FAARFIELD – NEW FAA AIRPORT THCKNESS DESIGN SOFTWARE

By:
Izydor Kawa, Ph.D.
SRA International
3120 Fire Road
Egg Harbor Twp., NJ 08234
USA
Phone: (609) 645-0900, Izydor_Kawa@sra.com

David R. Brill, P.E., Ph.D.
FAA Airport Technology Research and Development Branch
William J. Hughes Technical Center, AJP-6310
Atlantic City International Airport, NJ 08405
USA
Phone: (609) 485-5198, David.Brill@faa.gov

Gordon F. Hayhoe, Ph.D.
FAA Airport Technology Research and Development Branch
William J. Hughes Technical Center, AJP-6310
Atlantic City International Airport, NJ 08405
USA
Phone: (609) 485-8555, Gordon.Hayhoe@faa.gov

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ABSTRACT

The Federal Aviation Administration's (FAA) new airport pavement thickness design program, FAArfield (FAA Rigid and Flexible Iterative Elastic Layered Design), is expected to supersede LEDFAA 1.3 [1] as a standard design procedure in the next revision of Advisory Circular (AC) 5320-6. The FAA has made a preliminary version of this program, called FEDFAA, available for download since 2004. Unlike LEDFAA, the FAArfield program incorporates three-dimensional finite element (3D-FE) stress computation [2, 3, 4, and 5] for final design of new rigid pavements and rigid overlays. FAArfield continues to use LEAF [6] layered elastic analysis for flexible pavement and flexible overlay design, as well as for preliminary design of rigid structures.

Other significant changes from LEDFAA 1.3 include direct computation of slab edge stresses (using a 3D-FE model that accounts for stress reduction due to a stiff base layer) and a complete revision of the rigid pavement failure model using data collected in the National Airport Pavement Test Facility (NAPTF) CC2 full-scale tests conducted in 2004. In addition, the design algorithm for rigid overlays has been completely rewritten. For flexible pavements, an automatic base design procedure was implemented that computes the required standard base thickness to protect a subgrade of CBR 20. Additionally, run-time user guidance has been implemented based on relevant provisions of AC 150/5320-6D [7].

The main part of FAArfield 1.0, is written in Microsoft™ Visual Basic.NET™, and is compatible with the latest Microsoft™ operating systems.

INTRODUCTION

A forthcoming revision to the FAA's Advisory Circular (AC) 150/5320-6, "Airport Pavement Design and Evaluation," will adopt the computer program FAArfield (FAA Rigid and Flexible Iterative Elastic Layered Design) as the standard design procedure for civil airport pavements, replacing both the current computer program (LEDFAA 1.3) and the existing FAA design charts based on the California Bearing Ratio (CBR) and Westergaard methods. FAArfield is the culmination of a 10-year research and development effort by the FAA aimed at incorporating 3D-FE computational models in airport pavement design procedures for routine practice. This effort was driven by the need to overcome the well-known deficiencies of the layered elastic analysis (LEA) method for computing critical stresses in rigid pavements under complex gear loads. Currently, the 3D-FE structural model is used for new rigid pavement and rigid overlay design only. Flexible pavement design in FAArfield continues to use the LEA program LEAF developed by the FAA for LEDFAA 1.3 [1, 6].

This paper is not intended as a complete description of the FAArfield-based design procedure, nor as a user's manual. Rather, the intent of this paper is to document the major changes from LEDFAA 1.3. The basis of design, the cumulative damage factor (CDF) procedure, remains unchanged from LEDFAA 1.3. Most of the modifications described below are internal and do not affect either the "look and feel" of the program or its general functionality. However, the changes made will improve the ability of the program to produce reliable designs for all gear types and configurations, including complex gear configurations not yet developed. They will also ensure the compatibility of the program with current and future personal computer (PC) operating systems.

This paper discusses several aspects of the evolution of the LEDFAA 1.3 computer program into FAArfield 1.0:

- Minimizing 3D-FE computation time.
- Improvements to the rigid pavement failure model.
- Improvements to the overlay design algorithm.
- User-related improvements, including user options, run-time guidance and renovation of the built-in aircraft library.

