A Comprehensive System for Nondestructive Testing and Evaluation of Rigid Airfield Pavements

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ABSTRACT

A complete system is presented for nondestructive testing and evaluation of rigid airfield pavements based on the falling weight deflectometer and the ILLI-SLAB finite element analysis model. This system was developed to provide the engineer with specific guidelines for planning and conducting extensive evaluations of major installations, calculating stresses generated by aircraft gear loads, and predicting the future performance of rigid pavement features under a variety of loading conditions. Techniques are presented for determining the location of maximum damage to rigid pavement slabs for one or any combination of aircraft, and the validity of the calculated stresses is established through comparisons of measured and predicted deflections at joints. These stresses are then related to actual field performance of rigid airfield pavements through a complete ILLI-SLAB reanalysis of accelerated traffic test data. A correlation between backcalculated concrete elastic modulus and flexural strength is reported, and the procedures to determine total accumulated Miner's damage at the critical stress location are explained. Realistic formats for reporting remaining pavement structural life to operations personnel are suggested. Major study findings include (a) new feature designations based on actual loading conditions, (b) a statistical sampling plan to reduce testing requirements, (c) techniques for determining the location of maximum accumulated damage for each feature, (d) a field performance curve to relate stress to available coverages, and (e) computer programs for predicting remaining structural life for one or any combination of aircraft.

This research effort was undertaken to develop the concepts necessary for a complete nondestructive testing and evaluation (NDT & E) system for rigid airfield pavements that was capable of field testing and analyzing the many distinct features that typically exist on modern commercial and military airfields. Past destructive methodologies and current elastic layered analysis procedures are not capable of assessing the true impact of aircraft operations at rigid pavement joints under a variety of temperature conditions. After an extensive review of currently available NDT equipment and mechanistic models, the falling weight deflectometer (FWD) and the ILLI-SLAB finite element program were chosen for their tremendous versatility.

In another paper in this Record, the authors establish the repeatability of FWD loads and deflections over a wide range of temperature, load, and thickness conditions; when coupled with an ILLI-SLAB-based iterative computer scheme to backcalculate dynamic elastic and subgrade moduli, accurate predictions of FWD-generated deflections were achieved. Therefore, after the pavement feature has been characterized by the NDT equipment and analytical model, confidence can be placed in the accuracy of the stress calculations that must be made at the joints for a variety of gear loads and configurations operating on major airfields.

In that same paper, in addition to validating measurement consistency and deflection predictions of the FWD/ILLI-SLAB system, techniques are presented to describe the temperature-dependent behavior of joint load transfer. Thus, accurate stress calculations can be made at the point of maximum accumulated damage (invariably at one of the joints) for each feature at any temperature. It now remains to formulate these components into a comprehensive methodology that will guide and direct the engineer toward realistic projections of remaining pavement life. This objective will be accomplished in this paper by (a) introducing several new concepts into the evaluation process that are intended to link the major components, and (b) providing specific examples from Seymour-Johnson Air Force Base (AFB) in North Carolina, Plattsburgh AFB in New York, and Sheppard AFB in Texas to demonstrated the NDT & E process. The result will be a complete system on which to expand and improve. Figure 1 shows a flow chart that can be used as ready reference for the entire NDT & E procedure; Foxworthy should be consulted for particular details on its development (1).

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PLANNING AND CONDUCTING THE FIELD TESTING PROGRAM

The structural evaluation of any pavement network (such as all pavements at an airfield) is a twofold process: general network-level evaluation and specific project-level evaluation. The engineer must initially be concerned with the collection and analysis of information for all identifiable pavement features on the airfield network. By necessity, such a testing program must be broad enough in scope to permit the most efficient use of limited resources, yet detailed enough to identify potential problem areas. This general network evaluation program need not be overly concerned about the underlying causes

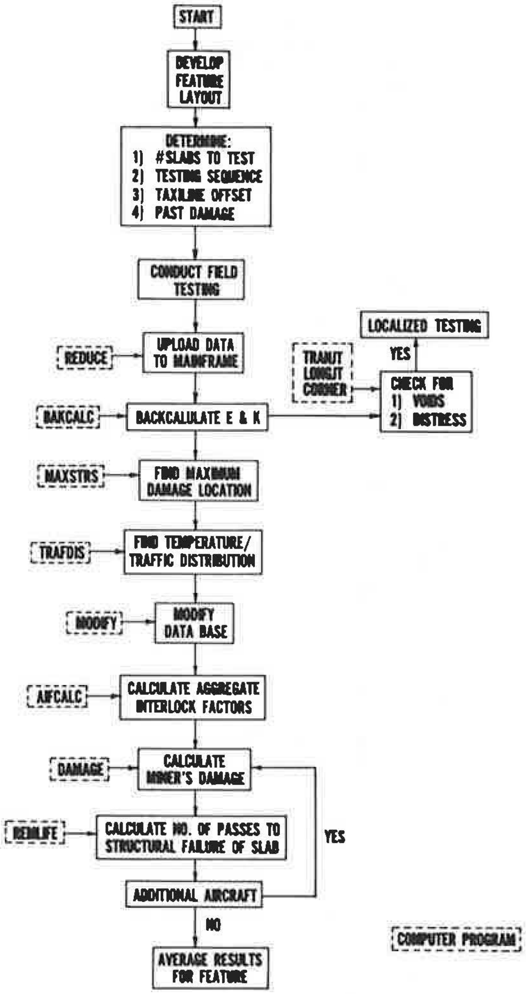

FIGURE 1 Flow chart of nondestructive testing and evaluation process.

of pavement distress, but rather should provide remaining structural life predictions for each feature and identify those features warranting additional investigation during the specific phase of the evaluation. The methodologies described here will address the first of these two phases, the general network-level evaluation.

Feature Identification

The tremendous challenge facing the engineer in planning and conducting an NDT & E program must begin in much the same way as conventional destructive evaluations. All available sources of information on the design, construction, maintenance, and repair of the airfield facilities must be reviewed, along with the results of any previous testing and condition surveys, to identify each distinct group of continuous pavement slabs that display nearly identical material properties, dimensions, construction histories, and maintenance practices. No limitations exist on the maximum or minimum feature size; however, the two primary purposes of feature designations are to (a) provide uniform pavement sections for ease of analysis, and (b) provide a convenient breakdown of the entire pavement system into smaller sections for maintenance and repair planning. This suggests that features smaller than about 10 slabs should be avoided to reduce testing and analysis requirements. Similarly, large parking aprons or entire runway widths seldom require maintenance or repair over the entire surface; generally keel sections and aircraft tie-down locations would receive priority for repair. Thus, the use of the pavement plays an important role in feature identification.

Historically, the concept of traffic area has been used in design to further subdivide pavement features into sections that not only have similar material properties, design, and geometrics, but also have consistent loading conditions. The designation of traffic areas has been based on the degree of channelization of the traffic and whether the airplanes are at full mission weight. These convenient designations have permitted reductions in the design of pavement thicknesses to take advantage of the lateral distribution of traffic along runway interiors and aprons, and lower fuel loads along ladder taxiways. In addition, construction difficulties are minimized by the designation of entire aprons and runway widths as single features.

