ANALYSIS OF REMAINING LIFE FOR RUNWAY 17R-35L AND TAXIWAY L AT DALLAS/FORT WORTH INTERNATIONAL AIRPORT

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Research Report Number ARC-702

VOLUME I EXECUTIVE SUMMARY

Prepared in cooperation with the

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August 1997

EXECUTIVE SUMMARY

INTRODUCTION

This report is the first of three volumes prepared by the Center for Transportation Research to document the evaluation of the remaining life of the primary runway and adjacent taxiway at Dallas/Fort Worth International Airport. Volume I, Executive Summary is a stand alone document to describe the testing developed and results of the field and laboratory testing undertaken for this research project. The Executive Summary also provides the conclusions reached that there is a concrete fatigue problem evident in the keel section of both the runway and taxiway. Volume II, Final Report is the complete description of the findings of the research study. Volume III, Data Appendices is a complete listing of the data gathered during this study. In addition to the printed reports, a MicroStation CAD file was delivered to the Airport with nearly all the distress data and deflection profiles provided in a geographic format.

When this project was proposed, most of the testing techniques had either never previously been applied to airport pavements or had only been used for experimental purposes. Much has been learned during both the research testing and the evaluation of the data, that will lead to improvements for future evaluations. The researchers conclude that this has been a very valuable research project: the data collected is valid, and the approach provides a far better method of evaluating present condition and predicting remaining life than the traditional FAA endorsed methodology.

DESCRIPTION OF THE PROBLEM

Dallas/Fort Worth (DFW) International Airport is the second busiest airport in the world with over 800,000 aircraft operations annually on the six runways that were operational when this study began. DFW began operations in 1974 as an origin-destination airport serving the DFW metropolitan area. After airline deregulation, DFW became a large hub airport for American, Delta and Braniff Airlines. The initial runway design was for a 20-year life based upon the projected aircraft origin and destination operations growth pattern. In addition to the fact that these runways have already exceeded their 20-year design life, aircraft operations on them have far exceeded design projections due to hubbing operations.

In 1988, the DFW Airport Board contracted with Harding Lawson Associates to develop a pavement management system and conduct a 100 percent survey of the existing pavement conditions for the airside pavements. That study was concluded in 1990 and provided a Pavement Condition Index (PCI) for all airport pavements surveyed. The predominate distress noted in the pavement survey was low-severity patching distress. Considering this high density of patching, it was predicted that the primary runways and taxiways would require full width reconstruction by 1995. Upon invitation from the Airport Board, the Center for Transportation Research (CTR), The University of Texas at Austin submitted a proposal suggesting that conventional PCI surveys were inadequate in predicting remaining life for air carrier operations and that remaining life should be forecast considering five different potential modes of failure: fatigue of concrete; surface roughness; surface distress; loss of subgrade support; and joint deterioration.

TESTING PROGRAM

CTR was awarded this research project in 1995 to analyze the condition and predict remaining life of a 11,400-foot section of Runway 17R/35L (this does not include a recent 2000-foot extension) and 11,700 feet of Taxiway L (formerly K). Both statistical and analytical analyses of the data in the pavement condition database were performed as part of this research project. The analyses were used to develop functional and structural performance relations for the various pavement sections.

An essential part of this study involved conducting both destructive and non-destructive testing of Runway 17R/35L and Taxiway L. A testing plan was developed by the Center for Transportation Research (CTR) team and submitted to the DFW team for review and approval. The field testing program was conducted to verify past test results, provide data to document changes, and provide data from new tests. The suite of nondestructive and destructive testing included the following:

- Cross-hole Seismic Analysis in certain locations where concrete cores were taken
- Distress survey with PCI (Pavement Condition Index) Survey review
- Extracting cores from the pavements (destructive)
- Heavy Falling Weight Deflectometer (HWD) testing (non-destructive)
- Measurement of Runway Profile for roughness analysis (non-destructive)
- Rolling Dynamic Deflectometer (RDD) testing (non-destructive)
- Shelby Tube extractions of subsurface materials (destructive)

Measurement of Runway Profile

The University of Texas and Airport Pavement Roughness Consultants (APR) of Medway, Ohio performed the profile measurements of Runway 17R/35L and of Taxiway L during the nights of October 31 and November 1, 1995. When an airport pavement becomes too rough, aircraft react adversely, as do the pilots and passengers. The aircraft experiences more relative damage during operation on a rough pavement than on a smooth pavement. Likewise, passengers feel uncomfortable during takeoff or landing when the pavement causes the aircraft to bounce or shake. Damage to the aircraft occurs when excessive vertical accelerations are developed in the aircraft due to surface roughness of the pavement. The dynamic loads imparted to the aircraft also result in dynamic loads to the pavement, accelerating the deterioration of load-related distresses. Finally, a rough runway can lead to increased aircraft stopping distances thereby reducing the calculated effective runway length for both takeoff and landings. Measurement of the runway profile is therefore important for the assessment of roughness.

Data for Pavement Condition Index (PCI)

During 1990, Harding Lawson Associates conducted a pavement condition index survey of runways and taxiways of DFW Airport. CTR personnel reviewed the field notes of the Harding Lawson survey and plotted individual distress types for each concrete slab of the runway and taxiway. CTR personnel also reviewed the videotapes of the runway and taxiway provided by PAVETECH to airport maintenance. The videotapes proved to be of poor quality and, as a result of the difficulty in extracting the exact locations of the distresses from the videotapes, CTR plotted the actual locations of the patching distress of only a small portion of the runway. The small sample size was, however, sufficient to observe that the majority of the patching shows a pattern unrelated to aircraft loading.

FAA Advisory Circular AC150/5380-6 and the ASTM D5340-93 procedure are identical in the identification of distresses. Neither the FAA or ASTM method specifically identifies fatigue cracking as a distress. In both methods, all cracking in rigid pavements must be classified as one of the following:

- shrinkage cracking;
- longitudinal, transverse or diagonal cracking or
- durability (D) cracking.

Subsurface Investigations

Subsurface evaluation was accomplished using several methods. Core samples were taken of the concrete and cement treated base. Shelby tube samples were taken from the lime-treated subgrade and natural subgrade. However, cross-hole seismic testing coupled with rolling dynamic deflectometer testing provided CTR with the best data for analysis of the subgrade materials.

Core Samples. Several different coring programs were included in the testing plan submitted to the DFW technical advisors for review. First, a coring and testing program was developed for Taxiway K before its reconstruction. The intent was to identify the properties of the concrete at the end of its service life. Another coring and cross-hole seismic testing program was developed for Runway 17R/35L, as well as for Taxiway L. The coring was done by Maxim Engineers located at the DFW airport. The purpose of the coring was to obtain concrete samples to test in the laboratory and to provide holes deep enough to perform the cross-hole seismic testing.

Since the aircraft wheel path is approximately located one-third of a slab width away from the centerline of the runway and the taxiway, it was desirable to obtain core samples from this location in order to test the properties of the concrete from a loaded portion of the pavement. This concrete from the wheel path section has been loaded by numerous aircraft over its service life and approximately half of the concrete cores were taken from the wheel path area of the pavements. The other half of the cores were taken from a portion of the pavement which has seen very little aircraft loading, near the edge of the pavement. The furthermost slab from the centerline sees little, if any, traffic loading over the years. The concrete taken from this location represents concrete that is in new condition, with the exception of environmental loads.

This difference in the historic loading patterns of the two locations provides a basis for analysis. A comparison can be made between the properties of the concrete taken from the wheel path and of those of the concrete taken from the non-trafficked area. In addition to observable differences of the trafficked and untrafficked concrete cores, differences were also observed in the testing data from concrete cores taken from the north end of the runway and cores taken from the south end.

Shelby Tube Samples. Shelby tube samples of the lime stabilized subgrade and natural subgrade were obtained from beneath Taxiway L and Runway 17R/35L using the core holes. Unfortunately, taxiway samples were extruded from the tubes by Maxim Technologies, the DFW contractor taking the samples, rendering them useless for testing. The runway samples were delivered as requested still in the tubes, however the ends were only partially sealed with wax. These samples were unable to be tested due to disturbance caused by the lack of proper sealing of the sample tubes.

Cross-hole Seismic Testing. Cross-hole seismic testing was performed at four locations on Runway 17R/35L and at eight locations on Taxiway L. At each of these locations, a pattern with 3 to 9 core holes was drilled into the pavement system to depths ranging from 3 to 9 feet. A typical pattern with three core holes is shown in Figure 1.

