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State of the Practice in Pavement Structural Design/Analysis Codes Relevant to Airfield Pavement Design

Ernie Heymsfield and Jeb S. Tingle

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Jeb Tingle

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180

Ernie Heymsfield

Department of Civil Engineering
University of Arkansas
Fayetteville, AR 72701

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Preface

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ABSTRACT

An airfield pavement structure is designed to support aircraft live loads for a specified pavement design life. Computer codes are available to assist the engineer in designing an airfield pavement structure. Pavement structural design is generally a function of five criteria: the pavement structural configuration, materials, the applied loading, ambient conditions, and how pavement failure is defined. The two typical types of pavement structures, rigid and flexible, provide load support in fundamentally different ways and develop different stress distributions at the pavement – base interface.

Airfield pavement structural design is unique due to the large concentrated dynamic loads that a pavement structure endures to support aircraft movements. Aircraft live loads that accompany aircraft movements are characterized in terms of the load magnitude, load area (tire-pavement contact surface), aircraft speed, movement frequency, landing gear configuration, and wheel coverage.

The typical methods used for pavement structural design can be categorized into three approaches: empirical methods, analytical (closed-form) solutions, and numerical (finite element analysis) approaches. This article examines computational approaches used for airfield pavement structural design to summarize the state-of-the-practice and to identify opportunities for future advancements. United States and non-U.S. airfield pavement structural codes are reviewed in this article considering their computational methodology and intrinsic qualities.

1. Introduction

The large concentrated dynamic loads that a pavement structure supports during aircraft movements make airfield pavement structural design unique. The typical methods used for pavement structural design can be categorized into three approaches: empirical methods, analytical (closed-form) solutions, and numerical (finite element analysis) approaches. This article summarizes the computational approaches used for pavement structural design and the computer codes that are available for airfield pavement structural analysis/design. The article is organized by first providing the reader with background on the computational approaches used for flexible pavement and rigid pavement structural design. The Computational Solution Approach section familiarizes the reader with similar theoretical approaches found among existing airfield flexible and rigid pavement structural codes. In the subsequent sections, U.S. and non-U.S. airfield pavement structural codes are reviewed considering their computational methodology and intrinsic qualities. The final section includes conclusions from this study.

2. Computational solution approach

Flexible pavement structural analysis/design software codes typically use the layered elastic design (LED) approach. Conversely, rigid pavement structural analysis/design typically is conducted using variations of a Westergaard analysis or the finite element method. Pavement structural codes incorporate transfer functions to convert the calculated stress/strain mechanistic values into flexible pavement behavior or distress. Transfer functions include the effect of multiple wheel loads, dynamic loading, and fatigue behavior. Pavement structural codes are generally configured as an analysis tool to determine pavement behavior summarized at the end of the pavement design life as the cumulative damage factor (CDF), or as a design tool to iteratively determine the required pavement thickness necessary to limit pavement distress during the pavement design life.

Computer codes that use the layered elastic design approach (LED) or the Westergaard solution approach are numerical applications of analytic solutions. The LED approach assumes axisymmetry. The Westergaard solution is limited in terms of pavement configuration and the pavement foundation structure. Flexible pavement structural codes and rigid pavement structural codes are available that incorporate the finite element method (FEM). The finite element analysis approach avails the engineer to more accurately model the actual pavement structure problem. The basis of the FEM is to subdivide (discretize) the problem domain into multiple elements. Force equilibrium for each element within the discretized domain must be satisfied, which leads to a series of equations that can be written in matrix form as [1]:

$$[K]\{\delta\} = \{F\} \tag{1}$$

where K is the global stiffness matrix of the entire problem domain, δ is a vector comprised of node deformations (displacement and rotation) and F is a vector including the externally applied node forces. The K matrix is symmetric through the reciprocal theorem. For rigid pavement structures, load transfer between adjacent slab panels due to dowels and aggregate interlocking is typically modeled using springs located at the node points.

2.1. Numerical method input information

Input for pavement structural design codes typically includes entries related to live load traffic, material characterization, ambient conditions, and design metrics (reliability, design life). The accuracy of the results is dependent on the accuracy of the input data and mesh discretization. Some codes use default values when site-specific values are unavailable. Consequently, differences between two code results may be partially attributed to default values included internally within the code.

Material layers in the pavement structure are defined by the pavement structural configuration (geometry), material properties (elastic modulus and Poisson's ratio), and pavement distress values. For flexible pavements, the pavement distress is typically related in terms of fatigue cracking and rutting. For rigid pavements, pavement distress is typically related to cracking and joint failure.

Ambient conditions are most frequently described in terms of temperature and moisture. Asphalt concrete surface materials typically used in flexible pavement designs are temperature sensitive. The elastic modulus for the asphalt concrete surface layer is dependent on material temperature, loading rate, and pavement age. Rigid pavement behavior is also sensitive to daily temperature change. The temperature gradient from the exposed rigid pavement surface to the pavement base causes pavement curling. In addition, uneven rigid pavement moisture content within the pavement slab results in pavement warping. Both conditions cause the rigid pavement to have a nonuniform contact surface between the pavement base and foundation. Consequently, sections of the pavement slab will separate from the foundation material causing additional pavement stresses. For both pavement materials, frost penetration depth must be considered for possible impact on the foundation material.

2.2. Failure criteria

Damage models are used to convert computer code calculated pavement mechanistic response values to pavement distress. Damage models are often referred to as transfer functions. Flexible pavement failure is manifested through fatigue cracking, temperature cracking, and surface distress. Surface distress results in increased pavement roughness and reduced pavement structural strength. Rigid pavement failure is displayed through fatigue cracking, faulting at transverse joints, punch-out, and surface roughness.

2.3. Flexible pavement structural analysis

Computer codes used for flexible pavement structural analysis typically use the layered elastic design (LED) approach, however FEM for flexible pavement design are available. Chen et al. [2] performed an early review of computer codes for flexible pavement structure analysis. Five computer codes were evaluated by Chen et al. [2]: ILLI-PAVE, MICH-PAVE, ABAQUS, DAMA, and KENLAYER. Table 1 includes the Chen et al. [2] comparison between these flexible pavement codes.