However, for purposes of evaluation the use of current traffic area designations must be modified to more accurately reflect actual loading conditions. This will result in a substantial increase in the number of features for evaluation than were required for design, but the speed with which data can be collected and analyzed with this system justifies this recommendation. For parking aprons, this will mean further subdivisions for (a) the highly channelized taxilanes, (b) the statically loaded parking spots, and (c) the unloaded pavement areas between parking rows and taxilines. For runways, separate features must be established for the highly channelized areas surrounding the centerline. This centerline feature may only be two slabs wide for the first 1,000 ft, and then expand to a four-slab width for the remainder of the runway interior to account for increased wander. The exact location of this widening point will vary with the gross loads of the mission aircraft and, therefore, cannot be fixed a priori. Observation of surface distress will be the primary indicator of proper feature change points on runways as well as aprons.

Figures 2 and 3 show examples of proposed feature designations on the runway at Plattsburgh AFB and the operational apron at Seymour-Johnson AFB. The A, B, C, and D identifiers used for design have been replaced by S, T, and U designations representing static, transient, and unloaded conditions, respectively. These three categories encompass the entire spectrum of loading conditions that are encountered and readily describe the relative importance of the feature in putting maintenance and repair work in priority order. When used in conjunction with pavement thickness, construction history, and distress patterns, a realistic feature layout can be developed for NDT & E of an entire airfield.

The vast majority of features on an airfield will receive either T or U designations, with only those slabs actually supporting parked aircraft falling in the S category. Unloaded or U features can, in many instances, be omitted altogether from the NDT & E program if the potential for their use by aircraft, now or in the future, is low. Later in this paper, the proper use of pass-per-coverage ratios for each of these feature designations will be discussed.

Random Sampling Within Features

Even with the ability to collect and analyze vast amounts of data, it would be highly impractical in the general evaluation to test every slab in every feature. Therefore, a sampling program must be developed to systematically test each feature. This sampling program must specify, through the use of

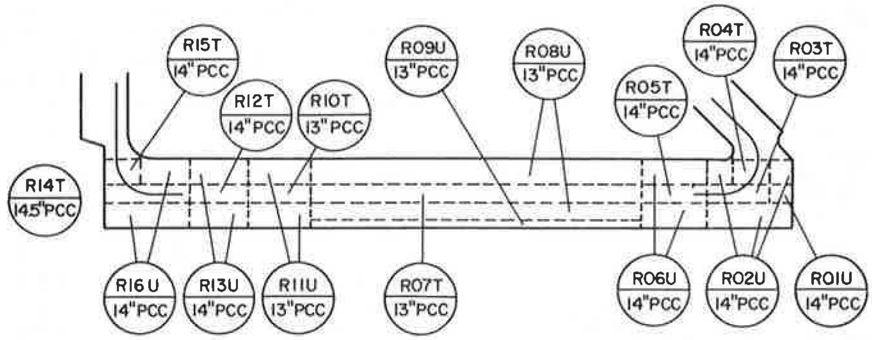

FIGURE 2 Proposed feature designations for Runway 17-35 at Plattsburgh Air Force Base.

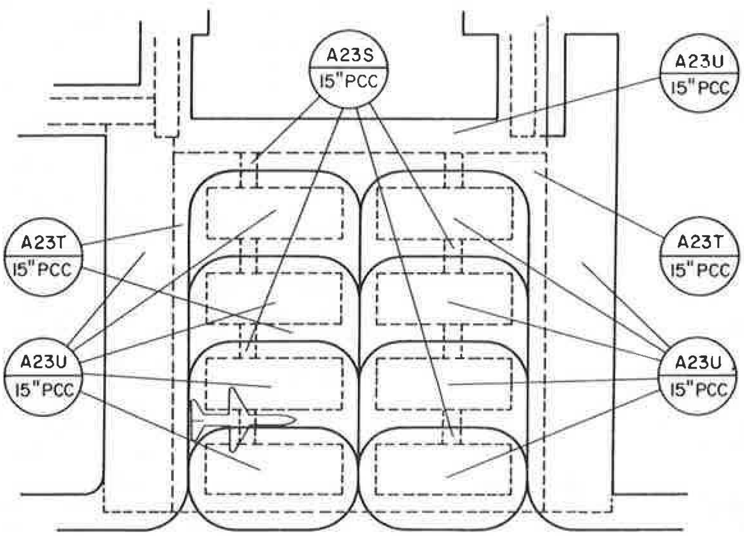

FIGURE 3 Proposed feature designations for the strategic air command apron at Seymour-Johnson Air Force Base.

statistical concepts, the number of slabs to be tested in a feature (or the number of replications) for a given level of desired precision. Because the engineer is unlikely to have the opportunity to return to the site for additional tests, the procedure must include a means by which to determine the number of tests required based on the previously established variability of the data being collected. The sampling program presented here is similar to the program developed for the pavement condition index (PCI) methodology described by Shahin et al. (2). Use of this statistical sampling plan will reduce testing requirements without significant loss of accuracy.

The number of slabs to be tested in a feature depends on the following:

- How large an error (e) can be tolerated in the estimate of the mean (X_E) of the feature elastic concrete modulus E (chosen over the subgrade reaction modulus K because of its greater variability; this is shown by the authors in another paper in this Record).
- The desired probability that the estimated mean of E (X_E) will be within this limit of error (e), usually set at 95 percent.
- An estimate of the variation of E from one slab to another within the feature, usually expressed as the variance (s^2) or the coefficient of variation (s/X_E).
- The total number of slabs (N) in the feature.

The allowable error (e) must first be expressed in terms of confidence limits. If e is the allowable error in estimating the mean elastic modulus (X_E) of the feature, and the desired probability that error will not exceed e is 95 percent, then the 95 percent confidence limits, computed from an approximately normally distributed sample mean, are

$$X_E \pm 2s/n^{0.5} \quad (1)$$

where n is the number of tested slabs. Therefore,

$$e = 2s/n^{0.5} \quad (2)$$

Solving for the required sample size n gives

$$n = 4s^2/e^2 \quad (3)$$

This expression can be used if the total number of slabs in the feature is large (more than 1,000). However, if the computed value of n is higher than 10 percent of the total number of slabs in the feature, a modified value n' should be used:

$$n' = Ns^2/[(e^2/4)\ (N-1) + s^2] \quad (4)$$

Before Equation 4 can be used to compute the required number of slabs to be tested, the total number of slabs in the feature must be estimated and the standard deviation and allowable error must be de-