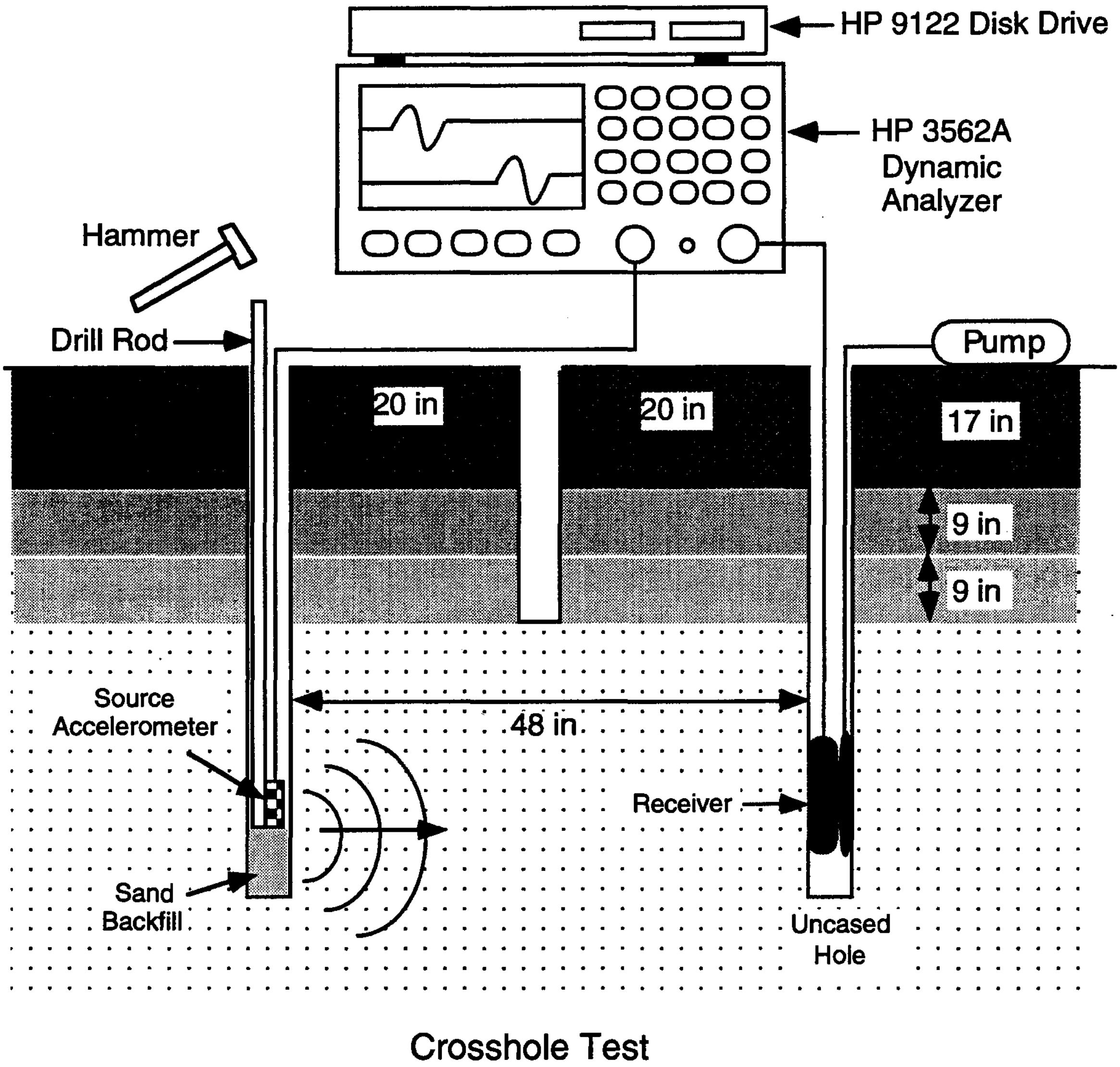

Figure 1. Cross-hole Seismic Test

Generally, horizontal spacing between core holes ranged from 3.5 to 7 feet. Testing was performed by initiating stress waves in one core hole and monitoring their arrivals in the adjacent core holes. The purpose of these tests was to evaluate the stiffness of each component of the pavement system independently and in-place.

The results shown in Table 1 were determined from measurements performed in midslab and joint areas in the traffic lanes and at the edge. Cross-hole seismic tests were also performed in the base, subbase and subgrade materials beneath transverse joints and longitudinal saw cuts. In each case, the moduli of the materials ranged from 35 to 95% of the corresponding moduli measured in the midslab areas. These results clearly show that additional damage has occurred to the supporting materials beneath the joints in the trafficked areas.

TABLE 1. DFW CROSS-HOLE TEST RESULTS

			Taxiway L		
Layer	North Runway E(ksi)	South Runway E(ksi)	EK E(ksi)	K7 E(ksi)	EM E(ksi)
Trafficked					
Concrete	5413	4588	5859	5284	4929
CTB	340	422	242	225	196
LTB	259	138	166	129	94
Subgrade	11	26	20	30	14
RDD Reading	3.98	3.78	3.16	3.03	3.54
Untrafficked					
Concrete	5472	6085	6087	5745	5002
CTB	727	679	342	395	233
LTB	262	275	281	112	110
Subgrade	15	18	N/A	33	15

The stiffness determined from the cross-hole tests were expressed in terms of Young's modulus of each material: concrete surface layer, cement-treated base, lime-stabilized subgrade (also called the subbase) and natural subgrade. The results show that, on Runway 17R/35L, the trafficked areas have more cumulative damage compared to the untrafficked areas. This damage is shown in Table 2 by the decrease in Young's modulus of each of the materials. Similar results were also found in Taxiway L as shown in Table 2.

TABLE 2. DAMAGE FROM CUMULATIVE TRAFFIC TO PAVEMENT LAYERS EXPRESSED AS A CHANGE IN YOUNG'S MODULUS OF EACH LAYER

	Runway 17L/35R	Taxiway L
Material	$E_{trafficked}/E_{untrafficked}$	$E_{trafficked}/E_{untrafficked}$
Concrete Surface Layer	0.87	0.95
Cement-treated Base	0.54	0.68
Lime-treated Subbase	0.75	0.77
Natural Subgrade	0.83	0.88

Deflection Testing

The test method using Heavy Falling Weight Deflectometer (HWD) was the method initially planned for and used for evaluating the deflections of the runways and taxiways. After the field data was analyzed by backcalculation procedures, it was found that the moduli-values obtained were unreasonable and inconsistent. Thus, the decision was made to explore and ascertain the capabilities of the Rolling Dynamic Deflectometer (RDD) for measuring deflections. In the following sections, the RDD and the RDD testing at DFW is described, since it is a relatively new piece of equipment.

Description of the Rolling Dynamic Deflectometer (RDD). The Rolling Dynamic Deflectometer (RDD) is a truck mounted device that measures continuous deflection profiles of pavements. A drawing of the RDD is shown in Figure 2. The device consists of a large truck with a gross weight of about 195 kN (44,000 lb) on which a servo-hydraulic vibrator is mounted. The vibrator has a 33-kN (7,500-lb) reaction mass which is used to generate vertical dynamic forces as large as 310 kN peak-to-peak (70,000 lb peak-to-peak) over a frequency range of about 10 to 100 Hz. Simultaneously, the hydraulic system generates a constant hold-down force ranging from 65 to 180 kN (15,000 to 40,000 lb). The static and superimposed dynamic forces are transferred to the pavement through two loading rollers as shown in Figure 3.