RUN-TIME EFFICIENCY

The introduction of 3D-FE models into the design procedure necessitated changes to the rigid pavement design algorithms compared with LEDFAA. Many of these changes were designed to minimize the time demands of the program. In finite element analysis, the problem size depends on the number of elements (subdivisions of the model), which in turn depends on factors including the gear configuration and the number of structural layers included in the model. The problem size is the greatest factor affecting execution time on a computer. Tables 1 and 2 show the number of equations that need to be solved in order to analyze the 3D-FE pavement structure for different aircraft group configurations, for new rigid pavements and rigid overlays respectively. The gear configuration designations in tables 1 and 2 refer to the designations in FAA Order 5300.7, "Standard Naming Convention for Aircraft Landing Gear Configurations." The mesh size required for each type is shown in figure 1. ("Complex refers to gear configurations larger than 3D, or those requiring a non-symmetrical 3D-FE analysis due to non-symmetry of the gear (such as a C-17), which significantly increases the problem size and required execution time. Tables 3 and 4 show the computation time needed to solve the 3D-FEM system. However, it must be emphasized that the 3D-FE solution times given in tables 3 and 4 for a single structure are not the same as the total design time. Pavement design is an iterative process. To calculate the life of a new rigid pavement structure with a given thickness, it is sufficient to calculate the stress at the bottom of the slab once, for each aircraft contributing to the total CDF. Pavement design, however, requires multiple iterations of the solution as the pavement thickness is modified. Computing the life of a rigid overlay on PCC involves multiple computations of stresses as additional increments of traffic reduce the modulus of the existing PCC slab [8].

Table 1.
Number of Equations for 3D-FE Analysis (New Rigid Pavements).

	Number Of Equations New Rigid Pavements		
Gear configuration	3 Layers	4 Layers	5 Layers
1D	3,362	3,804	4,246
2D	5,694	6,334	9,974
3D	5,834	6,501	7,168
Complex	15,776	17,426	19,076

Table 2.
Number of Equations for 3D-FE Analysis (Rigid-on-Rigid Overlays).

	Number Of Equations Rigid-on-Rigid Overlays		
Gear configuration	4 Layers	5 Layers	6 Layers
1D	4,954	5,396	5,838
2D	8,826	9,466	10,106
3D	8,998	9,665	10,332
Complex	24,948	26,598	28,248

Table 3.
Stress Computation Time for New Rigid Pavements.

	Time, sec.[a] New Rigid Pavements		
Gear configuration	3 Layers	4 Layers	5 Layers
1D	4.4	5.3	6.3
2D	8.6	11.2	20.3
3D	7.7	9.8	14.0
Complex	81.4	116.5	138.6

[a]desktop computer; Operating System: Microsoft Windows XP Professional; 1 GB RAM

Table 4.
Stress Computation Time for Rigid-on-Rigid Overlays.

	Time, sec.[a] Rigid-on-Rigid Overlays		
Gear configuration	3 Layers	4 Layers	5 Layers
1D	15.5	10.9	22.8
2D	25.2	35.8	46.1
3D	24.3	31.4	38.4
Complex	281.2	671.3	523.3