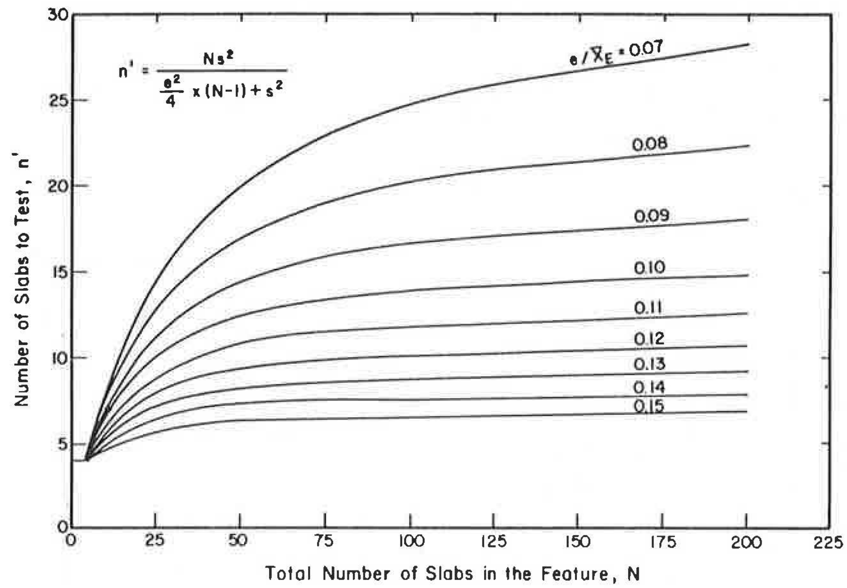

FIGURE 4 Determination of FWD testing requirements.

termined. From the repeatability studies on backcalculated FWD elastic modulus reported by the authors elsewhere in this Record, a coefficient of variation of about 20 percent was found for dynamic E. Because E values center around 5 x 10^6 psi, the standard deviation of E is approximately 1.0 x 10^6 psi. If an allowable error of 0.5 x 10^6 psi is permitted, the maximum number of slabs to be tested in a feature is

$$n = 4(1.0)^2/0.5^2 = 16 \text{ slabs.}$$

Figure 4 was developed from Equation 4 to permit a rapid determination of the number of slabs to be tested, if the total number of slabs in the feature has been estimated. Several alternatives for the allowable error, expressed as a percentage of the mean (e/X_E), are presented. A minimum of four slabs is required for every feature. As additional field verification of this procedure takes place, more accurate information on the true variance of the expected value of the mean of E will become available. This will probably result in a lower standard deviation and, therefore, a reduced testing requirement. Basing the determination of the number of slabs to be tested on the elastic modulus will ensure that modulus of subgrade reaction values, which display smaller variances, are determined with more than adequate precision.

The selection of which slabs to test is as important as the number to test. Not only is a random selection required to assure an unbiased estimate of the k and E parameters, but ideally they should be tested in a random order. However, such a procedure would be impractical because it would increase travel time between test locations dramatically. Therefore, it is recommended that the testing sequence shown in Figure 5 be used to systematically test the required number of slabs. A stratified random sampling procedure is recommended. The total number of slabs in the feature (N) is divided by the number to be tested (n) to establish the number of slabs skipped between tests. Testing should be accomplished in both directions along the feature unless only unidirectional movement of aircraft is allowed on the feature, in which case testing should proceed in that direction. Finally, only intact slabs should be tested because they are the only slabs that can be modeled relatively easily by the finite element program. Variation from the testing sequence of Figure 5 by one or two slabs to avoid broken slabs will not affect the random nature of the sequence.

The Nose Dock Apron at Seymour-Johnson AFB that was chosen as an example of the NDT & E process is

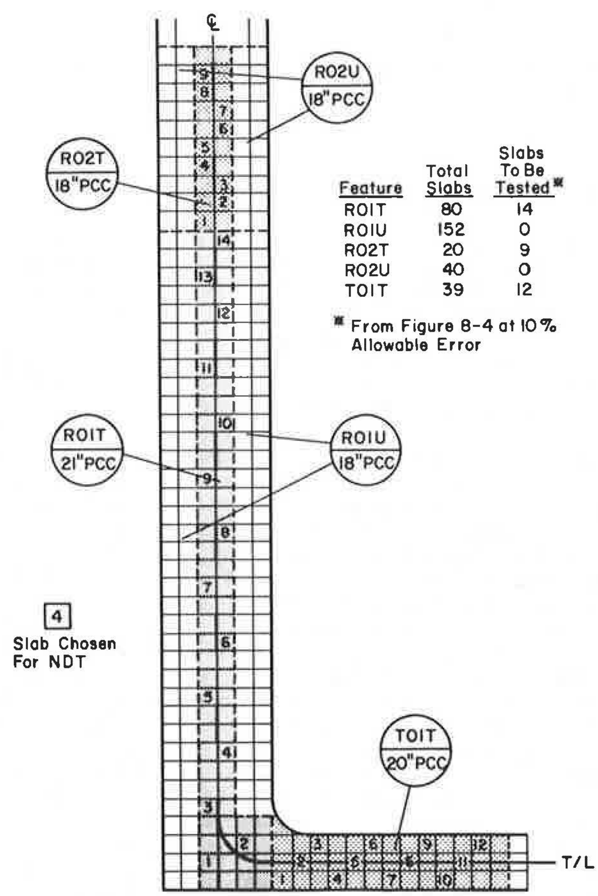

FIGURE 5 Recommended stratified testing sequence.

shown in Figure 6. Two features have been identified from the observed usage of the pavement: Feature A20T carries the aircraft loadings while Feature A20U remains unloaded. According to the information in Figure 4, 6 of the total of 24 slabs in Feature A20T are to be tested at an allowable error of 14 percent; Feature A20U does not require evaluation. Figure 6 shows which slabs were tested and the crack pattern development for the entire feature.

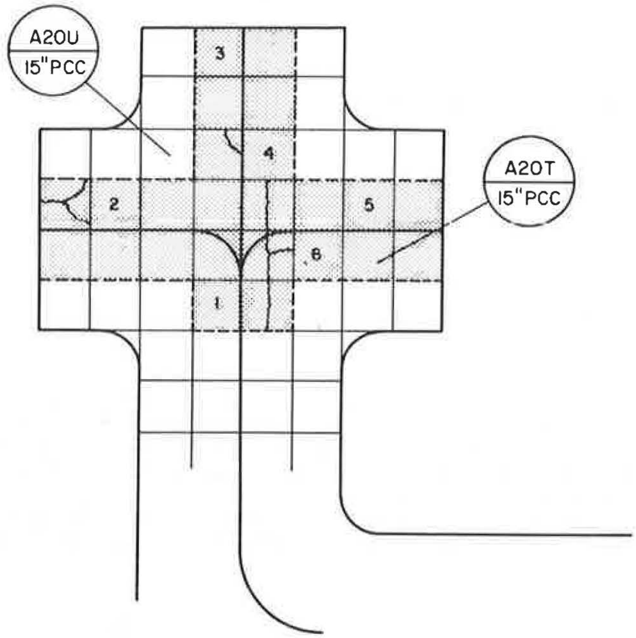

FIGURE 6 Crack development and testing sequence for Feature A20T.