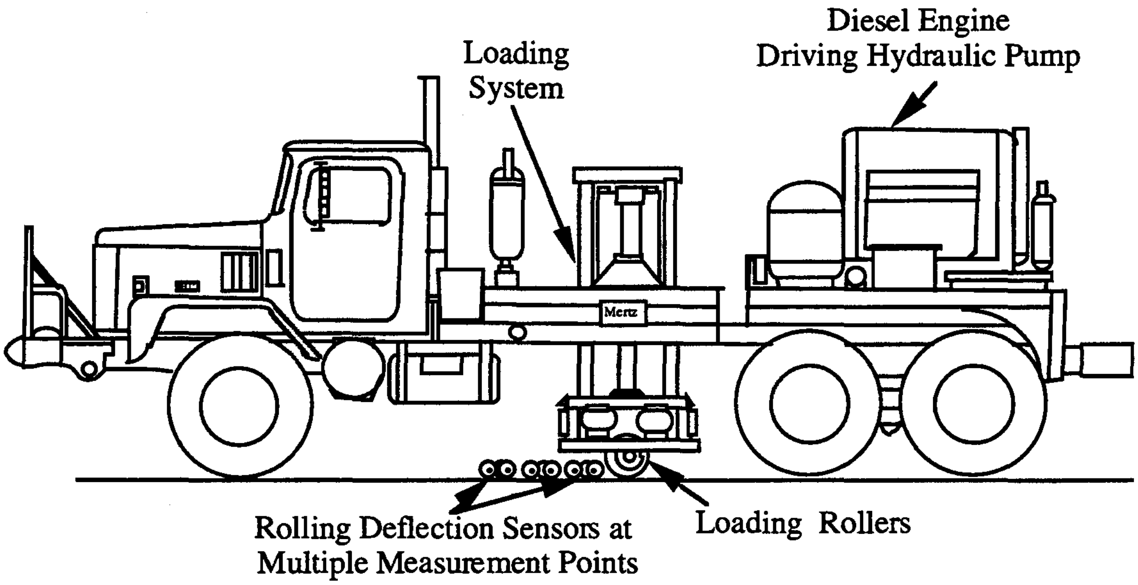

Figure 2. General Configuration of the Rolling Dynamic Deflectometer (RDD)

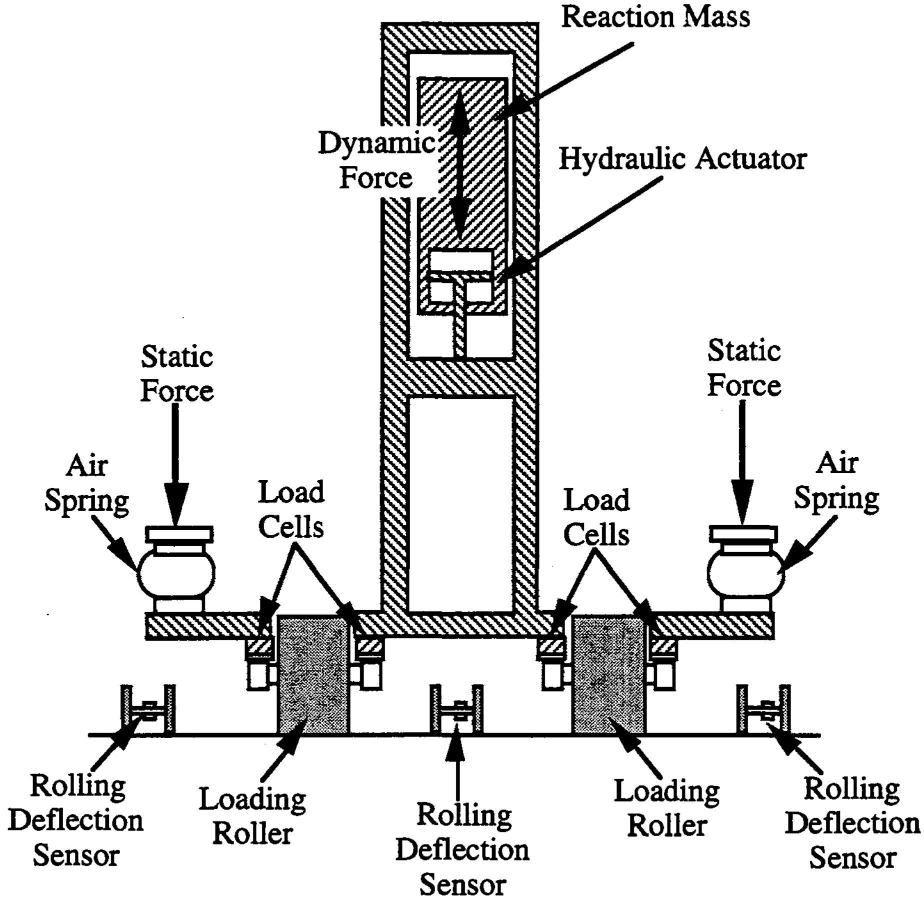

Figure 3. Front Cross-Sectional View of the RDD Loading and Measurement Systems

As the RDD slowly rolls over a pavement, it applies a cyclic load to the pavement surface through the loading rollers. Dynamic displacements are measured with four rolling sensors. By measuring the applied forces and the resulting deflections, a continuous deflection profile for the pavement is determined, with soft regions of the pavement exhibiting large deflections and stiff regions lower deflections.

RDD Testing at DFW. On July 28-29, 1996 and August 30-September 2, 1996 RDD testing was performed at DFW airport. Deflection profiles were measured along the entire length of Runway 17R near the runway center line. Three additional longitudinal profiles were measured on two 2000 foot intervals: between the centerline and the first saw joint; along the first saw joint; and, along the undowelled construction joint. Transverse profiling was also performed on eight alignments next to transverse joints. The same battery of tests was performed on Taxiway L, the entire taxiway length was profiled near the centerline and the three additional longitudinal profiles were measured on a single 2000 foot section. Transverse profiling was conducted at two locations on the taxiway near transverse joints.

Additional profiling was performed on the newly constructed Runway 17L/35R. These profiles provide a valuable comparison to the results from Runway 17R/35L by showing the effects of traffic on pavement degradation. The same battery of tests was performed on the new runway as on Runway 17R. Profiling was conducted on about 5000 foot on this runway near the centerline. At one 1000 foot section additional longitudinal profiles were measured between the centerline and the first longitudinal saw joint, at the saw joint and at the longitudinal construction joint. Two transverse profiles were measured next to transverse joints.

DATA COLLECTION AND LABORATORY TESTING

Determining fatigue of the Portland cement concrete (PCC) material was a major focus of the research study. To accomplish the analyses, data for past and future aircraft operations were analyzed and converted to equivalent Boeing 727 and MD-11 departures. Fatigue analyses and indirect tensile strength tests were conducted on all concrete core samples.

Current and Future Aircraft Operations Analysis

Analyzing historical aircraft traffic data is necessary to evaluate current runway pavement deterioration and to generate a correlation between cumulative runway traffic and current runway fatigue. From this, future traffic forecasts can be used to estimate remaining pavement life.

Historical traffic data was rather difficult to obtain for Dallas/Ft. Worth International Airport, as well as runway traffic distribution data. From 1991-1994, traffic data was obtained from the FAA Airport Activity Statistics. For 1995, traffic data was obtained from the DFW Airport Planning Department. Pre-1991 traffic data was obtained using assumptions from the Harding Lawson Pavement Evaluation Report. Traffic forecasts to the year 2010 were projected based on traffic growth from 1991 to 1995 and are shown in Table 3. At the bottom of the table the forecast traffic is converted to equivalent B727 departures.

TABLE 3. ANNUAL EQUIVALENT B-727 DEPARTURES FOR RUNWAY 17R/35L

Aircraft	<1990	1991	1992	1993	1994	1995	2000	2005	2010
B727		22066	19469	16104	13673	9429	7199	5201	2722
B737		8987	9297	10135	8560	11315	13882	16644	17968
B747		69	19	41	40	38	40	42	44
B757		6789	7423	9348	10677	11315	13882	14564	15245
B767		2742	2364	2380	2422	2263	2181	2081	2178
DC-8		175	59	866	1158	943	992	1040	1089
DC-9		6203	4218	3003	3214	2829	1487	0	0
MD11		5282	5298	3736	2036	1886	1983	2081	2178
MD80		37058	42227	43530	41922	43372	45612	47852	50092
L1011		1021	987	1238	1118	943	0	0	0
F100		0	2	1958	8492	9957	11899	14564	17423
Total 17R		90393	91363	92339	93312	94288	99157	104069	108940
B-727 Equiv.		37121	35236	33020	30022	26343	24965	24065	22475
Cumulative B-727s	568,750	605,871	641,107	674,127	704,149	730,492	836,061	938,762	1,033,722