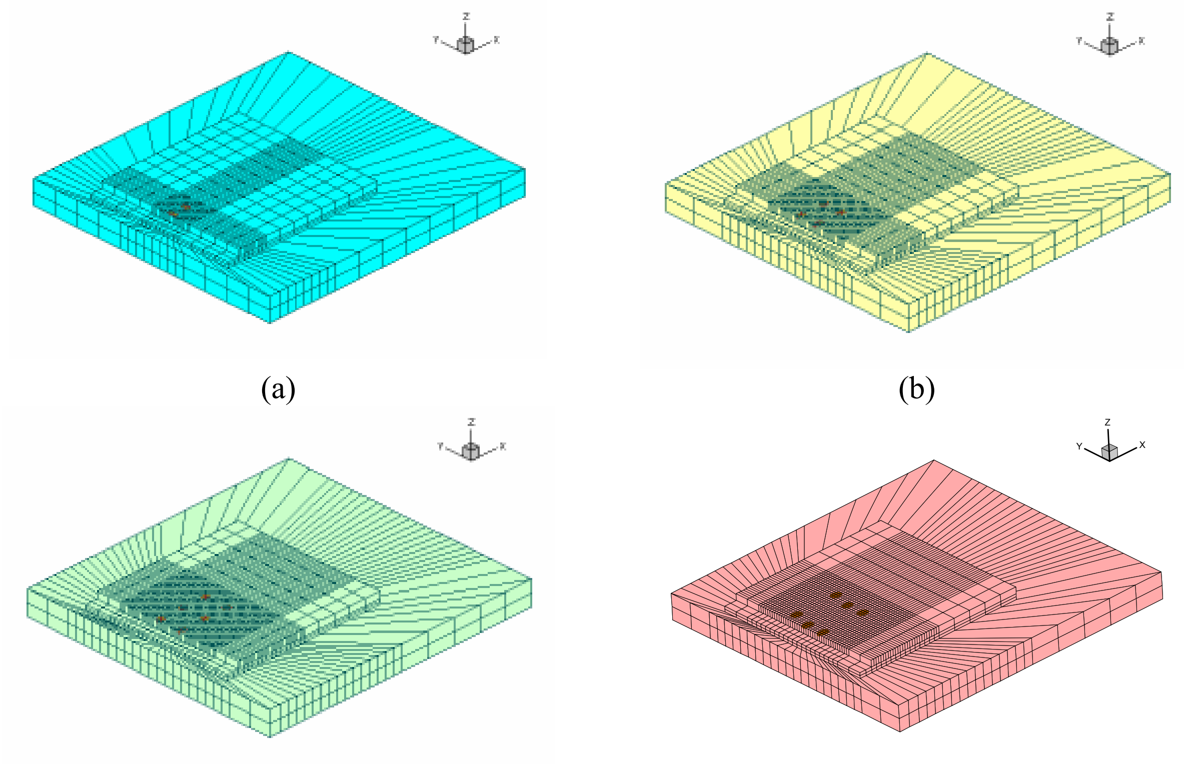
[a]desktop computer; Operating System: Microsoft Windows XP Professional; 1 GB RAM

The design algorithm implemented in LEDFAA 1.3, which is based on LEA for both flexible and rigid pavements, calculates a separate stress at each iteration point, for every aircraft in the traffic mix. Since the processing time required for an individual LEA computation using currently available PCs is not significant, this approach is reasonable. However, when 3D-FE was implemented for rigid pavements, it became apparent that modifications to the program design would be needed to reduce the number of time-consuming calculations. For example, considering a typical traffic mix of 20 aircraft, and assuming five iterations until convergence of the CDF to unity, this would have required approximately 100 individual calls to the internal 3D-FE computational engine. Based on the numbers in tables 3 and 4, this was certainly an excessive requirement. Therefore, a number of strategies were adopted that cumulatively reduced the level of computational effort to a point where it is practical for a routine office-based design procedure. These strategies have been discussed in detail elsewhere [2, 4, and 5], so they will only be listed here:

- All aircraft are grouped into one of the four categories shown in figure 1. Since the same 3D-FE mesh is used for all aircraft gears within a given category, the 3D-FE process needs to be called only once for each category, not once for each aircraft. Once the stress is computed for the first aircraft in the group, stresses for remaining aircraft are computed by backcalculation using the already decomposed stiffness matrix, a much less time-consuming process.

- A preliminary design is computed using LEAF to compute slab interior stresses (similar to the LEDFAA 1.3 procedure, but with modified interior-to edge stress transformation equations). The final design iterations are computed using 3D-FE. This step eliminates the need to use 3D-FE during early iterations, and gets the design thickness within "range" of the final value.

- Based on the preliminary LEAF-based design, those aircraft that exist in the traffic mix but contribute little or nothing to the total CDF are eliminated from further computations. This step prevents wasting computational effort on aircraft that have virtually no effect on the design thickness. For practical purposes, the threshold CDF contribution is internally set at 0.005. (For comparison, a CDF value of 1.0 indicates that the total pavement design life is consumed.)



(a) (b)

(c) (d)

Figure 1. FAArfield 3D-FE Meshes for Various Gear Configurations. (a) S or D (b) 2D (c) 3D (d) Complex Gear

NEW RIGID FAILURE MODEL

The failure model is the component of the overall design procedure that relates a computed response (vertical strain in the case of flexible pavements; horizontal PCC stress for rigid pavements) to the number of predicted coverages to failure. The failure model is empirical in that it is derived from analysis of full-scale traffic tests on test items with known loading and properties. In FAArfield 1.0, the rigid pavement failure model has been substantially revised based on analysis of full-scale tests at the NAPTF and re-analysis of historical rigid pavement test data. The model analysis has been discussed extensively in Brill et al. [5] and Brill [9].