Individual Slab Testing

During the field research, the testing pattern shown in Figure 7 was demonstrated to be an efficient method of testing the four key stations on each slab. This sequence is recommended for all general network-level evaluation testing. In addition, three drops of the FWD should be made at each station from a height that will produce loads in the 24,000-lb range. These three drops can then be averaged by the computer to improve deflection gauge sensitivity and reduce testing error for the backcalculation program.

The computer software supplied with the FWD can be programmed to create a data file for each feature on the airfield, with the total number of slabs to be tested input before beginning each feature. In addition, several other important pieces of information can be recorded on tape at this time for later use by the mainframe computer, including the installation name, the feature designation, transverse and longitudinal slab dimensions and joint types, pavement thickness, date and time of testing, and any remarks about the feature that may be pertinent. The air temperature will also be required, but is usually only available from the base weather station or the Federal Aviation Administration (FAA) Flight Service Station at the end of each day, and will have to be added separately to the mainframe's comprehensive data file. The taxiline offset distance, the transverse offset distance, and Miner's past damage, which will be discussed later, can be input to the FWD computer at the time of testing and will be retained throughout the evaluation sequence.

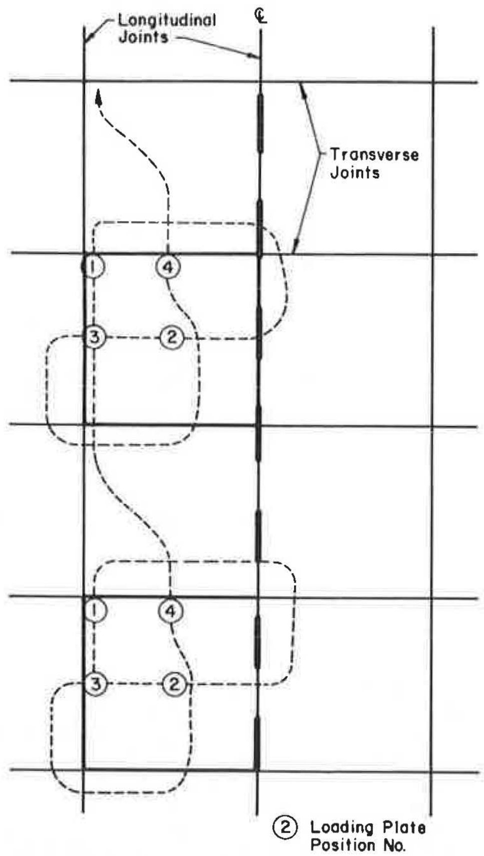

FIGURE 7 Recommended FWD testing pattern for network-level evaluations.

DATA PREPARATION

The field data collection program will typically result in the accumulation of more than 100 data files containing information on from 6 to 22 separate slabs and 12 drops per slab. These files must be transferred to a mainframe computer by using a terminal emulation program. In addition, the information stored on the cassette tapes is in metric units and unformatted, making it difficult to read the information directly from the file.

To solve this problem, a computer program REDUCE was written to create new individual files for each feature, with the information formatted for input into the backcalculation program. The metric units are converted to pounds force and mils of deflection, and the three FWD drops are averaged. The paper by Foxworthy should be consulted for specific examples of the computer inputs and products for REDUCE and the other programs described throughout the remainder of this paper (1).

BACKCALCULATION OF E, k, AND AGGREGATE INTERLOCK FACTORS

Backcalculation of the dynamic elastic modulus of the concrete and the dynamic modulus of subgrade reaction for each slab is performed by the computer program BAKCALC. This program is the first in a series of programs developed to analyze the response of the pavement slab to FWD loads at the key locations. The program uses an iterative scheme (1) and the ILLI-SLAB finite element program as a subroutine to determine these moduli values. These values are then reinput to compute the predicted deflections.

For the most part, measured and predicted deflections will be within about 2 percent of each other, particularly for the D0 reading. In the event that the two D0 deflections do not agree within this tolerance, an error in the estimation of the pavement thickness is probably to blame. A brief investigation into this phenomenon during analysis of the research data revealed that, when this occurs, a trial and error search for the thickness that will produce nearly identical values of measured and predicted D0s will provide the correct thickness. This technique has potential for the NDT & E of airfields for which pavement thickness information is unavailable.

Three other computer programs were developed as part of the rigid pavement evaluation process to compare predicted and measured deflections at the transverse joint (TRANJT), longitudinal joint (LONGJT), and corner (CORNER) of the slab. These programs utilize the backcalculated moduli from the center slab position, along with an iterative solution for the ILLI-SLAB aggregate interlock factor (AIF), discussed by Foxworthy (1), to provide the engineer with supplemental information about the performance of individual joints within a feature. Ideally it would be desirable to use actual joint measurements for the determination of E, k, and the AIFs, but the complexities surrounding support conditions at the joints makes such an undertaking impractical at this time. However, if the backcalculated values for the center slab could be assumed to exist at the joints as well, then selection of the proper aggregate interlock factor, based on a comparison of measured and predicted deflections at the joints, is reduced to an iterative computer solution.

The impact of making this assumption is much more significant for k than for E. Obviously, making this assumption for k ignores the potential loss of support that can occur at the joint from plastic deformation, pumping, and so forth. It also ignores the assumed nonexistence of shear across joints in the Winkler foundation. However, if this assumption will permit reasonably accurate ILLI-SLAB modeling of the joint's behavior under FWD loads, great confidence can then be placed in the calculated stresses under actual gear loads.

Table 1 presents the results of typical measured and predicted deflections across joints for a variety of pavement thicknesses and load transfer efficiencies. This remarkable agreement between measured and predicted deflections, across such a stark discontinuity as a keyed construction joint or dummy contraction joint, further reinforces the ability of ILLI-SLAB to accurately model behavior of joints. In the event predicted joint and corner deflections are well below measured deflections, subbase or subgrade support has probably been lost along that joint. If the opposite is true, that is, predicted values are much higher than measured, it is probably the result of a very low E modulus that was transferred from the center of the slab to the edges. Such an artificially low E value could arise from testing near a structural crack.

DETERMINATION OF CRITICAL STRESS LOCATION FOR EACH FEATURE

The next major task facing the engineer is the determination of that one key location on each feature where the critical stress is developed for each aircraft. At first glance, this might appear to be an extensive undertaking, but four simplifying assumptions ease this task considerably. First, aircraft do not generally operate randomly over the surface of a feature; they follow specific paths dictated by painted taxilines. Second, the location of this taxiline remains a constant distance from the slab's longitudinal joints throughout the feature. If not, a new feature should be designated where the taxiline shifts location. Third, the load transfer efficiency along transverse and longitudinal joints remains nearly constant, as shown by the authors in another paper in this Record. Finally, the critical tensile stress (and thus maximum damage) in a slab will occur at a transverse joint unless the gear travels within an average distance of about 12 in. from the longitudinal joint, in which case the critical stress is developed midway between transverse joints along the longitudinal joint.