The Harding Lawson Report assumed from a more detailed analysis that 37% of all aircraft departures occur on Runway 17R and 12% on 35L. Runway 17R/35L is a departure only runway, consequently there is no need to convert arrivals to equivalent departures. According to the Harding Lawson Report, 6.5 million equivalent MD-11 departures occurred at the airport before 1991; 2.4 million equivalent MD-11 departures were on Runway 17R/35L. To convert equivalent MD-11 departures to equivalent B-727 departures a conversion factor of one B-727 departure to four MD-11 departures was used. Therefore, prior to 1991, 568,750 equivalent B-727 departures occurred on Runway 17R and 177,066 on Runway 35L. After calculating and adding the equivalent B-727 departures for years 1991 to 1995, it was found that a cumulative total of 730,492 equivalent B-727 departures have occurred on Runway 17R and 227,420 on Runway 35L in 1995. Table 4 shows the equivalent departures per section of Runway 17R/35L and Taxiway L

TABLE 4. CUMULATIVE EQUIVALENT DEPARTURES BY SECTION

Section	1990	1990	1995	1995
Runway 17R/35L	MD-11	B-727	MD-11	B-727
1	2,386,578	568,750	3,059,237	730,492
2	2,386,578	568,750	3,059,237	730,492
3	2,386,578	568,750	3,059,237	730,492
4	607,239	143,985	779,695	184,877
5	746,974	177,066	959,115	227,420
6	746,974	177,066	959,115	227,420
7	746,974	177,066	959,115	227,420
8	746,974	177,066	959,115	227,420
Taxiway L	MD-11	B-727	MD-11	B-727
1	20,400	4862	26,150	6244
2	1,606,090	3,82,750	2,058,768	491,598
3	1,359,376	323,956	1,742,517	416,082
4	1,823,157	432,296	2,340,934	555,069
5	1,914,031	453,710	2,457,617	582,736
6	600,415	142,325	770,933	182,799
7	600,415	142,325	770,933	182,799
8	746,974	177,066	959,115	227,420
9	746,974	177,066	959,115	227,420

As expected, the greatest number of departures (load) occur on the north end of 17R/35L. For determining the number of departures on each section of the runway, it was determined that most of the aircraft operating at DFW rotate before the midpoint of Runway 17R/35L. As a result, the lightest loads occur in the center, with only 184,877 equivalent B-727 departures. After analyzing the traffic and developing a correlation between the number of departures and the amount of wear, a future amount of wear can be predicted. The remaining life in a runway can thus be predicted based on cumulative aircraft operations.

Fatigue Testing of Concrete Core Samples

The fatigue testing performed for this project consisted of selecting several core samples taken from the concrete pavements and preparing them for long term fatigue testing. The samples taken from the cores for fatigue testing were trimmed to two inches in length to accommodate the capacity of the test machine. Generally, the core samples selected were from the bottom two inches of the core, since tensile stresses in the pavement induced by aircraft loads occur at the bottom of the slab. Testing was accomplished by applying a cyclic load in the indirect tensile testing method. By changing the amount of cyclic stress applied to each specimen, and taking the ratio of the stress to the strength of the specimen, a fatigue curve can be produced. The number of cycles to failure, or the fatigue life of the concrete, decreases with increasing stress to strength ratio as shown in Figure 4.

In this figure, the cycles to failure is the number of load applications that each sample supported before failing in tension. The stress/strength ratio is the relationship between the tensile strength of the concrete and the tensile stress applied. The vertical axis is shown in the logarithm of the number of loads to failure for clarity.

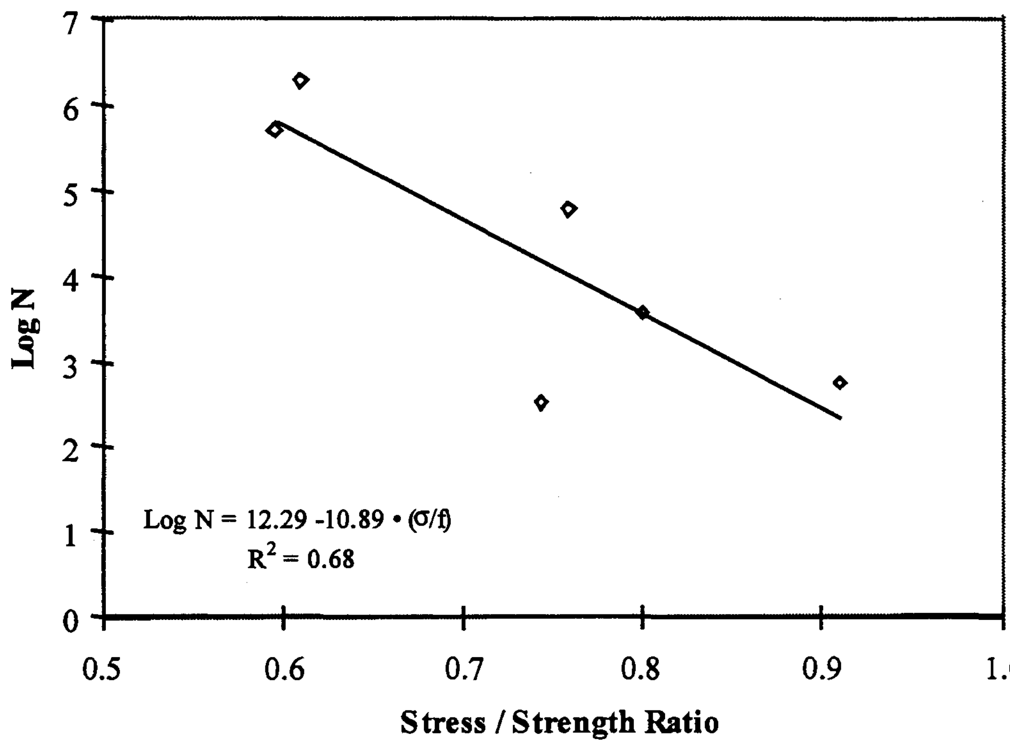

Figure 4. Fatigue Curve for RW 17R/35L and TW L Concrete Cores

The slope of the fatigue curve in the figure is -10.89, which is comparable to the slope of -20.224 obtained by Yimprasert and McCullough in CTR Report 123-16 *Fatigue and Stress Analysis for Modifying the Rigid Pavement Design System.* The curve represents the number of allowable cycles that the pavement can withstand before failing. In most of the samples in the figure, the allowable cycles to failure is measured on concrete that has already been exposed to many thousands of loads and this accounts for the slope of the fatigue curve in Figure 4 being only about half of that in Report 123-16. The concrete slabs from which the cores were taken have in fact been exposed to as many as 730,000 equivalent B-727 aircraft departures since construction. The results of the fatigue analysis will thus allow a prediction of remaining life based on the previous number of equivalent B-727 departures and the magnitude of the stress induced by those aircraft. The remaining life will be estimated by taking the difference between the previous and ultimate number of equivalent B-7,27 departures at the corresponding stress to strength ratio. If a different stress level is desired, Miner's hypothesis must be applied, which states:

$$\sum \frac{n_i}{N_i} = 1$$

where:

n_i = number of applications of a load i

N_i = Total allowable applications of a load i

Miner's hypothesis allows the fatigue relationship to be applied to mix of several different load levels.

ANALYSIS OF DATA

The data were analyzed with respect to individual failure modes surface distress, fatigue cracking, deterioration of slab support, and RDD deflection profiles as well as the interrelation of failure modes. The analysis is somewhat limited because previous data gathered by the airport was not always retrievable by the airport staff. Interviews were also held with people now retired who played important roles in the construction or design of the runway and taxiway in order to supplement construction history. The following sections detail the analysis of the data. .

Surface Distress

There is a distinct pattern of corner spalling and joint spalling that has been repaired with very small patches (most less than 2 ft. long) This spalling mostly occurs outside the trafficked portion of the runway. From our review of the Harding Lawson analysis, it was determined that the proliferation and subsequent patching of this distress led to the conclusion, through use of the PCI method, that the demise of Taxiway L was eminent. In Harding Lawson's defense, it is our belief that the FAA-sanctioned PCI method of analysis overestimates the effects of all surface distress, especially patching. In fact, if these spalls were not repaired with patches, because of their small size the PCI methodology would consider the slabs as being without distress. The formation of corner spalling and joint spalling will continue to require some inspection and maintenance activities in order to prevent foreign object damage to aircraft. The level of effort should remain constant since it is not load related distress and the level of distress does not affect remaining life.

Significant pumping distress was only observed by CTR in one location on Taxiway L which also had severe cracking from the resulting loss of subgrade support. This area was already being prepared for slab replacement during the RDD field testing. The Harding Lawson study reported more pumping (6 slabs on Runway 17R/35L and 108 slabs on Taxiway L) than was observed by the research team. The areas of pumping distress were generally grouped into small clusters of 50 to 200 feet in length. Pumping is a serious distress and refers to the pumping out of fines from the subgrade material when the slab is suddenly loaded and water is present.. Consideration should be given to slab replacement in those areas and the installation of edge drains to keep water out.