The new rigid failure model is based on two regression equations (equations (1) and (2)), which were developed using data from full-scale tests conducted by the U.S. Army Corps of Engineers between 1945 and 1971 [10, 11, 12, 13, 14, 15, 16, 17, and 18], and from the NAPTF Construction Cycle 2 (CC2) full-scale tests conducted in 2004.

$$DF = 0.7409 + 0.2465 \times \log(C_O) \quad (1)$$

$$DF = 0.5878 + 0.2523 \times \log(C_F) \quad (2)$$

where :

C_O = coverages to onset of failure (first full-depth crack, SCI = 100)

C_F = coverages to full failure (shattered slab condition, SCI = 0)

DF = design factor, defined as R/σ, where *R* is the concrete flexural strength and σ is the computed concrete tensile strength, and

SCI = Structural Condition Index, as defined by Rollings [8].

The final failure equation implemented in FAArfield, using equations (1) and (2), has the following form:

$$DF = \left[\frac{F_s' bd}{(1-\alpha)(d-b) + F_s' b} \right] \times \log C + \left[\frac{(1-\alpha)(ad-bc) + F_s' bc}{(1-\alpha)(d-b) + F_s' b} \right] \tag{3}$$

where:

a = 0.5878, b = 0.2523, c = 0.7409, d = 0.2465,

C = coverages

α = SCI/100,

and F_s' is a compensation factor that accounts for a high-stiffness (stabilized) base. Note that equation (3) is linear in log (*C*) for any value of F_s'. This is a departure from the LEDFAA failure model, where values of the stabilized base compensation factor less than one made the failure curve strongly nonlinear, and is based on analysis of performance of stabilized base test items at the NAPTF.

ALGORITHM FOR RIGID OVERLAYS ON PCC PAVEMENTS

In the algorithm for design of rigid overlays on PCC pavements, it is assumed that the base PCC layer continues to deteriorate during trafficking after it is overlaid [8]. The deterioration is expressed by a reduction in the modulus of elasticity *E*, which must be accounted for in the design. First, the pavement life (or more specifically, that part of the pavement life during which the SCI of the base PCC deteriorates from its initial value to zero) is divided into *NSection* intervals. As shown in figure 2, the traffic coverages during each interval vary, by the SCI reduction is constant. In FAArfield, it was determined that optimal value for the *NSection* parameter is 16. For each interval, a reduced value of modulus of deteriorated PCC slab is calculated, and the stresses in rigid overlay are computed based on the reduced modulus.