Critical Gear Position

The four assumptions discussed in the preceding section permit the engineer to make a rapid assessment of the critical stress location of the aircraft gear to produce the maximum damage to the concrete slab. As shown in Figure 8, the combination of fixed taxiline to longitudinal joint distance and aircraft centerline to outside of the gear distance firmly establishes the position of the gear relative to the longitudinal joint. If the gear is not within about 12 in. of this joint, the point at which it crosses the transverse joint becomes the critical stress location.

Undoubtedly many occasions will occur on which a particular slab width, load transfer efficiency, taxiline location, and aircraft gear configuration combine to make the critical stress location uncertain. To assist the engineer in such an eventuality, a computer program called MAXSTRS was developed, based on the ILLI-SLAB finite element model, to calculate the maximum tensile stress at the bottom of the slab for any position of the gear. Inputs to the program include the aircraft type; slab dimensions; backcalculated k, E, and aggregate interlock factors; and distances from each joint to the nearest point on the gear. The type of aircraft specified automatically sets up the proper finite element mesh, and the offset distances from the joints specify the gear position. Each potential critical location for the gear can then be checked quickly, including the remote possibility that it could lie in the interior of the slab if load transfer at the joints is high enough (at least 95 percent).

Effects of Mixed Traffic

At this stage in the evaluation process, a few comments on the effects of mixed traffic will greatly reduce or even eliminate repeated stress calculations for other than the primary aircraft utilizing the pavement feature. First, the failure of a slab, defined as the appearance of the first load-associated crack throughout the evaluation procedure, begins at only one point on the bottom of the slab, the point of greatest repeated stress damage. Second, this point of greatest damage will usually occur under the mean wander point of the primary aircraft gear. Third, unless the wheelpaths of two or more aircraft overlap, resulting in additive stresses at the bottom of the slab, only the primary aircraft needs to be included in the evaluation of the feature.

In special instances, such as for thicker pavements and certain aircraft mixes, the actual point of maximum stress damage might not be located directly under a wheel of either aircraft. This situation can be accommodated by analyzing the stress distribution of each gear separately and then summing the stresses to find the point of maximum total stress. This point then becomes the location of maximum damage.

TABLE 1 Comparison of Measured and Predicted FWD Deflections Across Longitudinal and Transverse Joints

Feature	Slab No.	Load (lbf)	Measured (M) or Predicted (P)	Sensor Deflections D0	D1	D2	D3 (mils)	D4	D5	D6	Load Transfer Efficiency (%)
Longitudinal Joints											
T04A	1	23182	M	5.3	4.1	3.6	3.2	2.8	2.4	2.0	77
			P	5.6	4.4	3.6	2.9	2.3	1.7	1.1	79
	2	23087	M	4.3	3.9	3.5	3.0	2.6	2.3	1.9	91
			P	4.3	3.9	3.3	2.6	2.1	1.6	1.1	92
	3	22626	M	5.0	4.5	4.1	3.6	3.1	2.8	2.3	90
			P	4.9	4.5	3.9	3.3	2.8	2.2	1.7	92
	4	23071	M	4.3	3.9	3.5	3.0	2.7	2.3	2.0	91
			P	4.2	3.9	3.3	2.7	2.2	1.7	1.2	92
A05B	1	25170	M	9.1	6.0	5.1	4.3	3.6	2.9	2.4	66
			P	8.5	5.7	4.8	4.0	3.2	2.5	1.8	67
	2	22896	M	7.6	7.2	6.3	5.4	4.6	3.9	3.3	95
			P	7.2	6.9	5.8	4.8	4.0	3.2	2.4	95
	3	26871	M	5.7	5.2	4.4	3.9	3.3	2.9	2.5	91
			P	5.5	5.1	4.2	3.4	2.8	2.1	1.5	93
	4	26505	M	8.6	6.9	5.9	5.0	4.3	3.7	3.1	80
			P	8.2	6.9	5.8	4.8	4.0	3.2	2.4	83
A08B	1	23055	M	17.2	10.4	8.5	6.7	5.2	4.1	3.1	60
			P	16.8	10.4	8.1	6.0	4.5	2.9	1.4	62
	2	24136	M	34.1	6.4	5.2	4.3	3.3	2.8	2.3	19
			P	28.1	4.1	3.1	2.3	1.7	1.0	0.4	15
	3	23898	M	22.9	6.7	5.7	4.7	3.9	3.2	2.7	29
			P	22.8	5.9	4.4	3.2	2.3	1.4	0.5	26
	4	22578	M	15.9	14.8	11.9	9.1	6.9	5.4	3.7	93
			P	15.5	14.5	11.1	8.2	6.1	3.9	1.8	94
Transverse Joints											
T04A	1	23914	M	6.2	4.0	3.5	3.2	2.8	2.5	2.1	65
			P	6.1	4.0	3.3	2.7	2.2	1.7	1.2	65
	2	26537	M	5.0	3.4	3.0	2.7	2.3	2.0	1.7	68
			P	5.0	3.5	2.9	2.4	2.0	1.5	1.1	69
	3	25520	M	4.5	4.1	3.8	3.5	3.1	2.8	2.6	91
			P	5.2	4.8	4.1	3.5	2.9	2.4	1.9	93
	4	25726	M	8.7	2.2	2.0	1.9	1.5	1.4	1.3	25
			P	8.6	2.2	1.8	1.4	1.1	0.9	0.6	25
A05B	1	25631	M	11.9	3.4	3.1	2.7	2.4	2.1	1.8	29
			P	11.7	3.0	2.5	2.1	1.7	1.3	0.9	26
	2	25138	M	7.7	7.0	6.0	5.2	4.5	3.8	3.3	91
			P	7.5	6.9	5.9	5.0	4.2	3.4	2.6	92
	3	25106	M	6.7	4.3	3.8	3.3	3.0	2.6	2.2	64
			P	6.8	4.4	3.6	3.0	2.4	1.8	1.2	64
	4	25822	M	8.1	7.3	6.3	5.4	4.5	3.9	3.3	90
			P	8.3	7.6	6.4	5.3	4.3	3.4	2.5	92
A08B	1	24359	M	11.6	11.4	9.3	7.5	6.3	4.8	3.8	98
			P	12.2	11.6	8.9	6.7	5.0	3.3	1.6	95
	2	23580	M	13.8	13.4	11.2	9.2	7.1	5.9	4.6	97
			P	14.1	13.5	10.4	7.7	5.8	3.8	1.9	95
	3	25615	M	12.5	11.8	9.7	7.6	5.9	5.0	4.2	94
			P	13.0	12.3	9.4	6.9	5.1	3.3	1.5	95
	4	23739	M	25.7	8.6	7.3	6.2	5.1	4.4	3.6	33
			P	23.1	7.0	5.4	4.0	2.9	1.9	0.8	30