Joint seal damage was evident only on Runway 17R/35L and not on Taxiway L. The damage was usually associated with trafficked areas near the centerline of transverse joints. This damage was not wide spread, but was visible in several areas of the runway. The joints on Runway 17R/35L had been resealed in the last 2 to 3 years

Fatigue Cracking

The majority of the cracking observed by CTR personnel at DFW airport on Runway 17R/35L and Taxiway L was definitely fatigue related cracking. The cracking was, as a rule, only visible in the slabs within 25 feet of the runway or taxiway centerline (those slabs receiving direct aircraft loading). The cracking was predominately in the longitudinal direction (parallel to aircraft traffic) and most visible in the aircraft wheel paths. The cracking was most pronounced either in the center of the slab or beginning near the transverse joint and proceeding toward the center of the slab. Although much of the cracking consisted of hairline cracking not visible by video survey, some was up to 1/8th inch in width and more easily observed. The cracking does not follow the pattern of durability cracking which is classified as parallel to or "D" shaped along the transverse joints. Neither does the cracking follow the pattern of shrinkage cracking because slabs poured as one slab and sawed longitudinally into two slabs show cracking only on slabs with frequent aircraft loading.

The cracking observed from the CTR partial inspection on the runway and taxiway is primarily a load related phenomenon. As shown in Figure 5, the cracking for the most part was not observed or reported in much detail in the Harding Lawson Associates report. Using the official PCI inspection guidelines, the cracking pattern observed would only be classified as low-severity shrinkage cracking, which is generally not assessed as a threat to remaining life but only as a cosmetic problem and as a possible foreign object problem. The cracking observed by CTR personnel was in fact fatigue cracking which is a much more serious threat to remaining life. For this study, a special visual inspection was conducted in nine different areas of the runway and taxiway using an more descriptive reporting procedure to identify the level of fatigue cracking. The fatigue cracking is a serious concern and fatigue of concrete is the most important potential mode of failure for Runway 17R/35L and Taxiway L.

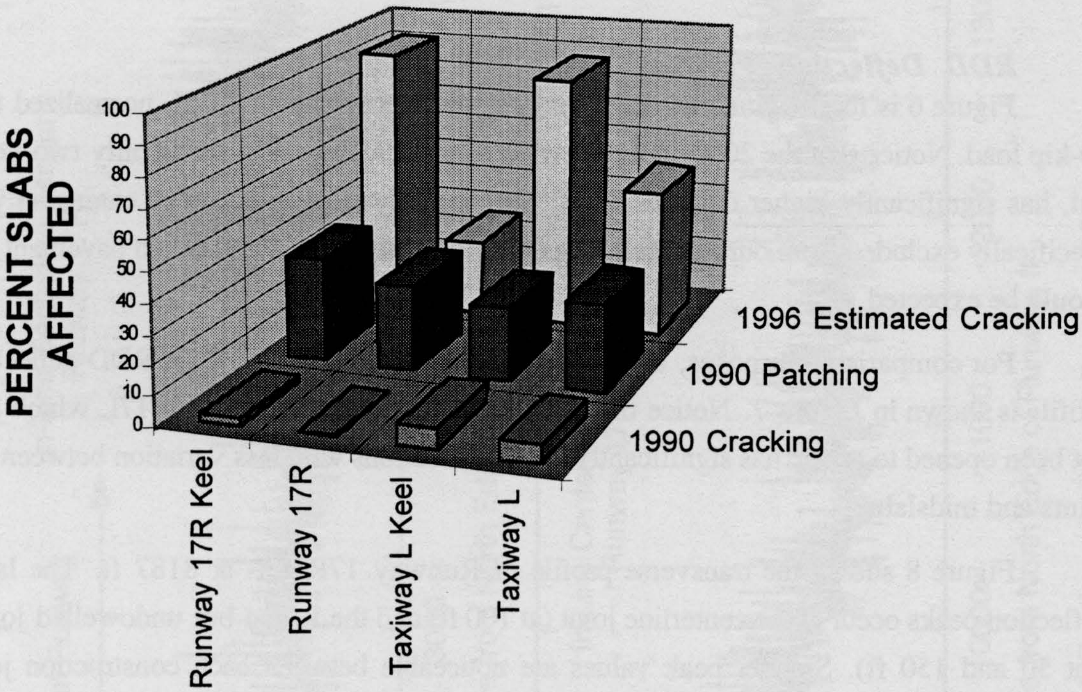

Figure 5. Percent of Slabs Affected by Cracking

Using the special analysis procedure it was possible to determine that fatigue cracking was more advanced or of greater severity in the north ends of the runway and taxiway than the southern or middle sections of each.

Slab Support Deterioration

Based upon the in-situ calculation of Young's modulus from wave velocities in the cross-hole testing, the stiffness of each layer of the pavement structure has weakened under aircraft trafficking. This loss of stiffness is significant both in terms of initial remaining life and remaining life of a rehabilitated pavement. If the base layer has consolidated in places, the slab may no longer be fully supported. The common misconception is that the base must have deformed a great deal to no longer support the slab. The fact is, however, that an aircraft causes 15 to 30 mils of deflection in the slab (based on data from RDD tests) and any permanent deformation more than this results in no base support.

Another significant point is that a reduction of stiffness in base, subbase and subgrade layers have a cumulative effect on decreasing slab support. It can be shown using linear elastic layer or finite or discrete-element analysis programs that this reduction in stiffness results in higher stress at the bottom of the concrete layer.

RDD Deflection Profiles

Figure 6 is the longitudinal deflection profile of Runway 17R/35L normalized to a 20-kip load. Notice that the 2000-foot extension of the runway, which was only two years old, has significantly higher deflections. Although, analysis of the runway extension was specifically excluded from our research, it appears that a significantly reduced pavement life should be expected.

For comparison purposes, a selected portion of Runway 17L/35R RDD deflection profile is shown in Figure 7. Notice that the deflection profile of Runway 17L which had not been opened to traffic has significantly lower deflections with less variation between the joints and midslabs.

Figure 8 shows the transverse profile of Runway 17R/35L at 8187 ft. The large deflection peaks occur at the centerline joint (at 100 ft) and the keyed but undowelled joints (at 50 and 150 ft). Smaller peak values are noticeable between each construction joint where the sawed reinforced joints are located. The poor performance of the doweled joints is evident on all the profiles. All longitudinal RDD profiles are provided in the data appendices in Volume III and their locations are depicted in reference to the slabs on the delivered MicroStation design file.