The weakness in the LED approach in flexible pavement structural analysis is how the approach approximates nonlinear soil behavior. Although layered elastic analysis codes may include a nonlinear material component, the approximate material property value is derived using an iterative process. This approximated value is then applied as a constant material property value to the entire plate layer. The treatment of nonlinear material behavior as a constant by the LED approach may lead to erroneous tensile stresses in the granular material layers. An expanded summary of the two LED computer codes listed in Table 1 is included in Table 2. Chen et al. [2] concluded that the DAMA computer code was best suited for pavement engineers to use to perform common pavement structural

Table 1
Computer codes for flexible pavement design [2].

COMPUTER code	ANALYSIS	PAVEMENT model	FOUNDATION model
ILLI-SLAB	FEM, 2-D axisymmetric	2-D plate elements	2-D plate elements
MICH PAVE	FEM, 2-D axisymmetric	2-D plate elements	2-D plate elements
ABAQUS	FEM, 3-D	3-D brick elements	3-D brick elements
DAMA	layered elastic design	horizontally infinite plate	horizontally infinite plate
KENLAYER	layered elastic design	horizontally infinite plate	horizontally infinite plate

Table 2
Layered elastic design computer codes for flexible pavement design [2].

	COMPUTER CODE	
	DAMA	KENLAYER
Analysis	Layered elastic design	Layered elastic design
Pavement Model	Linear elastic; constant MR within the layer	Linear elastic; constant MR within the layer
Foundation Model	Subgrade; linear elastic layers, constant MR within the layer Granular base; nonlinear elastic, constant MR within the layer	Subgrade; linear elastic layers, constant MR within the layer Granular base; nonlinear elastic, constant MR within the layer
Pavement-Foundation	Full contact	Full contact
Foundation-Foundation	Full contact	Full contact
Loading	Applied over circular area, dual wheel	Applied over circular area, dual wheel
error	Tensile stress in granular material	Tensile stress in granular material

analyses.

Table 1 includes two, two-dimensional (2-D) finite element analysis codes, ILLI-PAVE and MICH-PAVE [3,4]. The surface pavement domain in these two codes is modeled as multi-layer axisymmetric plates comprised of concentric rings. The remaining pavement structure is similarly modeled as concentric rings of varying thickness. Therefore the three-dimensional (3-D) problem is analyzed as a 2-D axisymmetric problem. Consequently, mechanistic values are independent of their circumferential location for a given radial and depth coordinate. Nonlinear soil material models are included that use the principal stress within the material layer at each iterative calculation step and the Mohr-Coulomb failure theory. Table 3 is an expanded summary of the two FEM codes.

In Table 1, ABAQUS is a commercially available 3-D FEM code. A 3-D FEM code is best able to capture the nonlinear behavior of the pavement structure foundation material and the viscoelastic pavement behavior. However, the improved accuracy comes at the cost of the number of user input entries required and computation time. A summary of the code is included in Table 4.

2.4. Rigid pavement structural analysis

Typically, a Westergaard analysis approach or the finite element method is used for rigid pavement analysis. The 2-D FEM enables modeling the rigid pavement structure as a stiff plate on a foundation subjected to asymmetric loading. The foundation material is modeled as a Winkler foundation, solid, or layered foundation. The Winkler foundation models the pavement foundation as a set of axial force springs. Conversely, the solid foundation and layered foundation approaches consider the foundation material as a continuous medium. The solid foundation is considered as a half-space and uses the Boussinesq equation for a solution. Conversely, the layered foundation approach models the pavement foundation as a set of layers using the Burmister LED approach.

The FEM approach is capable of capturing the interaction between the rigid pavement surface and the supporting pavement structure material without assuming axisymmetric behavior, which is used for flexible pavement structural analysis. Table 5 includes an overview of finite element codes that are available for rigid pavement structure design/analysis [5].

Table 3
2-D FEM computer codes for flexible pavement design [2].

	COMPUTER CODE	
	ILLI-PAVE	MICH-PAVE
Analysis	FEM, 2-D axisymmetric	FEM, 2-D axisymmetric
Pavement Model	non-linear resilient modulus	Non-linear resilient modulus 2-
Foundation Model	2-D plate elements Failure criteria (granular materials and fine grained soils); Stresses modified to satisfy Mohr-Coulomb failure envelope Constitutive relation: nonlinear	D plate elements Failure criteria (granular materials and fine grained soils) Stresses modified to satisfy Mohr-Coulomb failure envelope Constitutive relation: nonlinear
Vertical Boundary	Rigid boundary	Flexible boundary, assuming a homogeneous elastic half-space underneath
Radial Boundary	12* applied load radius	10* applied load radius
Live Load	Single load within a circular area	Single load within a circular area

Table 4
3-D FEM Computer code for Flexible Pavement Design [2].

	COMPUTER CODE
	ABAQUS
Analysis	FEM, 3D
Pavement Model	3-D brick elements, non-linear
Foundation Model	3-D brick elements, non-linear
Vertical Boundary	Full contact
Loading	Live load applied over a rectangular area, dual wheels, Material self weight

Table 5
FEM Computer codes for Rigid Pavement Design [5].

COMPUTER CODE	PAVEMENT MODEL	FOUNDATION MODEL	PAVEMENT - FOUNDATION INTERFACE
ILL-SLAB & SLAB 2000	2-D plate elements	Winkler Model, Boussinesq, nonlinear resilient, 2 parameter model, 3 parameter model	linear springs
JSLAB	2-D plate elements	Winkler Model	linear springs
WESLIQUID	2-D plate elements	Winkler Model	linear springs
KENSLAB	2-D plate elements	Winkler Model	linear springs
FEACONS III	2-D plate elements	Winkler Model	linear springs and torsional springs
EverFE 2.24	3-D brick elements	Winkler Model	linear springs and nonlinear springs, joint elements
ABAQUS	2-D plate elements 3-D brick elements	Winkler Model, 3-D brick elements (linear / nonlinear elastic, plastic, viscoelastic), user defined model	linear springs and nonlinear springs, joint elements
ANSYS	3-D brick elements	Winkler Model	linear springs and nonlinear springs, joint elements

ABAQUS and ANSYS are robust general application 3-D FEM codes that are applicable for rigid pavement analysis. Studies by Huang and Wang [6,7], Huang [8], Darter and Barenberg [9], and Chou and Huang [10] validated using the FEM approach for rigid pavement design by showing good agreement between the FEM and actual field measurements.