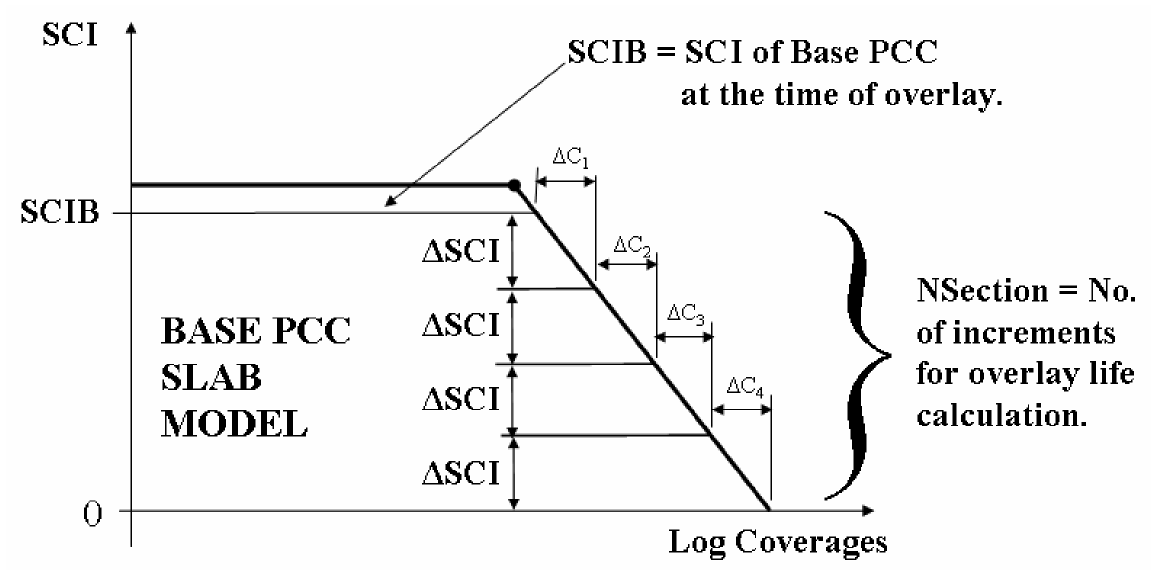


Figure 2. PCC Base Slab Deterioration Model for Rigid Overlay.

The incremental CDF for interval *i* is computed from:

$$CDF_i = \frac{\Delta C_i}{C_i} \quad (4)$$

where:

ΔC_i – number of coverages for interval *i*.

C_i – number of coverages for rigid overlay layer to reach SCI = 80 for interval *i*.

For each interval *i*, CDF is calculated, and the time required to apply ΔC_i to the overlay is added to the total life. For example, after the first two intervals, $CDF = \frac{\Delta C_1}{C_1} + \frac{\Delta C_2}{C_2}$ and the overlay life $t = t_1 + t_2$. These calculations are made for subsequent intervals, until the summation of CDF equals 1. The summation of time for all computed intervals is taken as the life of the rigid overlay. For design, this procedure is repeated until the computed life is 20 years, within a reasonable tolerance. The appropriate adjustments have to be made to the overlay thickness design procedure when the overlay design life is different than 20 years.

The above description is considerably simplified since it does not take into account mixed aircraft traffic, the case where the initial SCI is equal to 100 but some of the pavement life has nevertheless been consumed, etc. In FAArfield 1.0, the subroutines for the overlay design procedure were completely rewritten following the basic formulas. As a result, a number of errors in the earlier programming code were discovered and corrected. These did not result in significant errors in design thickness, but did cause the design to converge more slowly than it otherwise would. Therefore, the updated program justified a reduction in the default value of *Nsection* from 32 to 16, as noted above.

USER OPTIONS WINDOW

The user interface has been updated and now includes an Options window (Figure 3), giving the user the ability to modify many pavement structure options from a single location. Two variables give the user the ability to control the tolerance of pavement life computations in FAArfield. The *CDF Tolerance* parameter applies to the following pavement types: New Flexible, AC on Flexible, New Rigid, and PCC on Flexible. The *CDF Tolerance* parameter can be set in a range from 0.005 to 0.05. The *Life Tolerance* parameter applies to the following pavement types: AC on Rigid, PCC on Rigid (either unbonded or partially bonded overlays). The Life Tolerance parameter can be set in a range from 0.02 to 0.50. In general, the higher the tolerance, the shorter the execution time, but the less reliable the design.

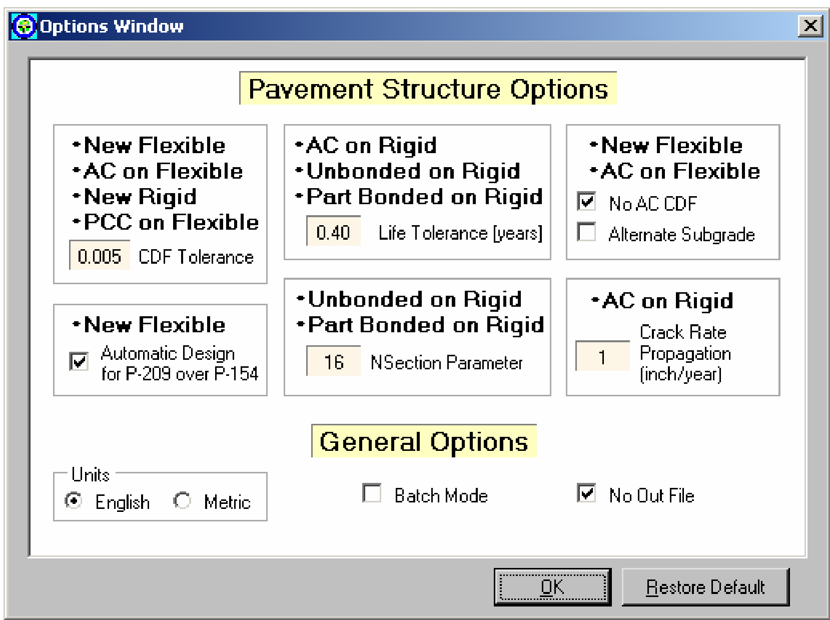


Figure 3. Options Window in FAArfield 1.0.