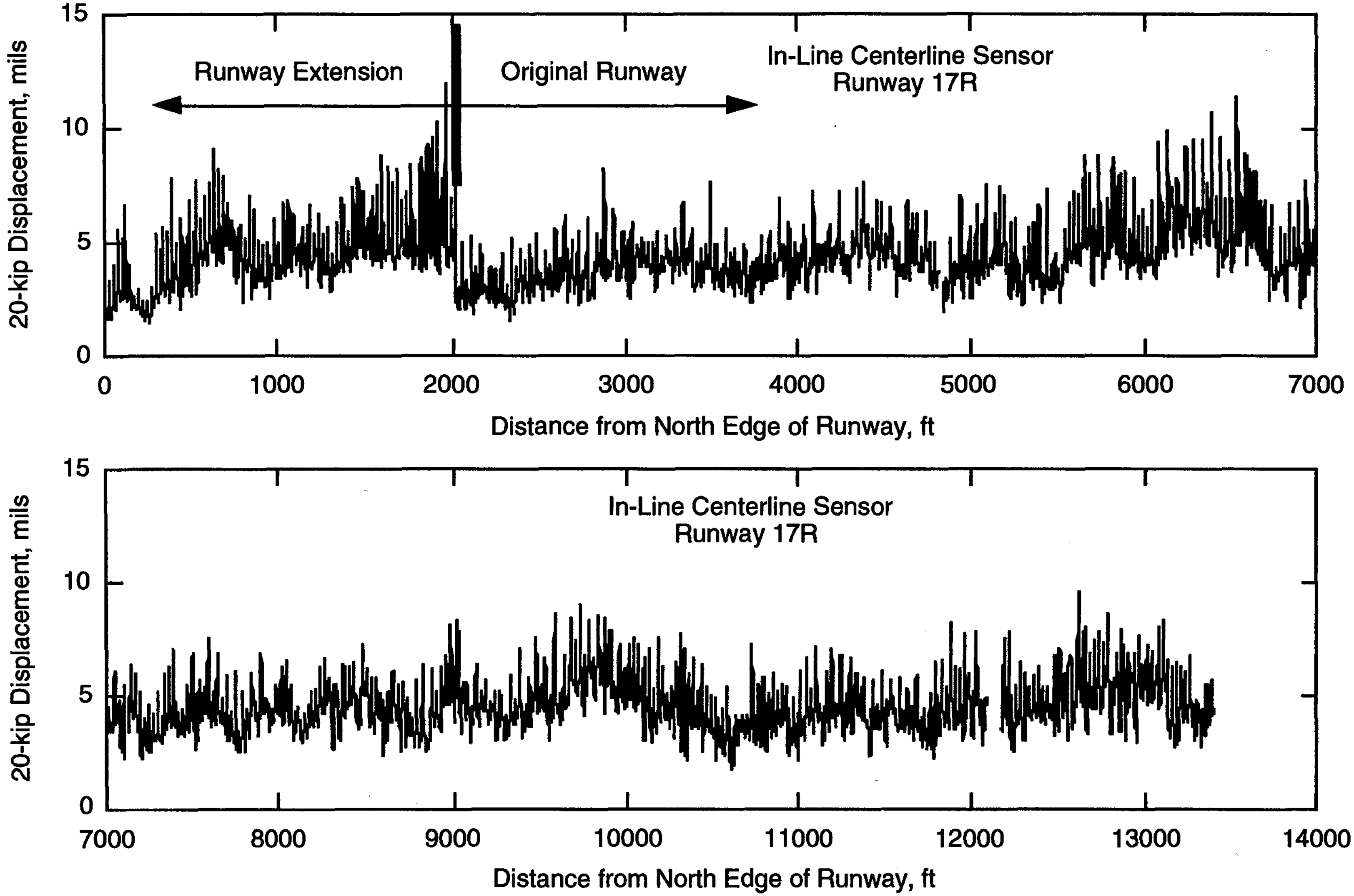

Figure 6. RDD deflection profile of Runway 17R

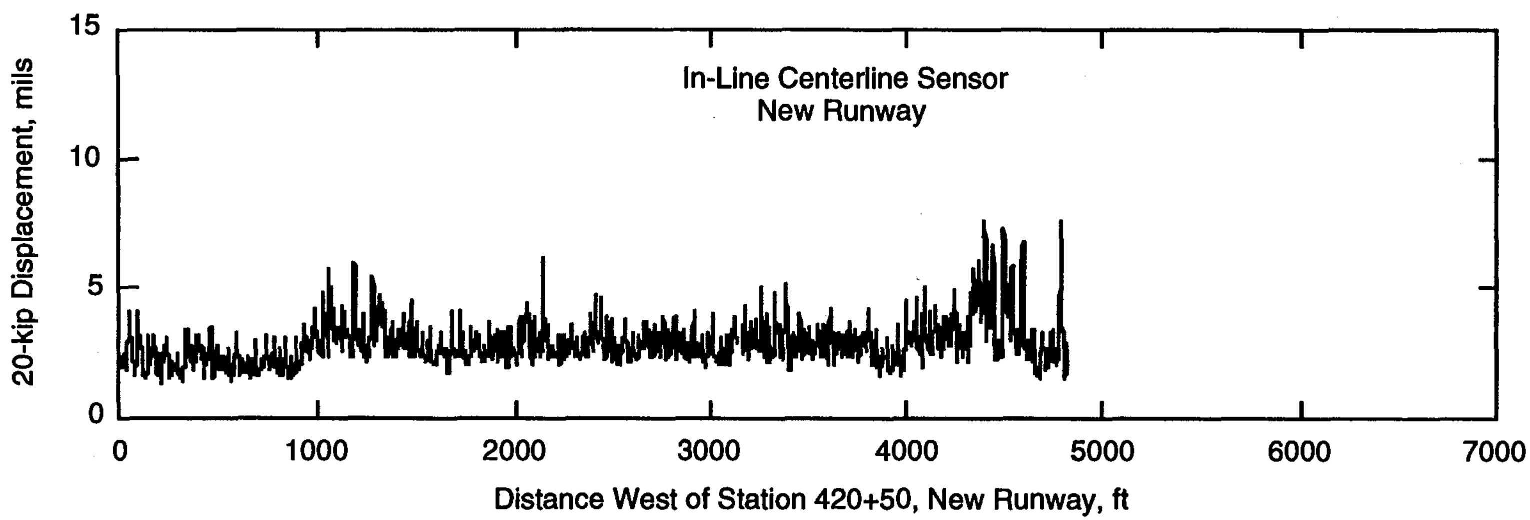

Figure 7. Partial RDD deflection profile of Runway 17L.

