Development of a Reliable Methodology for Assessing the Structural Performance of General Aviation Pavements

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Abstract

Existing airport pavement evaluation and design methodologies are primarily oriented toward heavy, air carrier size aircraft, and often do not adequately address the lighter loading conditions at General Aviation (GA) airports. Although GA pavements generally serve light aircraft, many GA airports need to accommodate heavier corporate or military aircraft on an occasional or periodic basis. Existing GA design methods cannot handle mixed traffic, or overload operations.

To address these shortcomings and to augment its formal strength rating program, the North Carolina Division of Aviation (NCDOA) conducted a two year study during 1997–1999 to develop standardized procedures for nondestructive testing (NDT) and evaluation of GA airport pavements and analytical software based on layered elastic design theory for evaluating pavement strength and "overload" operations.

This study focused on flexible pavements and consisted of the following four primary elements:

- Field Testing - Nondestructive and conventional tests were performed on one runway at each of six North Carolina (NC) GA airports.

- Data Analysis - Back-calculated NDT subgrade moduli were correlated with California Bearing Ratio (CBR) and laboratory resilient modulus test data for development of failure algorithms and to allow direct input of back-calculated Falling Weight Deflectometer (FWD) subgrade modulus into the evaluation procedure.

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- Subgrade Strain Criteria - The results of a literature search and design of Federal Aviation Administration (FAA) compliant pavements over a broad range of subgrade and traffic inputs formed the basis for a new subgrade strain failure criterion.

- Development of Analytical Software - Layered elastic evaluation and design software was developed using the FAA's LEDFAA software for air carrier pavement as a model.

The new software, termed LEDGA for Layered Elastic Design – General Aviation, incorporates the new subgrade strain criterion and permits multiple aircraft analysis and evaluation of "overload" operations based on cumulative damage concepts.

Introduction

Existing pavement evaluation and design methodologies are primarily oriented toward heavy, air carrier size aircraft, and do not adequately address the lighter loading conditions at GA airports, many of which consist of relatively thin flexible sections. Although GA pavements generally serve aircraft with gross weights of less than 13,607 kg (30,000 lbs.), most airports may need to accommodate heavier corporate or military aircraft on an occasional or periodic basis. Existing light aircraft design methods, such as those contained in FAA Advisory Circular 150/5320-6D[1, FAA (1995)] are not capable of handling mixed traffic, aircraft over 13,607 kg (30,000 lbs.), or non-standard pavement sections.

To address these shortcomings and to augment its formal strength rating program, the NCDOA conducted a two year study during 1997–1999 to develop:

- Standardized procedures for NDT evaluation and design of GA airport pavement structures; and

- Analytical software based on layered elastic design theory for evaluating GA airport pavement strength and "overload" operations.

Since most GA airport pavements consist of flexible pavements, the study focused on flexible pavements, only, although future expansion to include rigid pavements is possible.

For GA airport pavements, the results of the study will provide NCDOA, consultants, and aviation agencies in other states, with greater flexibility to:

- Utilize NDT procedures and mechanistic design methods;

- Evaluate changes in operational weights, frequency and type of aircraft;

- Assess occasional, or one time, aircraft "overloads";

- Report pavement strength;

- Estimate theoretical structural life;

- Conduct sensitivity analyses; and

- Extend visually based Pavement Management Systems (PMS) to include structural analysis.

The approach to the study consisted of the following four primary elements, and included the participation of NCDOA, NC Division of Highways (NCDOH), FAA Technical Center, and Roy D. McQueen & Associates, Ltd.:

- *Field Testing* - Nondestructive and conventional tests were performed on one runway at each of six GA airports in different areas of North Carolina. The primary focus of the testing program was to standardize NDT procedures with the FWD and correlate FWD and conventional test results.

- *Data Analysis* - Back-calculated FWD subgrade moduli were correlated with CBR and laboratory resilient modulus test data. The primary purpose of the data analysis program was to provide data for development of failure algorithms and to allow direct input of back-calculated FWD subgrade modulus into the evaluation procedure.