In the following sections, computer codes used for airfield pavement structural design are reviewed. Pertinent issues to describe these computer codes include: the theory used in determining the mechanistic values, loads, loading conditions, material characterization, and failure basis. Additional factors include the code organization, computer language, required input entries, default values, and effects due to ambient conditions.

3. Airfield pavement structure computer codes

3.1. FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layer Design Program)

U.S. Part 139 airfield pavements are required to be designed using FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layer Design program) to be Federal Aviation Administration (FAA) compliant. Consequently, the FAARFIELD airfield pavement structural pavement design code is most relevant to US airfield pavement engineers. The FAA formulated the FAARFIELD computer code specifically for airfield pavement structural design. The FAARFIELD computer code is used for both flexible pavement design and rigid pavement design. The FAARFIELD code is compliant with Advisory Circular (AC) 150/5320-6F specifications [11]. FAARFIELD uses a mechanistic-empirical design approach to determine the pavement thickness required for a 20-year design life. FAARFIELD is briefly described in the user help file that accompanies the computer code. Historical references providing details about FAARFIELD are included in Barker and Brabston [12], Parker et al. [13], Rollings [14], and Barker and Gonzalez [15]. References describing the recent developments of the FAARFIELD computer code are included in AC 150/5320-6F [11], Brill and Kawa [16], Tuleubekov [17], and Wang and Chen [18].

FAARFIELD runs in the Microsoft Windows environment. The FAARFIELD computer code is organized as two core subprograms, LEAF for flexible pavement design and NIKE3D for rigid pavement design. LEAF is a Microsoft Windows dynamic link library coded in Visual Basic 2013 and NIKE3D is a 3-D finite element analysis subprogram coded in Intel Visual Fortran. NIKE3D is a general purpose 3-D finite element computational code that was developed by the Lawrence Livermore National Laboratory (US DOE) and modified by the FAA. Input for NIKE3D is developed through the Microsoft Windows dynamic link library, FAAMesh. The other FAARFIELD computer modules are written in Visual Basic 2013.

The LEAF subprogram in FAARFIELD is a layered elastic computational program employed for flexible pavement design. The LEAF subprogram was originally a subprogram within the earlier FAA pavement design code, LEDFAA (layered elastic design FAA).

The FAA initially implemented the LEDFAA design approach to more accurately model pavement response due to the B777 dual tridem main landing gear [19]. LEDFAA was formulated using the layered elastic design approach and complied with FAA Advisory Circular (AC) 150/5320–16 [19]. The LEDFAA code represented the first iteration by the FAA to move from a purely empirical approach to a mechanistic-empirical approach. AC 150/5320–16 was cancelled in 2004 and replaced with AC 150/5320-6D (change 3), which allowed using the LED approach as an alternative design approach for all aircraft types [20]. AC 150/5320-6D was cancelled in 2009 and replaced with AC 150/5320-6E [21], which required pavement design using the FAARFIELD computer code. Prior to NIKE3D, FAA rigid airfield pavement design used an empirical approach including design curves based on a modified Westergaard solution for edge-loaded slabs as a function of the modulus of subgrade reaction.

The two approaches, the layered elastic design, LEAF, for flexible pavement design, and the finite element analysis, NIKE3D, for rigid pavement design, differ in the accuracy of the calculated mechanistic values and their computational speed. The computation time is generally longer for rigid pavement design than for flexible pavement design. To reduce rigid pavement computation time, FAARFIELD uses the LED as a preliminary design tool and then uses the 3-D FEM in the final design computation steps for calculating the mechanistic values. Full-scale test results were used to develop transfer functions for converting the mechanistic response values calculated by LEAF and NIKE3D into pavement distress. The full-scale tests include work conducted by the U.S. Army Engineer Waterways Experiment Station and more recent pavement testing performed at the FAA William Hughes Technical Center, National Airport Pavement Test Facility (NAPTF).

The end result of a pavement structural design using FAARFIELD is the design pavement thickness. The methodology used in determining the pavement thickness is an iterative process using the CDF and a 20-year pavement design life. The CDF considers the contribution of each aircraft that the design pavement is subjected to rather than the traditional single critical aircraft loading. Therefore, this approach calculates response due to the actual predicted aircraft traffic mix. Aircraft wheel configurations along with aircraft lateral wander are considered when determining the pass/coverage ratio, the number of repetitions a pavement point is subjected to an aircraft tire load. The pass/coverage ratio is calculated at the pavement surface for rigid pavement structures and at the top of the subgrade for flexible pavement structures. Aircraft wander is a measure of lateral eccentricity from the runway centerline. Aircraft wander is assumed to satisfy a normal distribution with a 775 mm (30.5-in) standard deviation.

Input information is entered into the FAARFIELD code through the FAARFIELD user entry interface. Input can be entered using either US customary units or metric dimensional units. If not specified, US customary units are used in FAARFIELD as default. Required user input includes: pavement layer properties, aircraft types, aircraft gross loads, annual aircraft departures for each aircraft type, and aircraft departure growth rate. The FAARFIELD user entry interface includes three major components: STARTUP, STRUCTURE, and AIRPLANE. The STARTUP component controls the code operations for data entry. The STRUCTURE component controls data entry for the pavement structure. Aircraft used for the pavement structural design are entered through the AIRPLANE component. Aircraft types used for the pavement structural design are included in the FAARFIELD AIRPLANE library along with each aircraft's geometry and wheel configuration. FAARFIELD assumes that 95% of the aircraft gross weight is applied through the main landing gear. The aircraft tire contact area is a function of the load and tire pressure. The tire-pavement interface is assumed as a rectangular contact surface for rigid pavement design and a circular contact surface for flexible pavement design. Both pavement types use an elliptical tire contact surface for the pass/coverage (P/C) ratio calculation.

FAARFIELD is capable of designing seven different pavement structure types:

1 New flexible pavement,
2 New rigid pavement,
3 Hot mix asphalt (HMA) overlay on an existing flexible pavement surface,
4 HMA overlay on a rigid pavement surface,
5 Partially-bonded PCC overlay on an existing rigid pavement surface,
6 PCC overlay on a flexible pavement surface, and
7 Unbonded PCC overlay on an existing rigid pavement surface.