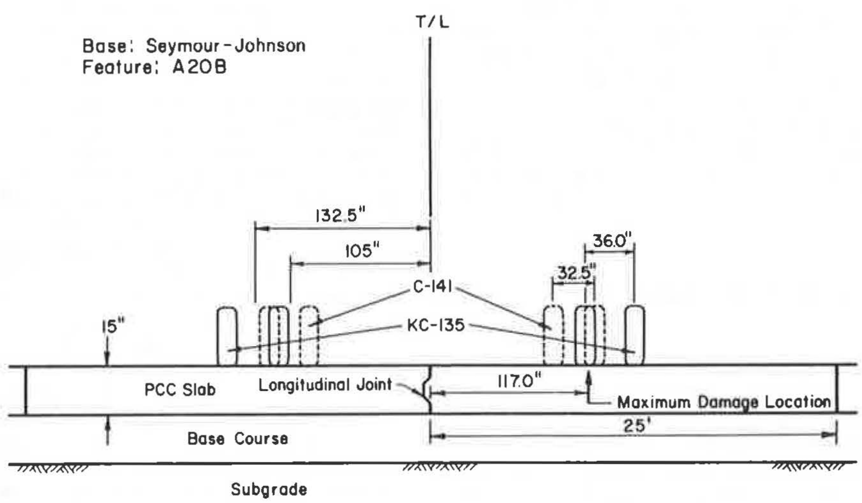

FIGURE 8 Determining the location of maximum accumulated damage for two or more aircraft.

The final determination of the critical aircraft gear may or may not coincide with the primary mission aircraft for the feature. It is entirely possible, for instance, that an aircraft producing high stress levels for 10 operations per day may cause more accumulated damage at its gear mean wander point than a lower stress-producing aircraft operating at 100 passes per day would cause at some other point on the slab. Generally, the critical aircraft for a feature will be apparent from the comparison of wheelpaths of all aircraft using the feature, particularly if an analysis of the critical stress has been performed on other similar features. In the event two or more wheelpath mean wander points do coincide, Miner's Damage Law must be used to account for the cumulative effects (3). This procedure will be discussed in detail later in this paper.

ACCOUNTING FOR TEMPERATURE AND PAST TRAFFIC EFFECTS

The tremendous variation of load transfer efficiencies experienced by any joint over the range of temperatures that joint is subjected to annually must be accounted for in the cumulative damage effects of the critical aircraft gear load. It is not sufficient to simply use an average annual load transfer efficiency exhibited by the joint when calculating the maximum stress because that stress is not linear with temperature or load transfer efficiency. It is possible, however, to distribute the total annual traffic at an installation into several temperature zones, calculate the maximum stress that would be generated by the critical gear at the average temperature of each zone, determine Miner's damage for that stress in each zone, and then sum the damage for each temperature zone to obtain the overall damage to the pavement in a year. This approach is recommended in this evaluation procedure.

A typical daily temperature cycle can be described approximately by the trigonometric relationship

$$T_H = [(T_{max} - T_{min})/2] \times \sin[15 \times (H - s)] = T_{avg} \quad (5)$$

where

T_H = temperature at any hour of the day;
T_{max} = maximum daily temperature (°F);
T_{min} = minimum daily temperature (°F);
H = hour of the day, from 1 to 24;
s = number of hours, from 1 to 24, between midnight and the occurrence of T_{avg}; and
T_{avg} = $(T_{max} + T_{min})/2$.

From this relationship, the temperature at any hour of the day can be approximated. If it is assumed that the variable s remains constant throughout the year, and that T_{max} and T_{min} are relatively stable over an entire month, then the average temperature of each hour of the year could be used to place that hour into 1 of 12 temperature zones. These zones were established in increments of 10°F from 0 to 100, as a compromise between the accuracy of smaller intervals and the increased analysis effort; temperatures below 0°F and above 100°F each comprise a zone. From the total number of hours in each zone, the percentage of the total hours in a year falling within each zone can easily be calculated.

If aircraft operations are assumed to be distributed evenly throughout the day, week, and year, the percentages just given become the percentages of aircraft operations on any feature within each temperature zone. Because the load transfer efficiency at any joint can be calculated for each temperature zone, the critical stress generated by the primary aircraft can be calculated for each of the 12 temperature zones in which it might operate. A computer program called TRAFDIS was written to perform these calculations.

The three assumptions made to complete this analysis do not appear to compromise the accuracy of this approach. The time of the day at which maximum and minimum temperatures occur remains fairly constant from month to month. The use of readily available monthly maximum and minimum mean daily temperatures will obviously not include those few hours of each year when temperature extremes exist, but the effect of these few hours on the total percentage is small. The greatest criticism could be levied at the assumption of evenly distributed traffic over time, particularly for commercial airport operations. However, for military airfields this assumption is not unreasonable because of their commitment to 24-hr readiness. The results of an analysis based on even distribution of traffic would probably lead to somewhat conservative estimates of remaining life because greater damage would be accumulated for night operations at colder temperatures. If an accurate traffic distribution pattern could be determined for a particular installation, it could be incorporated into the computer scheme to provide a more realistic analysis.

Estimating Past Traffic Damage

The prediction of remaining structural life in any pavement system must begin with an estimate of the past accumulated load damage based on Miner's Damage Law, which states that

Total Damage = Past Damage + Future Damage

Past damage can be estimated in two different ways, depending on the availability of past traffic loading data. If adequate data are available, a stress analysis can be conducted for each aircraft that has used the pavement, taking into account all of the factors that influence stress levels. From this extensive analysis, a summation of load damage can be made by using Miner's Damage Law. Usually, however, records on the movement of aircraft are inadequate, particularly for taxiways and aprons. Therefore, it is recommended that the estimate of past damage be obtained by using existing load-associated slab cracking information from the current PCI survey. If only load-associated damage is used, this technique will provide a quick, reasonable assessment of the accumulated damage, regardless of the type and mix of aircraft that produced it. The importance of an accurate distress survey thus becomes obvious.

The estimate of past damage is made by counting the number of slabs in the feature that contain any of the following distress types: corner breaks, longitudinal and transverse cracking, diagonal cracking, and shattered slabs. This number of distressed slabs is divided by the total number of slabs in the feature to arrive at the percentage of cracked slabs for the feature. Because the failure criteria have been established at 50 percent of all slabs with at least one load-associated crack dividing the slab into two pieces, a percentage of cracked slabs equaling 50 constitutes a Miner's damage of 1.00. It then becomes simply a linear transformation between the percent cracked slabs (%CS) and Miner's damage number (MDN). Expressed mathematically,

$$MDN = \%CS \times 0.02 \quad (6)$$

Only in those rare instances in which no load-associated cracking can be detected within the feature will an analysis of past traffic damage be necessary. In these cases, the feature would probably have been recently constructed, and such an analysis would be feasible.