- *Subgrade Strain Criteria* - The results of a literature search and design of FAA compliant pavements over a broad range of subgrade and traffic inputs formed the basis for a new subgrade strain failure criterion. The resultant subgrade strain criterion is a function of aircraft coverages (N) and back-calculated subgrade modulus (E).

- *Development of Analytical Software* – Layered elastic evaluation and design software was developed using the FAA's LEDFAA software for air carrier pavement as a model. The new software, termed LEDGA, incorporates the new subgrade strain criterion, permits multiple aircraft analysis and evaluation of "overloads" based on cumulative damage concepts, and allows for variable load repetitions and surface thicknesses. The LEDGA software and documentation is available from NCDOA.

Field Testing

In the Fall of 1997 and the Spring of 1998 NCDOH accomplished two series of conventional and nondestructive tests at the following airports:

• Coastal Region	-	Plymouth Municipal
	-	Wilson Industrial
• Piedmont Region	-	Montgomery County
	-	Siler City Municipal
• Mountain Region	-	Rutherford County
	-	Wilkes County

The purpose of the Spring and Fall tests were to investigate and identify, if possible, seasonal effects in pavement response.

For each seasonal period, the following matched sets of tests were performed by NCDOH at three or four locations on each of the six airports:

- FWD tests at multiple force levels;
- Pavement thickness measurements through test pits and core holes;
- Subgrade classification;
- Dynamic Cone Penetration (DCP) tests on base and upper subgrade layers;
- In-situ CBR; and
- Undisturbed samples for laboratory resilient modulus (M_R) testing.

In addition, these FWD tests were conducted at nominal 30m (100 ft.) longitudinal spacing in aircraft wheel paths. Condition surveys were also performed and Pavement Condition Indexes (PCI) computed for each runway during Fall 1997 and Spring 1998.

Soil types were varied across the study sites and included clays, silts, and granular materials. In-situ CBRs varied widely from 6% to over 50%. Subgrade moduli from back-calculated FWD data ranged between 27.6 MPa (4,000 psi) to 345 MPa (50,000 psi). The condition survey data indicated that most pavement distresses were related to climatic, rather than load induced, mechanisms. PCIs generally ranged between 50 and 90. Laboratory resilient modulus tests were performed at various deviator and confining stresses. Resilient modulus (M_R) results generally varied from 27.6 MPa (4,000 psi) to 276 MPa (40,000 psi), depending on soil type, moisture/density, and confining stress.

Correlations

Historically, airport pavement design methods for flexible pavements were based on the CBR methodology originally established by the U.S. Army Corps of Engineers[2, Ahlvin (1991)] in the 1940's. The methodology has been expanded over the years, but the basic principles and evaluation/design methods are still based on CBR tests and the familiar CBR equation.

However, the CBR method, although a reliable standard for many years, falls short in:

- addressing seasonal effects;
- assessing the effects of mixed traffic;
- evaluation of occasional "overload" operations; and
- utilizing rapid NDT methods.

For these and other reasons, mechanistic evaluation/design methods based on layered elastic theory have been developed and adopted by many agencies.

Since layered elastic methods use the elastic modulus (E) to characterize subgrade soils and existing conventional design methods for flexible pavements use the CBR, correlations between E and CBR become necessary. This will become more apparent when the development of the subgrade strain failure criteria is presented.

From the data acquired by NCDOH the following correlations were developed:

- E_{sub} from FWD back-calculation vs. in-situ CBR (E_{sub} - CBR derived directly)
- E_{sub} vs. laboratory resilient modulus (E_{sub} - M_R)
- M_R – CBR, and consequently (E_{sub} - CBR derived indirectly)

Due to the variation in the measured properties and the scatter exhibited for the same soil type and geographic location, some filtering of the data was necessary before the correlation analyses were performed.

Based on the direct and indirect regression analyses, the following equation was used for correlation of FWD E_{sub} results with CBR in North Carolina for the soil types sampled in the study:

$$E\ (\text{psi}) = 1000 \times CBR$$

This equation will also result in a more conservative subgrade strain criteria for GA airport pavement analysis than the equation currently used in LEDFAA (i.e., E=1500 x CBR). This is discussed further below.