New flexible pavement, new rigid pavement, HMA overlay on flexible pavement, and Portland Cement Concrete overlay on flexible pavement are designed based on attaining a cumulative damage factor (CDF) equal to 1 at the end of the pavement design life. Each aircraft wheel coverage contributes to the CDF based on Miner's rule [22]. The CDF calculation is performed using an iterative process until the CDF value is approximately equal to 1. FAARFIELD default values use a ± 0.005 tolerance for CDF and ± 0.40 years for life tolerance. Overlay design problems require input for the existing pavement condition in order to estimate the remaining pavement design life. The existing pavement condition is quantified through the Structural Condition Index (SCI) and the Cumulative Damage Factor Used (CDFU). The Structural Condition Index (SCI) is an index value (0 to 100) that provides a metric for pavement condition [14]. It is similar to the Pavement Condition Index (PCI), however the SCI only includes pavement distresses associated with load related damage [14]. The Cumulative Damage Factor Used (CDFU) represents the fatigue damage endured by the base pavement before an overlay is placed [14]. HMA overlay on rigid pavement, unbonded PCC overlay on rigid pavement, and partially-bonded PCC on rigid pavement are designed using an iterative process based on a 20-year design life. Eighteen layer types are available in the FAARFIELD user interface to help the user construct the pavement structure model. FAARFIELD calculates the aggregate layer modulus internally based on the input material type. FAARFIELD subdivides the aggregate layer into sublayers.

FAARFIELD user benefits include the capability of executing multiple pavement structure designs sequentially using a batch option. Output files are written in Extensible Markup Language (XML) file format, which allows the user to import FAARFIELD output files into other files written in applications supporting XML format.

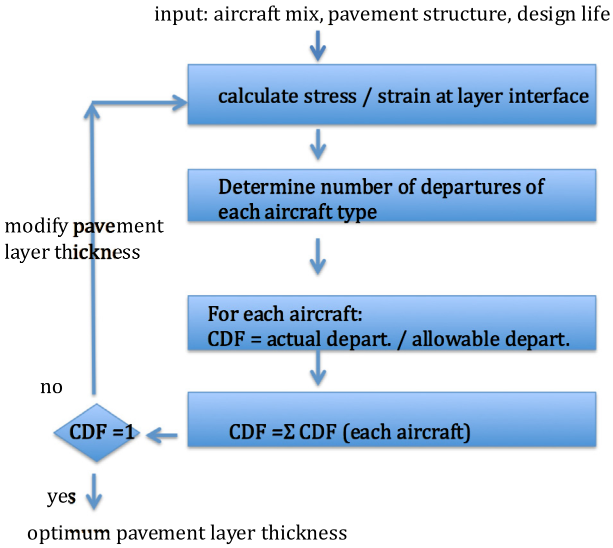

Fig. 1. FAARFIELD solution process.

3.1.1. Design approach

The FAARFIELD outline for pavement structural design is summarized in Fig. 1. The figure illustrates the iterative solution process used in FAARFIELD to determine layer thickness based on the cumulative damage factor and design life. The design methodology consists of 4 analysis steps: input (aircraft mix, pavement structure, design life), mechanistic calculations (stress/strain), aircraft departures, and pavement distress.

3.2. *Alize-airfield*

The French Aviation Authority (Directorate General for Civil Aviation, DGAC) is transitioning to a mechanistic-empirical approach for its airfield pavement design. The current French airfield design approach uses the CBR method for flexible pavement design and the Portland Cement Association (PCA) method for rigid pavement structural design [23]. This current French airfield design approach is included in the French design software DCA, Dimensionnement des Chaussees Aeronautiques [24]. However, the DCA software does not include: new material testing results, temperature effects, and new large aircraft (NLA) landing gear configurations. Consequently, the DGAC has adopted a new design policy to remedy these deficiencies. The new policy is outlined in the design guide "Rational Design Method for Flexible Airfield Pavements" [25]. An English version of the design guide is available.

The Alize-Airfield computer code incorporates this new approach for flexible pavement structural design. The Alize-Airfield computer code was developed by the French Civil Aviation Technical Center (STAC) and the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR). The code is mechanistic in nature and uses empirical relationships to convert calculated stress/strain response values to predicted pavement distress, Fig. 2. Alize-Airfield is a modified version of the Alize-Lcpc computer software currently used for French roadway design [26]. The current French airfield pavement design approach for rigid pavement structural design continues to use the PCA method. However, a new module using the FEM is being developed by STAC to be included in the Alize-Airfield computer code.

The empirical relationships, transfer functions, in Alize-Airfield used to convert the calculated mechanistic response values to pavement distress were developed from the A380 Pavement Experimental Program (PEP). The PEP testing program was conducted between 1998 and 2001 by AIRBUS at the Toulouse-Blagnax Airport in France. The experimental program included flexible pavement

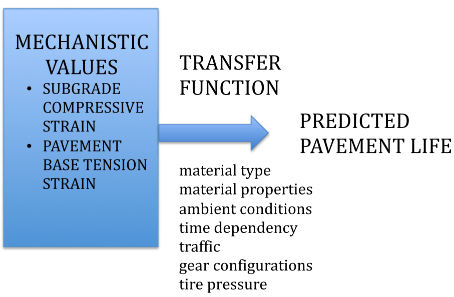

Fig. 2. Alize-Airfield Outline.

[27] and rigid pavement [28] testing.

Alize-Airfield calculates strains at multiple points within a horizontal plane at various vertical depths. The multiple strain values at each vertical depth allow the user to analyze aircraft wander effects. These multiple calculated strain values provide a resource to develop isostrain value plots. In comparison, FAARFIELD calculates strain values at a smaller number of points within the horizontal plane. Similar to FAARFIELD, Alize-Airfield uses an iterative approach for pavement structural design. An initial pavement structure with material types is used as input. Material layer thicknesses are modified through an iterative process until a cumulative damage value of 1 is attained at the pavement design life. French airfield pavements are typically designed for a ten-year design life. Alize-Airfield allows for the user to specify the amount of permissible damage over the pavement design life as a "risk of failure" in the damage calculation. The "risk of failure" is equivalent to establishing a maximum acceptable percentage of pavement length that can experience distress and still be considered acceptable.