Other options the user of FAArfield can modify are:

- *Batch Mode*, *No AC CDF*, *Alternate Subgrade*, *No Out File*. These four options were previously available (in LEDFAA 1.3 and FEDFAA 2.0) by double-clicking on the grey background on the *Structure* window. Their functions are covered in the LEDFAA 1.3 user guidance and will not be discussed here.

- *Automatic Design for P-209 over P-154* - This option invokes an automatic design procedure for base thickness in flexible pavements. Currently it is implemented only for new conventional flexible pavements (i.e., item P-209, crushed aggregate base, over item P-154, aggregate subbase, and calculates a minimum P-209 thickness required to protect a subgrade of CBR 20. The procedure is described below. The release version of FAArfield will extend the automatic base design capability to include stabilized bases (item P-401).

- *NSection Parameter* - AS described above , this parameter applies only to unbonded on rigid and partially bonded on rigid pavement structures and defines the number of traffic intervals for which the elastic modulus of the PCC base layer is recalculated. The default value is 16.

- *Crack Rate Propagation* - Crack rate propagation defines how quickly a crack extends in inches (cm) over an AC overlay per year. The user can specify the value of crack rate propagation in a range from 0.2 to 2 inches (.5 – 5 cm).

- *Units* - Throughout the FAArfield program, units can be displayed in Metric or English by selecting the appropriate radio button.

AUTOMATIC DESIGN FOR P-209 OVER P-154 FOR NEW FLEXIBLE PAVEMENTS

FAArfield introduces a new capability of automatic design of base layers for flexible pavements. Currently, this function applies only to conventional (P-209, crushed aggregate) base layers on standard (P-154) subbases, but will be extended in the near future to include stabilized (P-401) bases. For the conventional case, if the option for automatic design has been selected (as shown in figure 3), the program first designs a P-209 base thickness sufficient to protect a subbase of CBR 20 (treating the P-154 subbase as a subgrade layer of assumed CBR 20), then designs the final thickness of P-154 material. The subbase CBR is fixed at 20 and is not user-selectable. The whole design process is performed in two steps as described using the following example. Table 5 shows the layer data for a new flexible pavement section. In the first step, the P-154 layer is removed, and the CBR of the subgrade is changed to the assumed value of 20. Next, the P-209 design thickness is calculated, as shown in Table 6. In step 2, the P-154 layer is returned to the pavement structure, the CBR of the subgrade is changed back to its original value of 10, and the design thickness for P-154 is calculated, as shown in Table 7. The example was based on the following traffic: DC8-63/73 (411 annual passes at gross weight 358,000 lbs.) and B737-300 (12,365 annual passes at gross weight 140,000 lbs.).

Table 5.
Example New Flexible Pavement Structure.

Layer	Thickness , in.	Elastic Modulus *E*, psi
P-401	4.00	200,000
P-209	10.00	75,000
P-154	16.00	40,000
Subgrade		15,000 (CBR=10)

Table 6.
Step 1, Automatic Base Layer Design (Conventional Flexible Pavement).

Layer	Thickness , in.	Elastic Modulus *E*, psi
P-401	4.00	200,000
P-209	13.84	70,744
Subgrade		30,000 (CBR=20)

Table 7.
Step2 , Automatic Base Layer Design (Conventional Flexible Pavement).