Two points must be emphasized in making this estimate of the past damage. First, care must be taken during the initial counting of the distressed slabs to avoid including slabs that have cracked from other than load-associated causes. It is often difficult, for instance, to distinguish between a longitudinal crack caused primarily from load damage and a crack caused primarily from environmental or construction factors. Many cracks are caused by a combination of load and curling, warping, and shrinkage stresses. Cracking due to construction deficiencies, such as poor joint alignment or late sawing of contraction joints, must not be counted. Conversely, slabs that have been replaced must be counted as cracked slabs to avoid biasing the damage estimate for the other slabs (unless more than one-half of the slabs have been replaced, in which case it becomes a new feature). Good engineering judgment must be used to make this estimate because it has such a tremendous impact on the projection of remaining life.

The second point of interest is the potentially unconservative nature of the final damage estimate from distress survey results. It is entirely possible that, because of the mechanics of crack propagation, load-associated cracking may not have quite reached the surface of several slabs, where it could be counted. Thus, a feature could possibly exhibit no load-associated distress during the survey, and two weeks later 5 to 10 percent of the slabs display their initial crack. Only through the long-term monitoring programs currently under way will trends of this type be discovered. In the interim, this procedure provides the most reasonable approach to estimating past damage, certainly far better than the only other alternative.

Figure 6 shows the required crack development pattern to make this estimate of the total accumulated past damage. Of the 24 slabs in the feature, 5 contain a load-associated crack. From Equation 6, Miner's damage number for Feature A20T becomes 0.42.

DEVELOPMENT OF FINAL EVALUATION DATA BASE

The analyses conducted in the last sections have resulted in the establishment of three additional pieces of information, critical to the evaluation of each feature, which must be added to the data base. The taxiline offset distance is the distance from the taxiline of the feature, either painted or projected, to the closest longitudinal joint. This distance is used in conjunction with the airplane's configuration to position the gear on the slab for stress calculations. The transverse joint offset distance allows the positioning of the gear at some point other than the transverse joint, if the critical stress analysis revealed, for instance, that the maximum stresses were developed along the longitudinal joint. Finally, the past, accumulated, load-associated damage, expressed as a Miner's damage number, must be added to the data base. A simple computer program MODIFY has been written to generate this file.

Aggregate Interlock Factors for Each Temperature Zone

The dependence of the critical stress on air temperature, and hence load transfer efficiency, requires that the maximum tensile stress at the bottom of the slab be calculated for each of the 12 temperature zones. To accomplish this, aggregate interlock factors must be determined for each zone at both longitudinal and transverse joints for inclusion into the ILLI-SLAB program. Thus 24 aggregate interlock factors must be iterated for each slab tested. Fortunately, the computer program AIFCALC performs these calculations quickly and efficiently.

AIFCALC makes two assumptions in determining these aggregate interlock factors. First, load transfer efficiencies below 25 percent are elevated to 25 percent to avoid precision errors when slopes of lines near zero are encountered. Similarly, load transfer efficiencies above 95 percent are automatically assigned an aggregate interlock value of 30 x 10^8 psi to avoid a problem much the same as that which exists at the lower values. Second, the program assumes that load transfer efficiencies below 25 percent and above 95 percent, as measured in the field, have just reached these values at the time of measurement. Otherwise, no prediction of their behavior with temperature could be made (see paper by the authors elsewhere in this Record). The only alternative to this assumption would be a retesting of the slab joint at another time to obtain a load transfer efficiency between 25 and 95 percent. Fortunately, this situation does not occur often if testing is accomplished between 40 and 90°F.

PREDICTING THE REMAINING LIFE

The DAMAGE program reads the slab dimensions, backcalculated moduli, and aggregate interlock factors for the first temperature zone to calculate the maximum stress generated by the specified aircraft, with adjustments to the dynamic k moduli for static loading conditions, if necessary. This stress is used as the basis for determining the stress in each of six gross weight categories. For example, an aircraft loaded at 80 percent of its gross weight will produce a stress at the bottom of the slab equal to 80 percent of the stress produced at its maximum gross weight.

The flexural strength of the concrete is then determined through a correlation developed during this research with backcalculated concrete elastic moduli, adjusted for traffic area. When divided by the calculated stress for each gross weight category, the evaluation factor for each category is established. Equation 7, developed from an ILLI-SLAB reanalysis of accelerated traffic test data and shown graphically in Figure 9 is as follows:

$$\text{Log}_{10}\ \text{COV} = 1.323 \times (\text{FS/CS}) + 0.588 \quad (7)$$

where

COV = coverages to initial crack failure,
FS = flexural strength,
CS = critical stress,
R^2 = 0.64, and
SEE = 0.52.

Equation 7 then relates the evaluation factor to the number of coverages that can be expected for each gross weight category in the first temperature zone. Next, the damage caused by one coverage of the aircraft is distributed among the temperature zones according to the percentage of total aircraft operations occurring in each zone. Finally, this entire process is repeated for each of the 12 temperature zones, and the damage from each zone is summed to provide the total damage resulting from one coverage of the aircraft in each gross weight category.

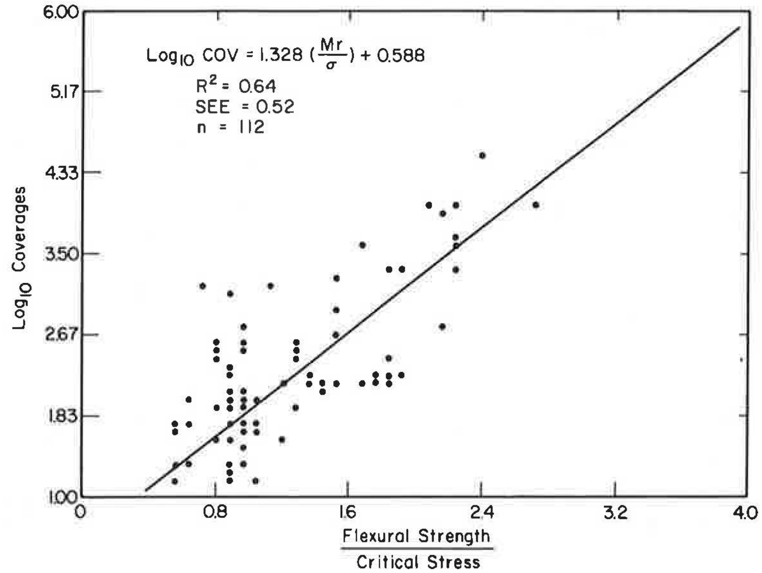

FIGURE 9 Relationship between strength and stress of concrete slabs and their field performance—the transfer function.

Relating Future Damage to Remaining Coverages

From the calculation of the damage caused by one coverage of the specified aircraft, it is a simple procedure to calculate the remaining coverages to initial crack failure. REMLIFE calculates the future damage allowed for one coverage of the aircraft by subtracting the past damage from a total permitted Miner's damage of 1.0. The remaining coverage level for each gross weight category is simply the total future damage divided by the total damage for one coverage of the aircraft. This entire process is then repeated for every slab tested.