3.2.1. *Material characterization*

Asphalt concrete material behavior is dependent on the loading frequency and temperature. The elastic modulus (*E*) for each layer within the surface course is determined by the Alize-Airfield code based on temperature and loading frequency. The Poisson's ratio is set at 0.35 for each asphalt concrete layer. Alize-Airfield uses a simple relationship to convert the static analysis load to an equivalent dynamic load using aircraft speed:

$$f = V/10 \tag{2}$$

where f is frequency (hertz, cycles/s) and V is aircraft velocity in km/h. Aircraft velocity is a function of the particular airside section (apron, taxiway, runway) being analyzed. Within the airfield, the runway section experiences high aircraft speed; therefore, a velocity of 100 km/h is used. However, taxiways and aprons use smaller values of V, 30 km/h and 10 km/h, respectively, for the frequency calculation. Temperature dependency is incorporated into the Alize-Airfield analysis using an "equivalent temperature". The equivalent temperature represents an average temperature used in the CDF calculations. For France, the equivalent temperature is 15 °C. Increasing the loading frequency (equivalent to an increased aircraft speed) or lowering the ambient temperature leads to a higher material stiffness. Conversely, decreasing the loading frequency (equivalent to lowering the aircraft speed) or increasing the ambient temperature leads to a lower material stiffness.

3.2.2. *Aircraft load characterization*

Alize-Airfield stores aircraft parameters within an internal aircraft library. The Alize-Airfield aircraft library includes 250 aircraft types, which cannot be user modified. The pass/coverage ratio approach used in FAARFIELD is not used in Alize-Airfield for aircraft wander. Instead a probabilistic approach is incorporated where each wheel load is considered as an individually applied load. The applied wheel load is modeled as a uniform vertical pressure applied within a circular contact area. The size of the circular area is calculated based on the aircraft tire pressure. Aircraft wander is assumed to occur with a normal distribution. Aircraft in higher speed areas experience greater wander than in low speed areas. Consequently, the standard deviation for the normal distribution is assumed at 0.75 m within the runway area, 0.5 m on the taxiways, and 0 m within the apron areas.

3.2.3. *Damage model*

Two failure modes are considered in the Alize-Airfield analysis approach: tensile strain at the bottom of the asphalt concrete (ε_t), which is a metric of fatigue failure of the asphalt mix, and vertical strain at the top of the subgrade (ε_{zz}), which is a measure of subgrade failure (rutting). ε_t and ε_{zz} are calculated at the level of interest at multiple grid points on a horizontal plane intersecting the point of interest.

The incremental change in damage, ΔD, is:

$$\Delta D = \frac{1}{N(\mathcal{E}_{max})} = \left(\frac{\mathcal{E}_{max}}{K}\right)^{\beta} \tag{3}$$

where $\mathcal{E}_{max}$ is the maximum strain induced by the aircraft wheel load, N is the number of load applications at $\mathcal{E}_{max}$ to cause failure, and β and K are damage parameters. Damage parameters for granular materials were developed empirically from lab results from the French National Institute of Science and Technology for Transport, Development and Networks (LCPC), and from in-place highway/airfield pavement observations. The default damage parameters used for granular materials are: $K = 16{,}000$ and $\beta = 4.5$, which are based on lower bound values.

For asphalt concrete materials, damage parameters are dependent on material fatigue characteristics, temperature effects, scatter, and subgrade material behavior [29]:

$$K = 10^{6/\beta} k_{Tf} k_s k_r k_c \bar{\varepsilon}_{10**6} \tag{4}$$

where.$\bar{\varepsilon}_{10**6}$ = strain resulting from a fatigue test using 106 cycles at 25 hz/10 °C,k_{Tf}= temperature and frequency parameter,k_s = subgrade bearing capacity heterogeneity,k_r = probabilistic issues, and.k_C = calibrating factor between field performance and experimental.

Based on experimental results, β is set equal to 5.

The cumulative damage calculation procedure in the Alize-Airfield code uses Miner's rule, but with continuous integration. Consequently, unloading along the wheel path between wheel loadings during aircraft movement in a multiple axle configuration reduces damage. For example, the incremental change in damage for a tridem gear configuration is [30]:

$$\Delta D_{tridem} = \left(\frac{\varepsilon_{t\ wheel1}}{K}\right)^{\beta} - \left(\frac{\varepsilon_{t\ unloading\ 1-2}}{K}\right)^{\beta} + \left(\frac{\varepsilon_{t\ wheel2}}{K}\right)^{\beta} - \left(\frac{\varepsilon_{t\ unloading\ 2-3}}{K}\right)^{\beta} + \left(\frac{\varepsilon_{twheel3}}{K}\right)^{\beta} \tag{5}$$

where $\varepsilon_{t\ wheel1}$ is the tensile strain developed from wheel 1 loading, $\varepsilon_{t\ wheel2}$ is the tensile strain developed from wheel 2 loading, $\varepsilon_{t\ wheel3}$ is the tensile strain developed from wheel 3 loading, $\varepsilon_{t\ unloading\ 1-2}$ is the tensile strain between wheel 1 and wheel 2 loading, and $\varepsilon_{t\ unloading\ 2-3}$ is the tensile strain between wheel 2 and wheel 3 loading. The unloading that occurs between wheel loadings reduces the incremental damage.

3.2.4. Freeze-thaw

A frost atmospheric index, *I*, within Alize-Airfield is determined using one-dimensional heat propagation theory and ambient air temperature data. The frost quantity, $Q_{CALCULATED}$*(subgrade)*, is calculated at the top of the subgrade and compared with the allowable frost quantity, $Q_{ALLOWABLE}$*(subgrade)*. If the calculated value, $Q_{CALCULATED}$*(subgrade),* does not exceed the allowable, $Q_{ALLOWABLE}$*(subgrade),* freeze-thaw will not govern the pavement structure design.