Layer	Thickness , in.	Elastic Modulus *E,* psi
P-401	4.00	200,000
P-209	13.84	68,544
P-154	9.49	24,787
Subgrade		15,000 (CBR=10)

RUN-TIME USER GUIDANCE

Run-time user guidance has been implemented in FAArfield 1.0 based on relevant provisions of AC 150/5320-6D [7]. It was implemented for the following paragraphs:

- §302.a. The standard design life for pavement section is 20 years.
- §303.a. Design for 95% Gross Aircraft Weight (GAW) on main gears.
- §320. Stabilized subbase is required for new flexible pavement for aircraft in excess of 100,000 lbs GAW.
- §328. Stabilized subbase is required for new rigid pavement for aircraft in excess of 100,000 lbs GAW.
- §409. Minimum thickness of PCC overlay on flexible is 5 in.
- §409. Minimum thickness of unbonded/partially bonded PCC overlay on rigid is 5 in.

As an example of how the user guidance has been implemented, Figure 4 shows a pavement section in the pavement structure window of the FAArfield program. The traffic consists of two aircraft: DC8-63/73 (gross taxi weight 358,000 lbs.), and B737-300 (gross taxi weight 140,000 lbs.). Since at least one of these aircraft weighs more than 100,000 lbs., and since the pavement section does not have any stabilized base, a warning message with the text “Non-Standard Structure” appears at the level of subgrade. If the user moves the cursor over the textbox and clicks on the left mouse button, a message box appears as shown in Figure 4, explaining the reason for the “Non-Standard Structure” message. In this particular case, when a pavement section is loaded with an aircraft weighing more than 100,000 lbs, according to §320 a pavement section should contain a stabilized base or subbase courses.

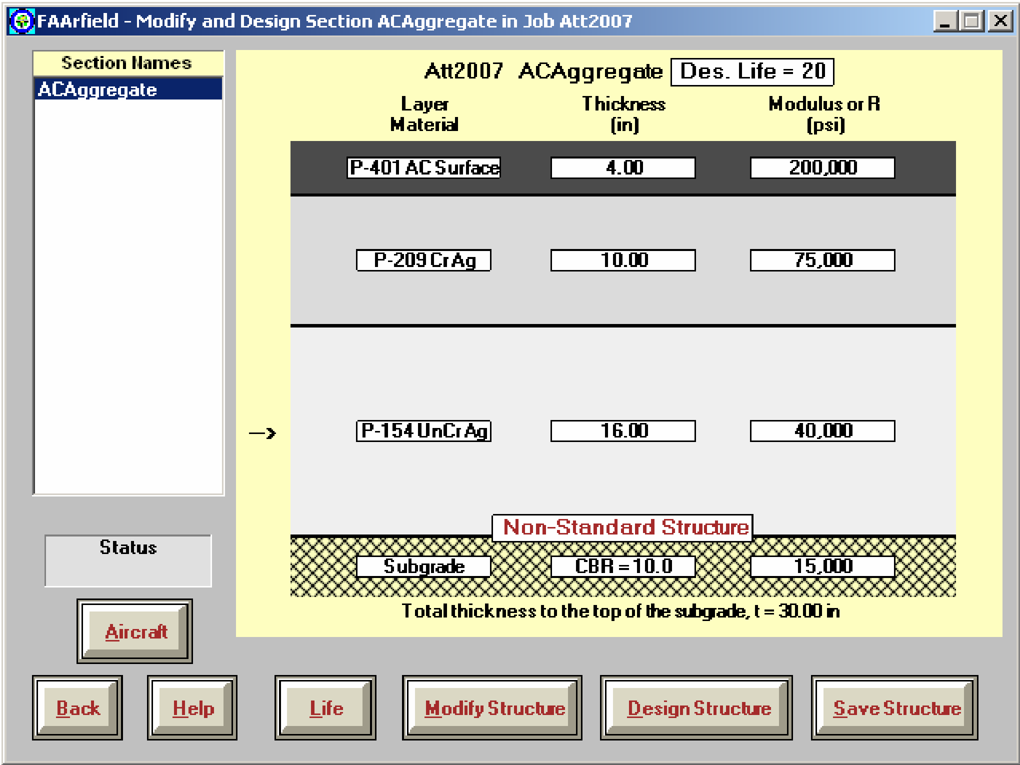


Figure 4. Pavement Structure Window.