Seasonal Effects

The Spring and Fall nondestructive and conventional test data were also analyzed to identify seasonal variations in pavement and subgrade strength, i.e., seasonal variations in E-value and Impulse Stiffness Modulus (ISM) and E_{sub}. If variations in pavement strength could be identified from the test data, these results could be used with cumulative damage concepts in the mechanistic design model for assessing load carrying capability at different seasons.

However, the analysis did not detect any significant differences in subgrade strength for the pavements and time periods that were used for the study. Weather records for the Spring and Fall periods indicated only minor variations in temperature and rainfall, and for subgrade moisture and in-situ CBR, there was no difference between the Spring and Fall data sets.

Therefore, a cumulative damage seasonal adjustment factor was not incorporated into the GA pavement evaluation design procedures at this time. However, this feature can be added in the future if the results of longer term testing and analysis warrant.

Analysis of FWD Data

Back-calculation methods were investigated and procedures and computer programs recommended. Also, since FWDs were conducted at varying force levels, non-linear effects from loading were evaluated from the back-calculated E_{sub} and the ISM data. These results were used to standardize FWD and data reduction procedures. Guidelines for FWD testing and data analysis for GA airport pavements were recommended. The FWD procedures involve conducting tests at a force range of from 4,080 kg (9,000 lbs.) to 5,445 kg (12,000 lbs.) and using either the MODULUS or WESDEF programs for back-calculating subgrade modulus. Both programs incorporate computation of the depth to an apparent "stiff" layer. The results of the back-calculation analysis can be significantly inaccurate by excluding such a layer or by not locating this layer, particularly if its depth is less than 6m (20 ft.). The back-calculated subgrade modulus can be used as a direct input to the new layered elastic design procedures for GA airport pavements.

Literature Search

A literature search was conducted to identify research reports on airport pavement evaluation, design, NDT, and available subgrade failure criteria. The results of the literature search are summarized as follows:

1. **Report 80-9:**[3, FAA (1980)]

$$\varepsilon_V = 0.0063548 \times N^{-0.17985}$$

2. **Report GL-94-12:**[4, Barker/Gonzalez (1994)]

$$\varepsilon_V = 0.003077 - 0.00045 \times \log_{10} N$$

3. **LEDFAA (AC 150/5320-16):**[5, FAA (1995)]

$$\varepsilon_v = \left(\frac{10,000}{N}\right)^{1/b} \times a$$
$$a = 0.000247 + 0.000245 \times \log_{10} E_{SUB}$$
$$b = 0.0658 \times E_{SUB}^{0.559}$$

4. **TAI, DAMA Model:**[6, Asphalt Institute (1983)]

$$\varepsilon_V = \left(\frac{0.1365 \times 10^{-8}}{N}\right)^{1/4.477}$$

Where:

ε_v = subgrade vertical strain
N = load repetitions

Application and comparison of each subgrade strain criterion are compared in Table 1.

N	Report 80-90	Report GL-94-12	AC 150/5320-16*	TAI DAMA
10	0.00420	0.00263	0.00207	0.00626
100	0.00278	0.00218	0.00176	0.00374
1000	0.00183	0.00173	0.00149	0.00224
10000	0.00121	0.00128	0.00127	0.00134
100000	0.00080	0.00083	0.00108	0.00080
1000000	0.00053	0.00038	0.00092	0.00048

* E_{SUB} = *103 MPa (15,000 psi)*

Table 1. Summary Limiting Subgrade Strain Criteria

As shown, while the criteria tend to converge at higher load repetitions (N), they diverge significantly at low "N", i.e., $N < 1,000$. Since evaluation of overload situations will occur at low N, additional investigation of strain criteria was necessary, as discussed below.

Development of Subgrade Strain Criterion

The current LEDFAA subgrade strain criterion is E-sensitive and may not be reasonable at low coverage levels, and, possibly at the lower strain levels associated with GA aircraft. As such, it required modification for the GA airport pavement evaluation model.