3.2.5. Sensitivity analysis

Caron et al. [31] performed a computational sensitivity analysis between Alize-Airfield and FAARFIELD to compare the two pavement structural design codes. FAARFIELD 1.302 and Alize-Airfield 4.1.0 were compared considering nine flexible pavement structures. The sensitivity analysis included pavement structures with three different CBR subgrades (3, 8, and 15) and three different aircraft loadings: A320, B777-300ER, and a heavy aircraft mix (A340–600, B777-300ER, A380–800, and B747—200B). Aircraft gross weight, subgrade CBR, base asphalt thickness, surface asphalt modulus, base asphalt modulus, and aircraft number of passes were varied to examine the sensitivity of each code's calculated cumulative damage factor to these parameters.

The CDF sensitivity at the top of the subgrade is summarized in Table 6 for the two computer codes [31]. For the given parameters, the cumulative damage factor is most sensitive to aircraft gross weight. Both computer codes show high damage factor sensitivity to subgrade CBR and base asphalt thickness. Both computer codes showed low sensitivity to: surface asphalt modulus, base asphalt modulus, and number of passes. At the top of the subgrade, the CDF calculated using FAARFIELD is more sensitive to input data than ALIZE AIRFIELD. The CDF sensitivity at the bottom of the asphalt base layer is summarized in Table 7 for the Alize-Airfield computer code [31]. The CDF calculated by Alize-Airfield is highly sensitive to aircraft gross weight and base asphalt thickness considering the given parameters. The CDF is moderately sensitive to the asphalt modulus and insensitive to the subgrade CBR and number of aircraft passes.

3.3. PCASE pavement-transportation computer assisted structural engineering

PCASE (Pavement-Transportation Computer Assisted Structural Engineering) is a computer code developed by the U.S. Army Engineer Research and Development Center (ERDC) for designing and evaluating pavement systems [32]. It is used by the U.S. military for airfield and roadway pavement structural design and analysis. PCASE is a Windows-based computer code configured in modules: traffic; design; evaluation; dynamic cone penetrometer evaluation (DCP); and material characterization using non-destructive testing equipment and back calculation.

3.3.1. Flexible pavement

For flexible pavement structural design, the PCASE user can choose between the CBR empirical design approach and the LED approach. In the CBR empirical approach, PCASE determines the required layer thicknesses based on user supplied CBR values for the pavement structure base, subbase, and subgrade. CBR values for the base course are limited to: 100, 80, and 50 based upon US Department of Defense material specification criteria. The 50 CBR value is restricted to roadway design. PCASE allows for the flexible pavement structure to include a drainage layer.

In the LED approach, an elastic modulus and Poisson's ratio are used for material characterization instead of CBR. PCASE default values for material characterization in a flexible pavement structure using LED are included in Table 8. However, the user can input

Table 6
Cumulative damage factor (CDF) sensitivity at top of subgrade (ranking 1 = most sensitive) [37].

Computer Code	Senstvty Level	Arcrft GWt	Subgrd CBR	Base Asphlt t	Surface Asphlt Mod.	Base Asphlt Mod.	No. of Passes
FAARFIELD	High	X	X	X			
		1 (most sensitive)	2	3			
	Low				X	X	X
ALIZE AIRFIELD	High	X	X	X			
		1 (most sensitive)	2	3			
	Low				X	X	X

(note: Senstvty Level = Sensitivity Level; Arcrft GWt = Aircraft Gross Weight; Subgrd CBR = subgrade CBR; Base Asphlt t = Base Asphalt Thickness; Surface Asphlt Mod. = Surface Asphalt Modulus; Base Asphlt Mod. = Base Asphalt Modulus; No. of Passes = Number of Passes; numerical sensitivity level: 1 cumulative damage factor is most sensitive to this parameter)

Table 7
Cumulative Damage Factor (CDF) Sensitivity at Bottom of Base Asphalt Layer [37].

Computer code	Senstvty level	Arcrft GWt	Subgrd CBR	Base asphlt t	Surface asphlt Mod.	Base asphlt Mod.	No. of passes
ALIZE AIRFIELD	High	X		X			
	Mod.					X	
	Low		X				X

(note: Senstvty Level = Sensitivity Level; Arcrft GWt = Aircraft Gross Weight; Subgrd CBR = subgrade CBR; Base Asphlt t = Base Asphalt Thickness; Surface Asphlt Mod. = Surface Asphalt Modulus; Base Asphlt Mod. = Base Asphalt Modulus; No. of Passes = Number of Passes)

Table 8
PCASE default values for flexible pavement structure design [38].

Material type	Elastic modulus (psi)	Poisson's ratio
Asphalt	350,000	0.35
Base Course	30,000	0.35
Drainage Layer	30,000	0.35
Subgrade	15,000	0.40

custom values based upon material test data or realistic assumptions. Slip at the layer-layer interface can be included in the analysis. A value of 1 for slip corresponds to a no-slip condition between layers. Conversely, a value of 1000 for slip is equivalent to a frictionless layer boundary. The LED approach in PCASE provides the user the option to account for seasonal changes over the design pavement structure life.

3.3.2. Rigid pavement design

Two analysis methods are available in PCASE for rigid pavement structural design/analysis, an empirical approach and the Westergaard solution. The empirical approach for PCASE rigid pavement structural design uses the subgrade reaction modulus (*k)* criterion. For rigid pavement design, material characterization includes the design concrete slab flexural strength, the *k* (subgrade reaction modulus) value for each of the foundation layers, and the *k* value for the subgrade. As a design tool, PCASE calculates the required layer thickness as a function of aircraft mix, pavement materials, and design life.

PCASE includes a second approach for rigid pavement structure design using the Westergaard solution. The Westergaard solution models the rigid pavement structure as a slab on a liquid foundation (Winkler foundation) [33]. Critical loading occurs when the wheel load is applied at the slab edge. Consequently, the problem is asymmetric and the solution cannot be analyzed using the classic layered elastic design approach. However, the Westergaard solution is applicable for wheel loads applied at the slab edge (longitudinal edge or transverse joint) and at points within the slab area. The contact surface of the wheel loading in PCASE is applied over an elliptical area where the tire shape (longitudinal length / width) default value is 1.652. Elastic modulus and Poisson's Ratio are material parameters used in PCASE for rigid pavement structure design to characterize the foundation materials. The PCASE default values for the concrete elastic modulus and Poisson's ratio are 27,580 MPa (4,000,000 psi) and 0.15, respectively. PCASE defaults to a 25% load transfer across airfield pavement panel joints. Conversely, PCASE assumes 0% load transfer at roadway joints. Similar to the asphalt pavement structural design, slip at the layer interface can be included in the analysis using a friction value between 1 (no-slip) and 1000 (frictionless interface).

