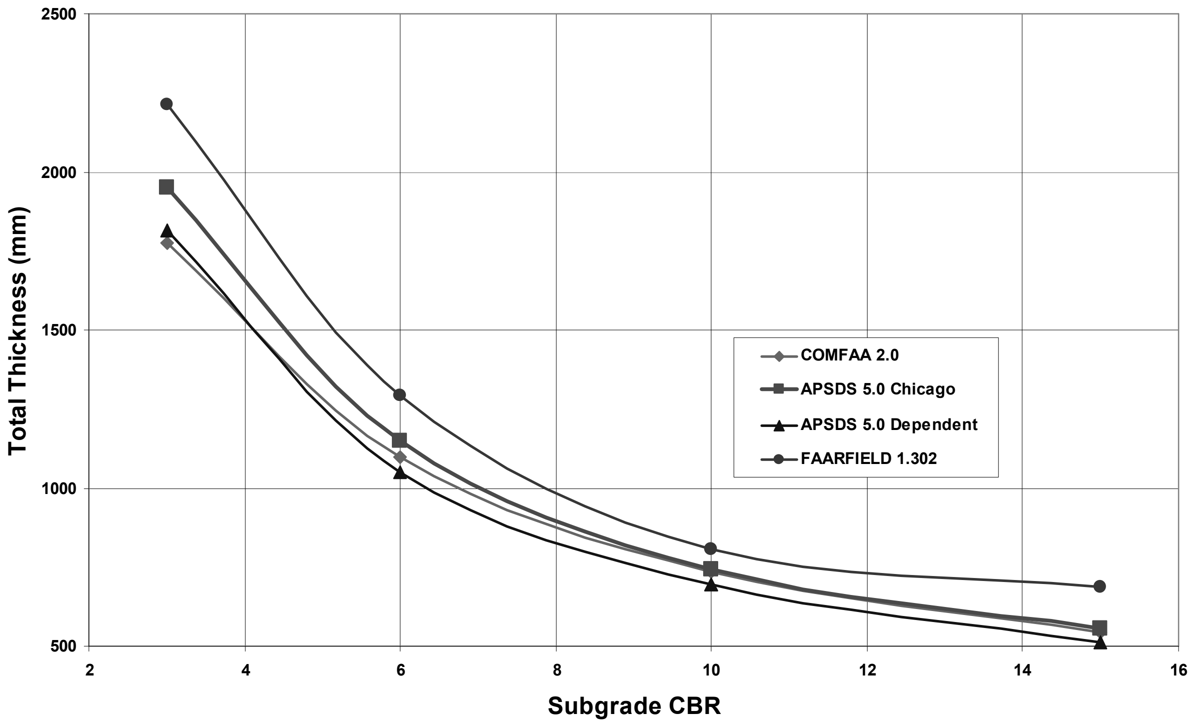

Figure 3: APSDS, COMFAA and FAARFIELD B747-400 pavement thicknesses (100,000 aircraft passes)

SUMMARY AND CONCLUSIONS

The US Corps of Engineers' CBR design method, S77-1, has been recently updated to reflect the results of recent full-scale tests undertaken to determine the pavement thicknesses required by new generation aircraft, in particular the Boeing 777 and the Airbus A380 both of which have 6-wheel configurations.

The layered elastic pavement design tool, APSDS 5.0, has been recalibrated to produce pavement thickness designs that correlate well with the updated S77-1 design procedure. It now reflects the results achieved from the full-scale pavement tests.

Although the recalibration was carried out only for CBR values of 3%, 6%, 10% and 15%, regression equations are provided in the Appendix to allow calibration parameters k and b to be calculated for any subgrade CBR.

The improved correlation between S77-1 and APSDS pavement thicknesses obtained by using different calibration parameters for each wheel configuration is:

- 12.0 mm (2.4%) for a single wheel,
- 11.6 mm (2.2%) for a 2 wheel configuration
- 23.4 mm (4.1%) for a 4 wheel configuration and,
- 21.5 mm (2.9%) for a 6 wheel configuration.

This is a significant improvement on the 2001 calibration for which the correlation was 60 mm.

The benefits of APSDS 5.0 are:

- Any degree of aircraft wander can be specified, and the effect of wander is more rigorously treated than is done by current alternative design methods.
- The different tracking paths of aircraft types relative to the pavement centreline are taken into account.
- Pavement thicknesses for combinations of aircraft types and frequencies are quickly and automatically calculated.
- The effect of different pavement materials, including asphalt and stabilised materials can be quickly analysed.

All APSDS inputs, including material moduli, degree of aircraft wander, various wheel loadings, and material performance relationships can be specified by the designer. The ability to select a wide range of input parameters provides designers with a valuable tool to analyse a variety of loading combinations and trial pavement compositions utilising the full capabilities of the layered elastic model.

Pavement designs for complex mixes of aircraft types and alternative layered structures can be quickly produced that are consistent with those produced by the S77-1 design procedure which was recently updated to reflect the results of the most recent full-scale pavement tests.

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AUTHOR BIOGRAPHIES

Dr. Leigh Wardle is the author of the leading pavement analysis programs, CIRCLY, HIPAVE and APSDS. His research interests include layered elastic analysis, mechanistic pavement design and development of pavement design methods for airfields and heavy duty loads.

Bruce Rodway has forty five years experience in the design, construction and maintenance of road and aerodrome pavements, gained initially with the Commonwealth Departments that had engineering responsibility for Australia's civil and defence aerodromes and then, from 1989 as Chief Engineer-Pavements for the Federal Airports Corporation until its closure in 1998. Since then he has been a private consultant. His special interest in recent years has been the mechanistic design of airfield pavements using the layered elastic method. He was the Australian representative on the International Civil Aviation Organization's (ICAO) committee examining interaction effects between multi-wheeled undercarriages of large aircraft.

APPENDIX: CALIBRATION EQUATIONS

For each wheel configuration, third order polynomials have been determined for the variation of k and b with subgrade modulus (E) in units of MPa.

Table 4: Equations for k and b as a function of number of wheels on gear

Number of wheels on gear	Equations for k and b
1	$k = 0.00382$ $b = 1.243\ 10^{-6}\ E^3 - 5.577\ 10^{-4}\ E^2 + 9.236\ 10^{-2}\ E + 5.498$
2	$k = 1.17710^{-9}\ E^3 - 4.177\ 10^{-7}\ E^2 + 4.451\ 10^{-5}\ E + 0.001549$ $b = 9.259\ 10^{-7}\ E^3 - 9.259\ 10^{-6}\ E^2 - 0.001667\ E + 12.43$
4	$k = 5.0\ 10^{-10}\ E^3 - 1.2\ 10^{-7}\ E^2 + 1.165\ 10^{-5}\ E + 0.001785$ $b = 6.878\ 10^{-7}\ E^3 - 4.521\ 10^{-4}\ E^2 - 0.06636\ E + 16.20$
6	$k = -2.249\ 10^{-10}\ E^3 + 1.142\ 10^{-7}\ E^2 - 1.286\ 10^{-05}\ E + 0.002289$ $b = 27.1$