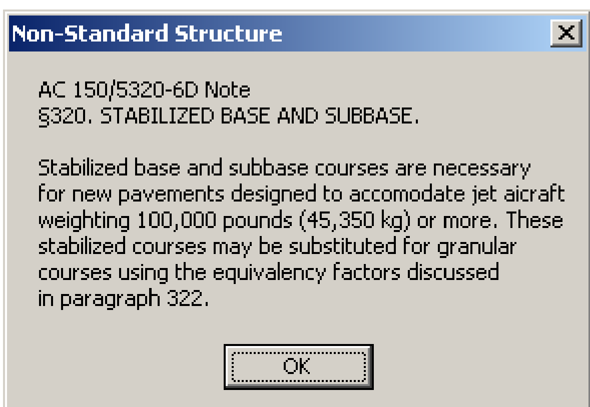


Figure 5. Non-Standard Structure Message.

THE INTERNAL FAARFIELD AIRCRAFT LIBRARY UPDATE

Finally, the internal FAArfield aircraft library has been updated to include additional Boeing, Airbus, Antonov and Ilyushin models, as well as general aviation airplanes.

Currently, an updated Boeing library list contains 36 aircraft, and Airbus 41 aircraft. Antonov models An-124 and An-225, Ilyushin models IL62, IL76T, and IL86, Tupolev models TU134A and TU154B have been added to the Other Commercial aircraft library category.

The Antonov aircraft are unique in that the An-124 has five duals in tandem (5D) and the An-225 has seven duals in tandem (7D). Therefore, the calculation of the coverage-to-pass ratio for flexible pavements had to be modified for these aircraft. Three cases are considered:

- Case 1: The total thickness of the flexible pavement is less than the tandem distance between duals. In this case, the coverage to pass ratio computed for one dual is multiplied by 5 for the An-124, and by 7 for the An-225.

- Case 2: The total thickness of the flexible pavement is greater than the tandem distance between duals, but less than twice the tandem distance between duals. In this case, the tandem factor for the coverage-to-pass ratio is calculated using equation (5) (for An-124) and equation (6) (for An-225).

$$Factor_{An-124} = 9 - 4 * \frac{T}{B} \tag{5}$$

$$Factor_{An-225} = 13 - 6 * \frac{T}{B} \tag{6}$$

where

T = total pavement thickness to the top of the subgrade.

B = tandem distance between duals (center to center of axles).

- Case 3: The total thickness of the flexible pavement is greater than twice the tandem distance between duals. In this case, the coverage-to-pass ratio for both the An-124 and the An-225 is equal to the ratio calculated for one dual (i.e., the tandem factor equals one.).

UPGRADING FAARFIELD TO VB.NET

Source code for LEDFAA 1.3 is written in Microsoft™ Visual Basic™ 6 (VB6) while FAArfield in the latest upgrade to Visual Basic product, Visual Basic 2005 which is the latest iteration of Visual Basic .NET. Since VB.NET breaks compatibility with VB6, there was a significant programming effort involved in migrating LEDFAA subroutines and functions to FAArfield Visual Basic 2005. However, the latest version of Visual Basic eliminated many of the shortcomings of VB6, for example, like poor error handling capabilities or “DLL hell” which refers to the set of problems that occurs when a program is behaving strangely or is no longer loading what can happen when some components of the program are written as dynamic link library, like LEAF. FAArfield, as VB.NET program, require one time installation of a set of files call .NET Framework, which can be downloaded free of charge from the Microsoft™

website. However, there are many positive advantages that include better memory management, easier testing, debugging, and supporting VB.NET applications over the long term.

CONCLUSIONS

This paper describes current progress in the FAA R&D effort aimed at the development of a new computer-based airport pavement design procedure which will be adopted by a forthcoming revision to the FAA's Advisory Circular (AC) 150/5320-6, "Airport Pavement Design and Evaluation" as the standard design procedure for design of civil airport pavements. FAArfield program demonstrates a successful application of a 3D-FE model for analyzing rigid pavements and practical implementation of NAPTF testing data in development of failure models. This paper shows that a significant progress was achieved minimizing 3D-FEM computation time, important corrections were made to the rigid overlay over rigid design algorithm, and user related improvements, including addition of user options window, run-time guidance and renovation of the built-in aircraft library. The FAArfield program is posted at the NAPTF website http://www.airporttech.tc.faa.gov/naptf/download/ and available to the general public for testing.

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