3.4. PAVERS pavement evaluation and reporting strength

The PAVERS (Pavement Evaluation and Reporting Strength) computer code is used for flexible and rigid pavement structural design [34]. The code was developed by the Dutch PAVERS consulting firm. A flexible pavement structure is analyzed in PAVERS using the Burmister layered elastic design method [35]. However, the LED method is modified in PAVERS so that the bottom layer in the multi-layer pavement structure is anisotropic using different material properties in the planar and vertical directions. Interface interaction between adjacent layers is included through slippage ranging between full bond and full slip.

The Westergaard approach has theoretical limitations when applied to rigid pavement multi-layer systems. Firstly, the Westergaard approach assumes thin plates. Secondly, using the equivalent k-modulus for the layered pavement structural system is appropriate only when layers within the pavement structure have an elastic modulus much less than the elastic modulus of the concrete slab. Therefore, for the stabilized base case, the Westergaard theory is actually inappropriate. The PAVER code remedies this theoretical limitation using a modified Westergaard approach for rigid pavement design. Instead of a slab on springs, PAVER incorporates the Pasternak two-parameter foundation to convert the PAVER rigid pavement structure to a Westergaard slab on a Pasternak foundation. The Pasternak model introduces shear strength into the analysis. Consequently, Westergaard-Pasternak solutions and multi-layered theory solutions become more agreeable when comparing similar type problems. The pavement structure is modeled using the Van Cauwelaert's multi-slab model so that interlayer slip between adjacent layers is considered. The numerical models within PAVERS enable a closed-form solution for determining the mechanistic values within the pavement structure. PAVERS includes lateral wander in the wheel path by assuming a normal distribution for the lateral wheel load wander. The lateral wander for each aircraft within the aircraft design mix is combined to develop a critical longitudinal pavement strip for designing the pavement structure.

3.5. APSDS 5.0 airport pavement structural design system

APSDS (Airport Pavement Structural Design System) is a computer code used in Australia for flexible airport pavement structural design [36]. APSDS uses a mechanistic-empirical approach to predict flexible pavement structure behavior. Mechanistic response values are calculated using the layered elastic theory. Transfer functions are then used to convert the APSDS calculated mechanistic response values to pavement distress. The APSDS code is a modified version of the LED code CIRCLY used for roadway design based on the road design standards used in Australia and New Zealand, Austroads Pavement Design Guide [37].

The empirical transfer functions used in APSDS were developed from full-scale aircraft testing conducted by the U.S. Army Engineer Waterways Experiment Station and at the NAPTF [38]. These full-scale testing results proved that pavement distress is a function of the number of wheels included in the aircraft undercarriage. Consequently, the APSDS transfer functions are dependent on the number of aircraft undercarriage wheels.

Chai et al. [39] performed an airfield pavement design analysis at a major airport comparing FAARFIELD and APSDS. The pavement structure thicknesses from the two codes were approximately the same when the subgrade CBR was greater than 10. However, in cases where the CBR was less than 10, FAARFIELD calculated a greater pavement structure thickness. Chai et al. [39] proposed that the difference in the required pavement thickness is due to how the two codes calculate the maximum subgrade strain; FAARFIELD uses all of the aircraft wheels whereas APSDS uses a single wheel group loading. This discrepancy occurring when using the FAARFIELD 1.3 version has been addressed in the recent FAARFIELD 1.4 version with a change in how certain multi-gear aircraft are analyzed.

3.5.1. Material characterization

APSDS allows for anisotropic material behavior in the unbound material layers and the subgrade half-space within the pavement structure. Unbound material layers are subdivided within the code internally into sublayers during the mechanistic calculation to permit for varying the material elastic modulus as a function of depth.

3.5.2. Cumulative damage

APSDS calculates the cumulative damage at multiple points within a horizontal plane at the critical section level [40]. This approach replaces the pass/coverage ratio approach that is limited to only a few assumed "critical" points to calculate maximum strain values. Subgrade strains in APSDS are derived by accounting for all points across the pavement cross-section and recording the contribution of each aircraft wheel to damage considering the aircraft's wander position. The incremental damage caused by the calculated strain, ε, at each point due to the aircraft wheel loading for pass "*i*" is based on the number of strain cycles that can be withstood at the ε strain point before pavement failure occurs [40]:

$$N_{DESIGN\ LIFE} = \left[\frac{k}{\varepsilon}\right]^b \tag{6}$$

where $N_{DESIGN\ LIFE}$ is the number of cycles at ε required to develop pavement failure. k and b are material parameters and are determined through field or laboratory testing. APSDS uses $N_{DESIGN\ LIFE}$ in Miner's damage formula to calculate the CDF. Design life for the pavement structure considering the input aircraft mix corresponds to a calculated CDF equal to 1.0.

3.5.3. Aircraft wander

The APSDS mechanistic calculations include aircraft wander in order to correctly model cumulative damage at a strain analysis point. Damage in APSDS is calculated at multiple strain analysis points at a constant depth assuming the aircraft longitudinal path wanders in the lateral direction about the runway centerline with a normal distribution [38]. Strains are calculated at multiple analysis points along the pavement structure cross-section transverse axis. These calculated strains contribute to the incremental change in the cumulative damage calculation. APSDS calculates the cumulative effects of the wheels to the damage increment uniquely by using the "reservoir" method. The "reservoir" method involves using a stress range spectra from the load stress time history [38]. The "reservoir" method better represents the effect of multiple on-off loading due to multiple wheels passing over a point than the pass/coverage ratio.