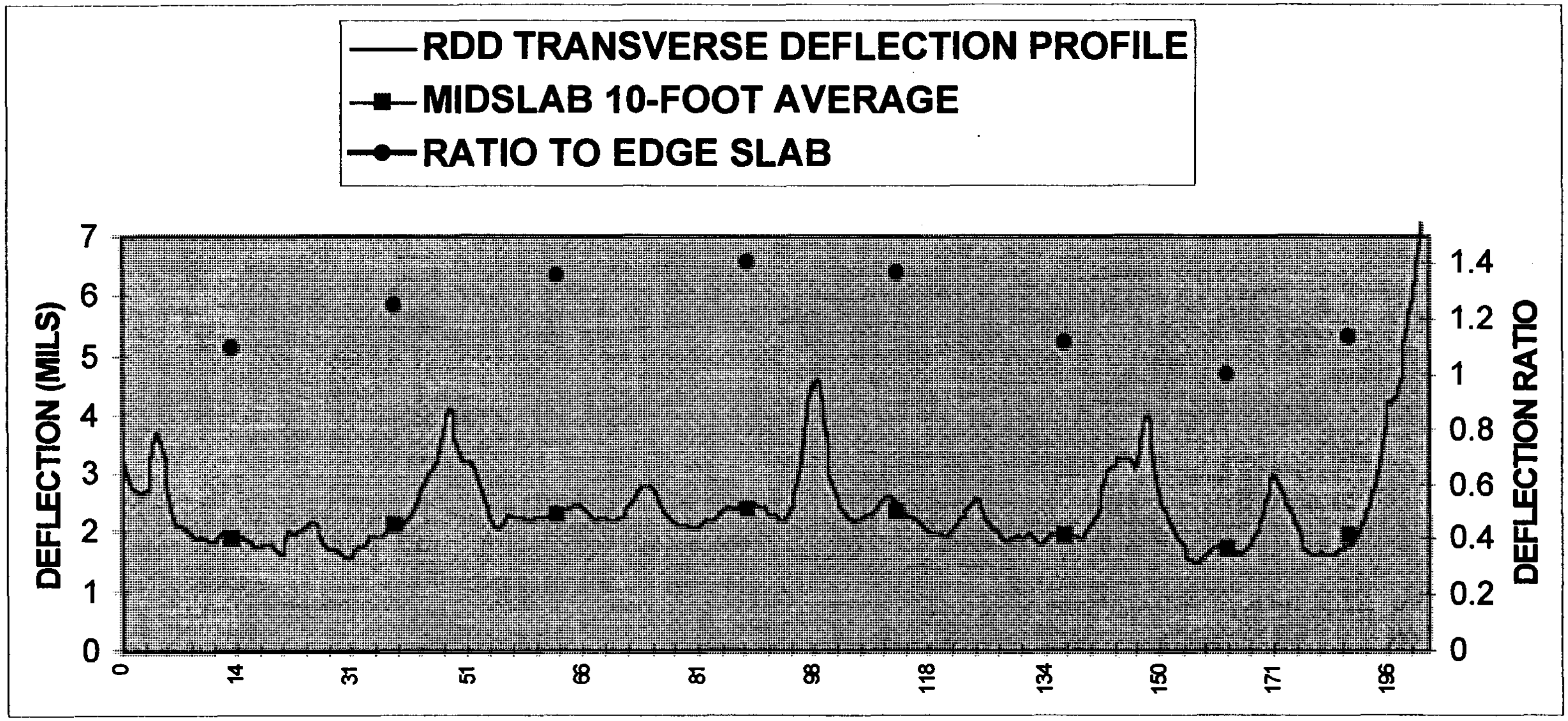

Figure 8. Runway 17R/35L Transverse Deflection Profile

Additional analyses were performed on the transverse and longitudinal data files by using a computer program to locate the joints and then calculate the average midslab deflection and standard deviation. In Figure 8, notice the average midslab deflection values as they cross the runway profile. The figure shows that even the midslab deflection of the slabs closest to the shoulder is influenced by the free end conditions. Also in Figure 8, the ratio of midslab 10-ft average to a reference deflection near the edge of an untrafficked slab were calculated and are plotted as dots using the scale on the right. From Figure 8, it can be seen that the two midslab points in the keel section (87.5 and 112.5 ft) have 30 to 40 percent greater deflections than the midslab average at 162.5 ft. This greater deflection is due to aircraft trafficking in spite of the fact that the transverse profile shown is in the area of lightest accumulated traffic. Unfortunately, identifying evidence of trafficking was not part of our testing plan. Therefore we have an insufficient number of transverse profiles to substantiate this since the transverse profiles were not picked in the best locations to demonstrate deterioration due to trafficking. In Figure 8, one can also note that higher than normal ratios are observed at distances of 37.5 ft and 62.5 ft from the west edge. However, upon closer examination these slabs are really receiving traffic because of the high speed exit taxiway adjacent to those slabs, aircraft are moving closer to the west edge.

In Figure 9, compare the transverse profiles of Runway 17L/35R, which was tested before it was opened to traffic, with the profile in Figure 8. Notice that the new runway does not exhibit increased deflection in the keel section .

Figure 10 shows the longitudinal plot of the average and standard deviation of the midslab deflections over 10 feet for the entire length of Runway 17R/35L. The areas of highest deflection are the areas of greatest concern for future performance under traffic. Those areas which receive heavy traffic and have high deflections are most likely to show load related distress sooner.

In Figure 11, the plot of midspan average deflections is shown for Taxiway L. The taxiway generally has lower average midspan deflections under a 20 kip load than the runway. Notice in Figure 11 that there appears to be an abnormally high deflection (5 mils) around the 3600-foot location. When this taxiway was tested, preparation for slab replacements were started and those slabs had already been saw cut into smaller free slabs. This higher deflection would indicate a worst case limit for pavement performance.