Pass-per-Coverage Ratios

Brown and Thompson documented the background, development, and application of the current procedure for converting coverages to passes, and provided a limited amount of data on which the current pass-per-coverage (P-C) ratios, still in use by many agencies, are based (4). These data were collected at several Air Force bases in 1956 and 1960, using B-47, KC-97, B-52, and KC-135 aircraft. Approximately 1,176 observations of aircraft taxi, takeoff, and landing operations were made at 1,000-, 2,000-, and 5,000-ft points on runways, and along curved portions of taxiways.

The primary result of the study was a method for calculating P-C ratios based on a channelized traffic wander width of 70 in. and a nonchannelized wander width of 140 in. Recognizing that the lateral distribution was continuously changing along the runway for each aircraft, these wander widths were arbitrarily established for design purposes.

In 1975, the Federal Aviation Administration sponsored an extensive research effort by HoSang to determine realistic lateral distribution patterns for commercial aircraft traffic at civil airports (5). Data were collected at nine airports representing a wide range of operating and environmental conditions. More than 10,000 observations of lateral distribution were made at three runway locations and on parallel and high-speed taxiways.

The results of this study verified the P-C ratio calculation procedures developed by Brown and Thompson, and also provided lateral distribution characteristics more representative of today's aircraft operations. Particularly noteworthy is that, for all practical purposes, the standard deviations along the entire length of runways and taxiways can be assumed constant. On runways, some additional wander was evident at the point of rotation, but in general, a standard deviation of 6.5 ft is representative of the entire length. On taxiways and apron taxilanes, a standard deviation of 3.0 ft is typical. The vast amount of data collected and the instrumentation utilized make this report extremely valuable in the pavement evaluation process. The P-C ratios presented in Table 2 were developed from HoSang's recommendations and allow the user to select values that are appropriate for a given situation (5). The average P-C ratios stated here are used in the REMLIFE computer program.

Final Evaluation

The last step performed by REMLIFE in the evaluation for a single aircraft is the application of the aircraft's P-C ratios to the calculated coverage level for each gross weight category. This produces the predicted number of aircraft passes remaining in each slab until initial crack failure occurs. However, it remains for the engineer to condense these individual slab predictions into a single prediction for the entire feature.

Ideally, a representative slab could have been developed for the evaluation of each feature by averaging FWD deflections and backcalculating an overall E and k for the feature. This technique was shown as a part of this research to produce results that agree precisely with backcalculated E and k values obtained for each slab and then averaged for the entire feature. The savings in computer processing time is substantial, and such a procedure is recommended if only E and k values are desired from FWD deflections.

However, when the evaluation process is extended to remaining life projections, the representative slab concept will not work. The required average load traffic efficiency for each joint in such a representative slab would not accurately reflect the

TABLE 2 Pass-per-Coverage Ratios for Selected Aircraft at Various Standard Deviations of Wander Width for Rigid Pavements

	Standard Deviations of Wander Width (ft)								
Aircraft	1	2	3	4	5	6	7	8	9
F-4	3.42	6.84	10.26	13.67	17.06	20.26	22.92	24.67	25.24
A-10	4.78	9.55	14.32	19.10	23.81	28.15	31.58	33.54	33.95
F-15	3.54	7.08	10.62	14.15	17.55	20.43	22.26	22.75	23.16
F-16	4.56	9.11	13.13	14.57	15.38	16.84	18.59	20.50	22.50
T-38	7.72	15.43	23.10	29.95	33.84	34.56	36.25	38.66	41.48
F-111	1.99	3.98	5.95	7.57	8.21	8.46	9.69	10.46	11.29
C-130	0.85	1.71	2.56	3.41	4.20	4.79	5.04	5.11	5.28
DC-9	2.24	3.00	4.17	5.41	6.65	7.75	8.54	8.89	8.97
B737	2.45	3.14	4.20	5.37	6.56	7.66	8.50	8.94	9.03
B727	2.17	2.99	3.76	4.72	5.72	6.70	7.54	8.14	8.41
C-141	1.16	1.50	1.98	2.53	3.09	3.61	4.02	4.26	4.31
KC135	1.10	1.48	1.89	2.39	2.91	3.44	3.95	4.41	4.77
C5	0.83	1.31	1.39	1.52	1.72	1.94	2.17	2.40	2.61
DC10	1.00	1.80	1.98	2.33	2.76	3.21	3.67	4.14	4.62
L1011	1.01	1.78	1.97	2.34	2.77	3.23	3.71	4.19	4.67
E4	1.00	1.53	1.81	2.14	2.33	2.40	2.43	2.45	2.46
B52[a]	0.55	0.75	0.95	1.16	1.29	1.31	1.37	1.45	1.54

[a] These pass-coverage ratios are one-half of the values calculated by the program to account for the large distance between the bicycle gears.

increased stresses that develop as joints open in colder temperatures. Therefore, each slab must be evaluated separately for remaining passes to failure, and then an average remaining pass level for the feature can be determined easily.

The evaluation of the feature for a mix of aircraft requires an additional step in the REMLIFE program. The DAMAGE outputs for each aircraft must be combined in a specific manner for each gross weight category and slab to determine the total damage from the assumed traffic. The P-C ratio for each aircraft and the proportion of each aircraft in the total are utilized to arrive at the final remaining life predictions. The current capabilities of the REMLIFE program will permit any mix of aircraft.

SUMMARY

A complete system for NDT & E of rigid airfield pavements has been presented. Techniques for identifying and statistically sampling individual features will reduce testing and analysis costs while ensuring accurate results. Computer programs have been developed to calculate stresses at joints for any gear configuration and for any temperature profile. These stresses are related to field performance by a transfer function derived from accelerated traffic test data. Finally, the structural life of the feature can be predicted for any mix of aircraft.

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REFERENCES

1. P.T. Foxworthy. Concepts for the Development of a Nondestructive Testing and Evaluation System for Rigid Airfield Pavements. Ph.D. thesis. University of Illinois at Urbana-Champaign, Urbana, 1985.
2. M.Y. Shahin, M.I. Darter, and S.D. Kohn. Condition Evaluation of Jointed Concrete Airfield Pavement. ASCE Transportation Engineering Journal, Vol. 106, No. TE4, July 1980, pp. 381-399.
3. M.A. Miner. Cumulative Damage in Fatigue. Journal of Applied Mechanics, Sept. 1945.
4. D.N. Brown and O.O. Thompson. Lateral Distribution of Aircraft Traffic. Miscellaneous Paper S-73-56. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., July 1973.
5. V.A. HoSang. Field Survey and Analysis of Aircraft Distribution on Airport Pavements. FAA-RD-74-36. Federal Aviation Administration, U.S. Department of Transportation, Feb. 1975.

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