4. Innovations in airfield pavement design codes

4.1. Pavement structural design using artificial neural network (ANN)

The mechanistic-empirical approach includes numerous parameters for predicting future pavement distress behavior: traffic loading, pavement structure material properties, climatic conditions (moisture/temperature), the pavement structure model, and the pavement distress prediction model (transfer function). These parameters are warranted to accurately calculate the mechanistic response values (stress, strain, displacement). However, in choosing the numerical method to use, the accuracy of the analysis method (2-D or 3-D) needs to be balanced with the expected input data accuracy, accuracy of the transfer function, and computation time since the computation time warranted in a finite element analysis is significant. Because of the significant computation time included in a FEM rigid pavement structural analysis, the artificial neural network (ANN) approach is being considered as an alternative approach in airfield pavement codes for quickly determining the mechanistic values. The ANN approach is included in the highway pavement AASHTOWare Pavement ME Design code [41]. The code is a computerized version of the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures (MEPDG) approach specified for highway pavement design [41]. Details of the code are available in NCHRP [42]. The MEPDG software uses neural networks based on results from the ISLAB2000 2-D finite element analysis code [43]. To better model top-down cracking for airfield rigid pavement design, research is currently being conducted at Iowa State University to incorporate the ANN approach into FAARFIELD [44,45]. The ANN approach is implemented using equivalency concepts and model simplification. The equivalency approach classifies the problem according to equivalent thickness, equivalent temperature gradient, and equivalent slab. The problem solution is then related to the neural network solution for an equivalent system. Neural network models are currently available for predicting response in jointed plain concrete airfield pavements [46,47,48,49]. Although the ANN approach is suitable for rigid pavement structural design, it is not currently considered appropriate for flexible pavement structure design due to the number of variables required to accurately characterize flexible pavement behavior.

4.2. Rigid pavement top-down cracking

Typically pavement computer codes use horizontal stress at the base of the concrete pavement slab as a governing condition. FAARFIELD uses the maximum calculated horizontal stress at the slab bottom edge for predicting pavement structural life as specified in 150/5320-6F [11]. This mode of failure assumes bottom-up cracking. However, top-down cracking was identified during the A380 Pavement Experiment Program [28]. Although the stress at the top of the concrete slab is lower than the stress at the bottom of the slab, the tensile strength at the slab top is smaller. Rodchenko [50] showed the significance of including top-down cracking in an analysis evaluating the pavement structure life for an A380–800. Rodchenko [50] determined a pavement structure life 30% less than that calculated by an earlier version of FAARFIELD, FAAFIELD 1.3. The primary cause of this reduced pavement structure life is due to including the top-down cracking design criterion. The recent FAARFIELD 1.4 version makes an initial attempt at addressing the issue of rigid pavement top-down cracking by using a four-slab 3-D FEM with initial temperature curling to develop adequate slab thickness designs [44]. However, an accurate analysis is dependent on including neural network models in future FAARFIELD computer code revisions.

5. Conclusions

This article provides the reader with a summary of available airfield pavement structural analysis and design computer codes along with a brief description of their methodologies. Code summaries include each code's pertinent assumptions and features. Five airfield pavement structure computer codes were evaluated: FAARFIELD, Alize-Airfield, PCASE, PAVERS, and APSDS. FAARFIELD and PCASE are computer codes developed in the United States. Conversely, Alize-Airfield, PAVERS, and APSDS are non-U.S. computer codes. References are included at the end of this article and provide a resource to the reader for additional information.

Three approaches are used for pavement structural analysis/design: empirical, closed-form solutions, and numerical. Typically, the LED method is used for flexible pavement structural analysis/design. Rigid pavement structural analysis/design typically is conducted using variations of a Westergaard analysis or the FEM. In a rigid pavement structural analysis/design, a 3-D finite element analysis (FEA) is capable of incorporating nonlinear material behavior and modeling the pavement structure configuration accurately. However, a 2-D FEA is normally implemented to reduce the substantial number of calculations and computation time inherent to a 3-D FEA pavement structural analysis/design. A major difference between the reviewed computer codes considered is how aircraft wander in the wheel loading is implemented into the code and how pavement damage accumulates. FAARFIELD uses the pass/coverage ratio. However, instead of using a pass/coverage ratio other codes use a more direct approach by calculating mechanistic values at significantly more points than FAARFIELD on a horizontal plane.

There are three major resources available for calibrating transfer functions used in airfield pavement work: test data from the U.S. Army Engineer Waterways Experiment Station (WES)/U.S. Army Engineer Research and Development Center (ERDC), tests conducted at the National Airport Pavement Test Facility (NAPTF), and results from the Pavement Experimental Program (PEP) tests performed by AIRBUS in Toulouse, France. The NAPTF tests and PEP tests consider the new large commercial aircraft, such as the B777 and A380.

A major challenge of implementing a numerical approach in an airfield pavement structural design is balancing the design accuracy with the warranted computational time. An attractive approach to improve computation time is the artificial neural network (ANN) approach, which will most likely be incorporated into future airfield pavement structural design codes. The ANN approach provides the opportunity to significantly reduce computational time without jeopardizing computational accuracy in the pavement structural design process. In addition, future airfield codes should investigate the potential for top-down cracking failure. Future aircraft types include complicated main gear configurations that may cause failure modes that were not previously identified in earlier aircraft types.

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14. ABSTRACT

An airfield pavement structure is designed to support aircraft live loads for a specified pavement design life. Computer codes are available to assist the engineer in designing an airfield pavement structure. Pavement structural design is generally a function of five criteria: the pavement structural configuration, materials, the applied loading, ambient conditions, and how pavement failure is defined. The two typical types of pavement structures, rigid and flexible, provide load support in fundamentally different ways and develop different stress distributions at the pavement – base interface.

Airfield pavement structural design is unique due to the large concentrated dynamic loads that a pavement structure endures t support aircraft movements. Aircraft live loads that accompany aircraft movements are characterized in terms of the load magnitude, load area (tire-pavement contact surface), aircraft speed, movement frequency, landing gear configuration, and wheel coverage.

The typical methods used for pavement structural design can be categorized into three approaches: empirical methods, analytical (closed-form) solutions, and numerical (finite element analysis) approaches. This article examines computational approaches used for airfield pavement structural design to summarize the state-of-the-practice and to identify opportunities for future advancements. United States and non-U.S. airfield pavement structural codes are reviewed in this article considering their computational methodology and intrinsic qualities.

15. SUBJECT TERMS

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