The development of the modified strain failure criterion consisted of the following basic steps:

- Design FAA compliant pavement structures for different aircraft, traffic, coverages, and subgrade CBR, using the FAA's "ACN COMP" program. ACN Comp is based on the CBR design method and incorporates the CBR design equations in the design procedure.

- Compute subgrade vertical strain from the imposed aircraft loading for each compliant structure.

- Plot data and perform non-linear regressions to establish failure algorithm as subgrade strain (ε_v) as a function of N load repetitions and subgrade CBR, or:

$$\varepsilon_v = f(N, CBR)$$

- Substitute E_{sub} for CBR from the E_{sub} - CBR correlation resulting in:

$$\varepsilon_v = f(N, E_{sub})$$

- Compare to other criteria and adjust, if necessary.

This resulted in the following subgrade strain failure algorithm:

$$\varepsilon_v = \left(\frac{10^4}{N}\right)^{\frac{1}{f_2}} \times f_1$$

$$f_1 = a + b \times \log_{10}\left(\frac{E_{sub}}{1000}\right)$$

$$f_2 = c \times \left(\frac{E_{sub}}{1000}\right)^d$$

When compared to the criteria summarized in Table 1, the new subgrade strain criterion generally:

- Falls below other criteria at low "N";
- Is consistent with other criteria at mid to high "N".

The data correlation used for development of the subgrade strain criterion was very robust ($r^2 = 0.91$). The GA pavement strain criterion parallels the strain criterion contained in LEDFAA, but provides better correspondence to conventional designs for low and high strength subgrades. The new strain criterion also allows higher vertical strains for low coverages than LEDFAA. Low "N" strain repetitions are a primary concern for evaluating occasion aircraft overloads.

The GA pavement subgrade strain criterion is compared to the strain criterion contained in FAA's LEDFAA program in Figure 1. The GA strain criteria is the top surface.

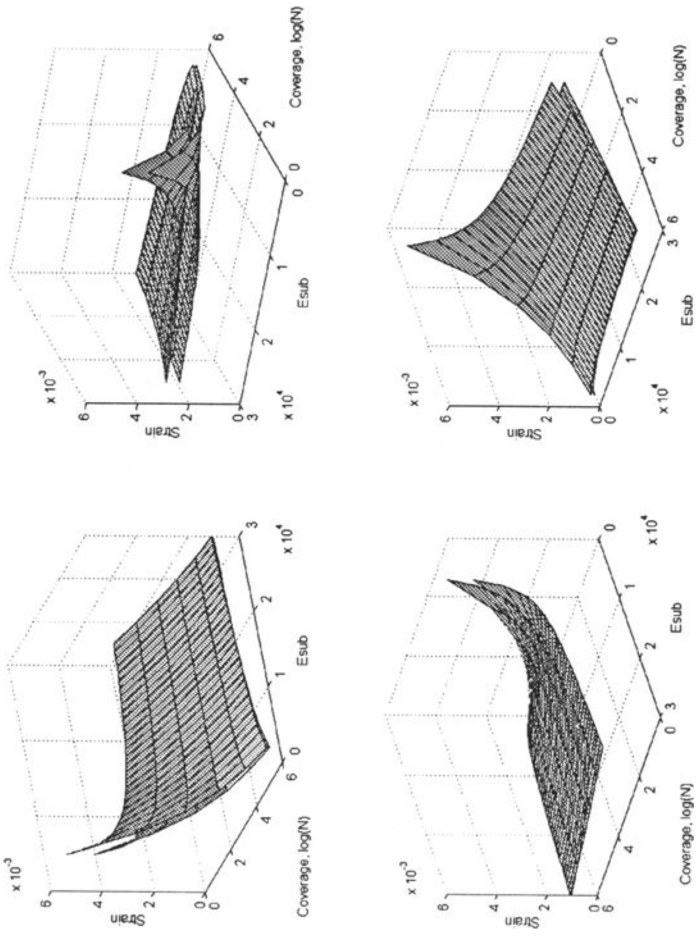

Figure 1. 3D Representation of NCDOA Equation vs. LEDFAA Equation