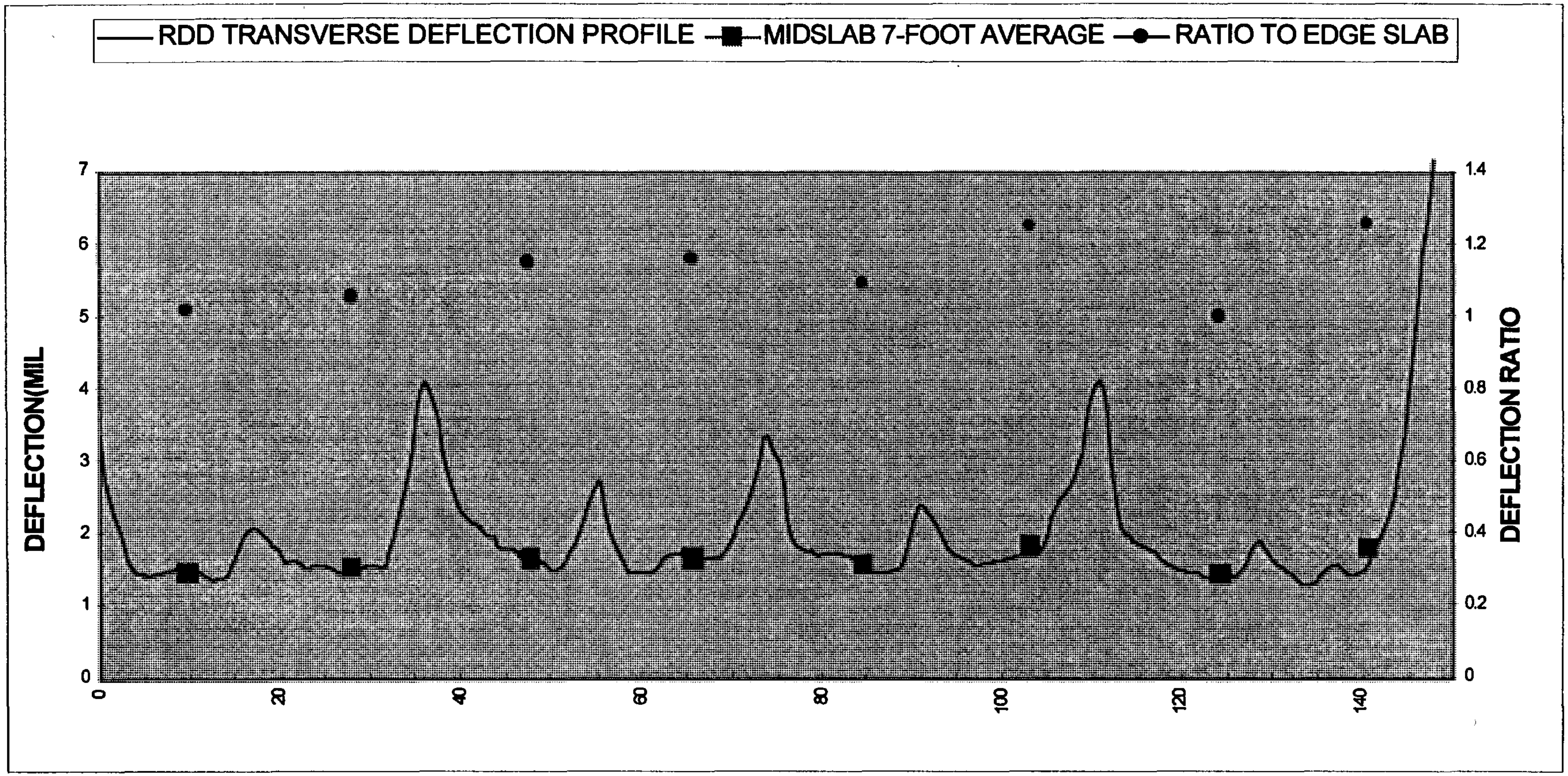

Figure 9. Runway 17L/35R Transverse Deflection Profile

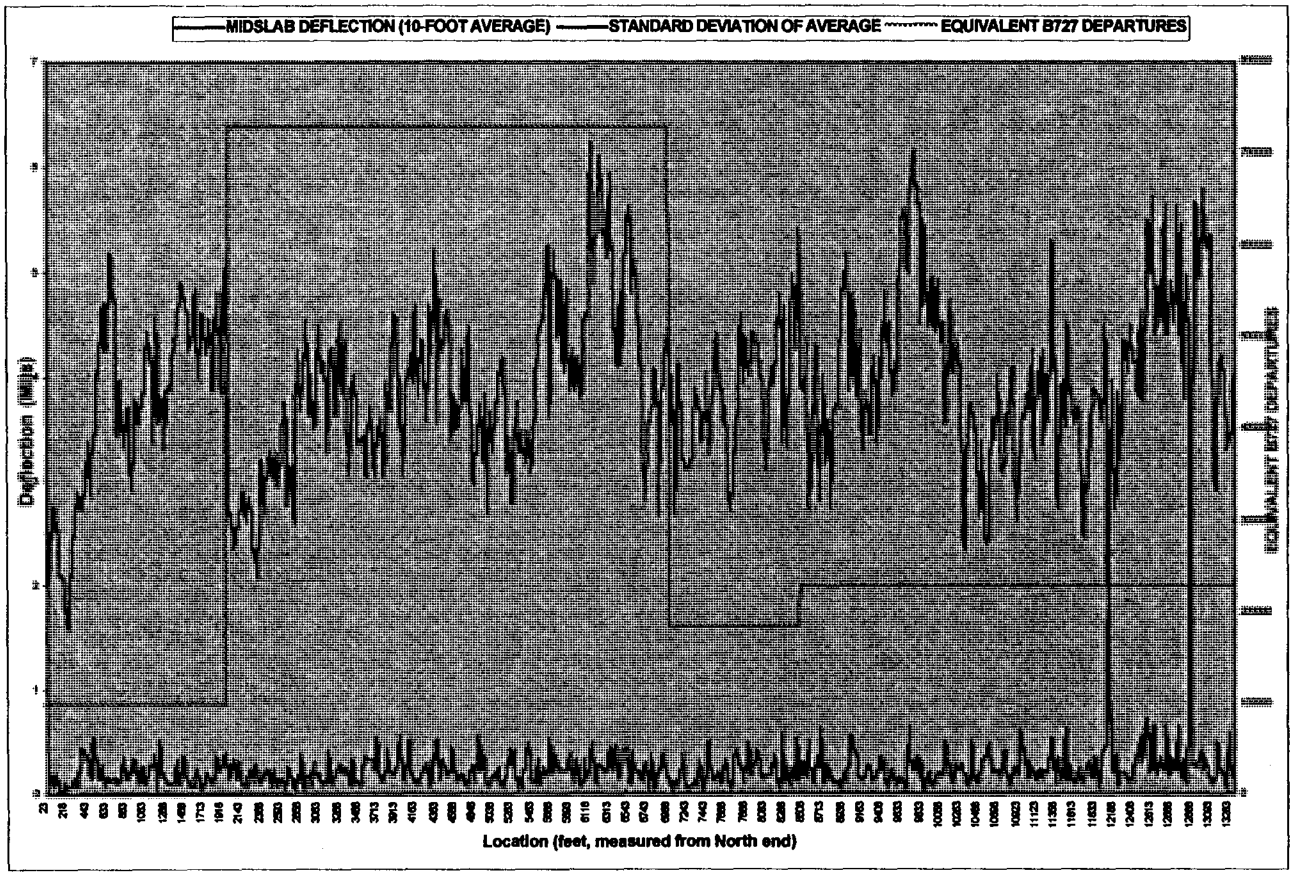

Figure 10. Runway 17R/35L Midslab RDD Deflections

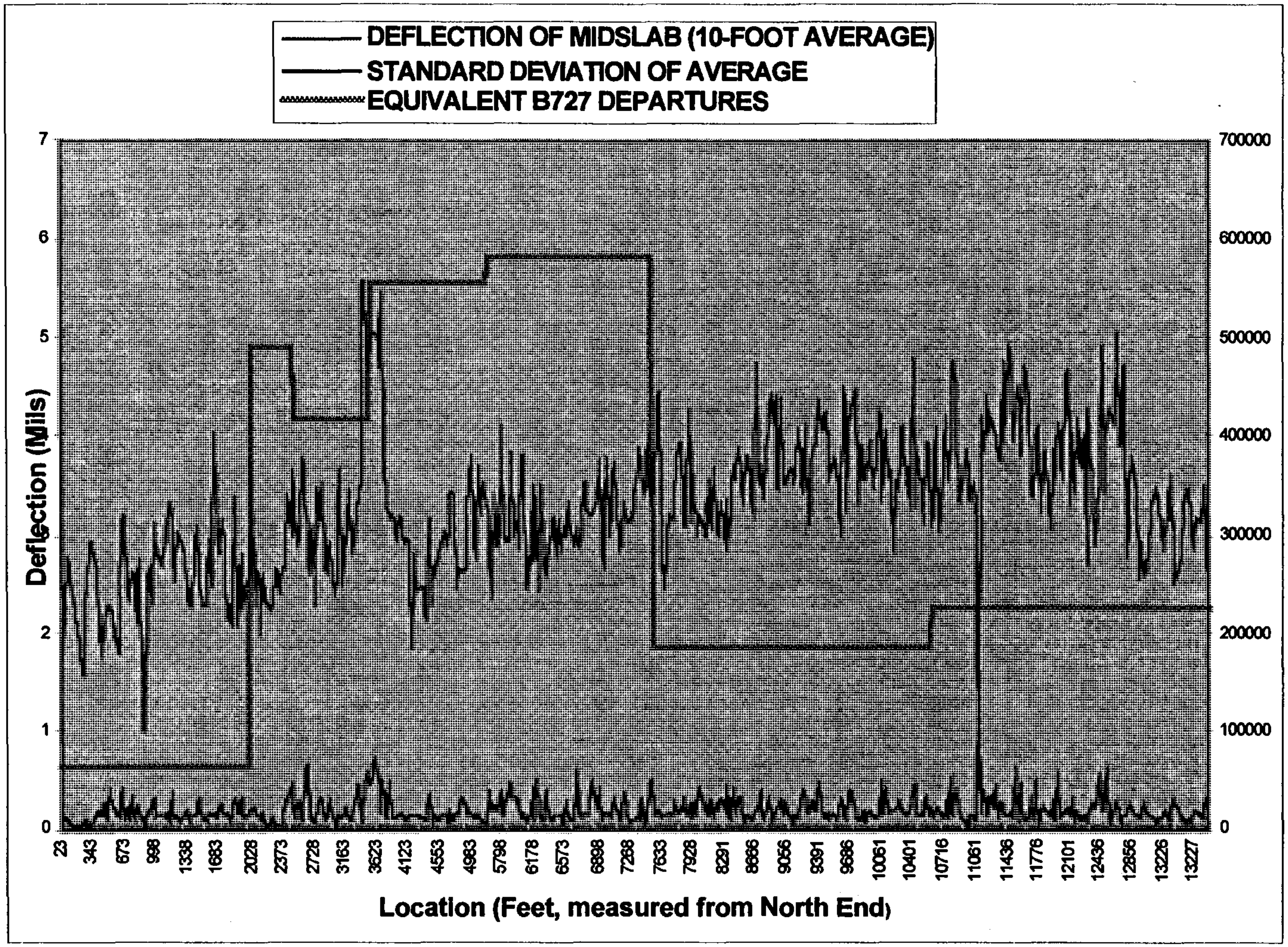

Figure 11. Taxiway L Midslab RDD Deflections

Joint Load Transfer Deterioration

The analysis to estimate the performance of the joints uses the results of the Rolling Dynamic Deflectometer to calculate the load transfer efficiency (LTE) of the joint. In Figure 12, the load transfer is very low for the centerline doweled joint in the first 2000 feet. This section is the extension of the runway which was constructed only a few years ago. This general trend indicates that the performance of the joint was already poor immediately after construction since the LTE of the joint after 2000 feet is much better and this section has been in service for over 20 years.

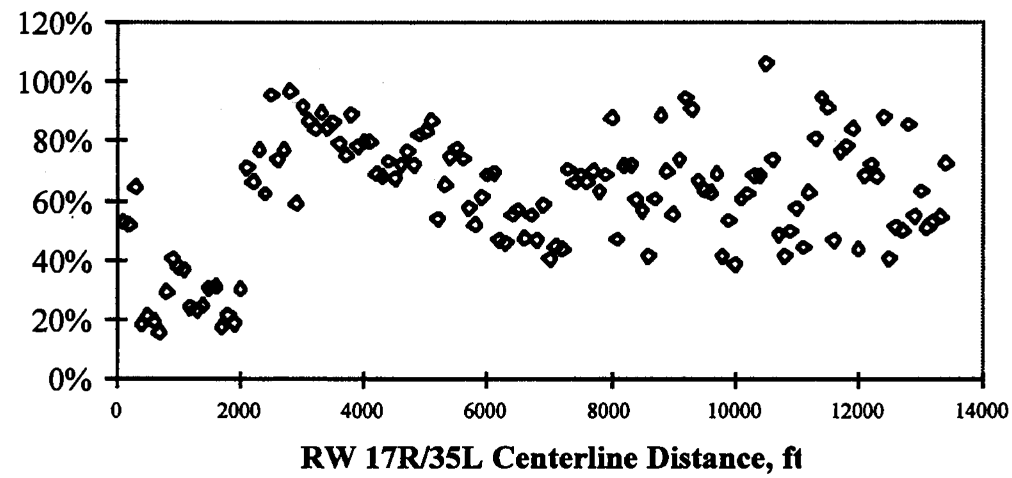

Figure 12. Load Transfer Efficiency Along Length of Runway 17R .

Figures 13 and 14 show the LTE of the keyed joint which is offset 50 feet from the centerline joint. The location of the measurements in Figure 13 is at 2000 ft from the north end, or the threshold of the original runway. The LTE ranges from about 60% to 100%. Figure 14 shows the same joint at a location of 7300 to 8300 feet from the original runway threshold. The range of LTE in this section of the runway is from about 40% to 90%.

Predicting the future performance of the joints is difficult since a logical trend is not evident in the data. Several specific instances in the RDD data show individual locations and joints that have failed, but these are fairly rare and to not imply a widespread problem with the joints. The RDD is capable of finding failed joints, or those that do not transfer loads to the adjacent slab across the joint.

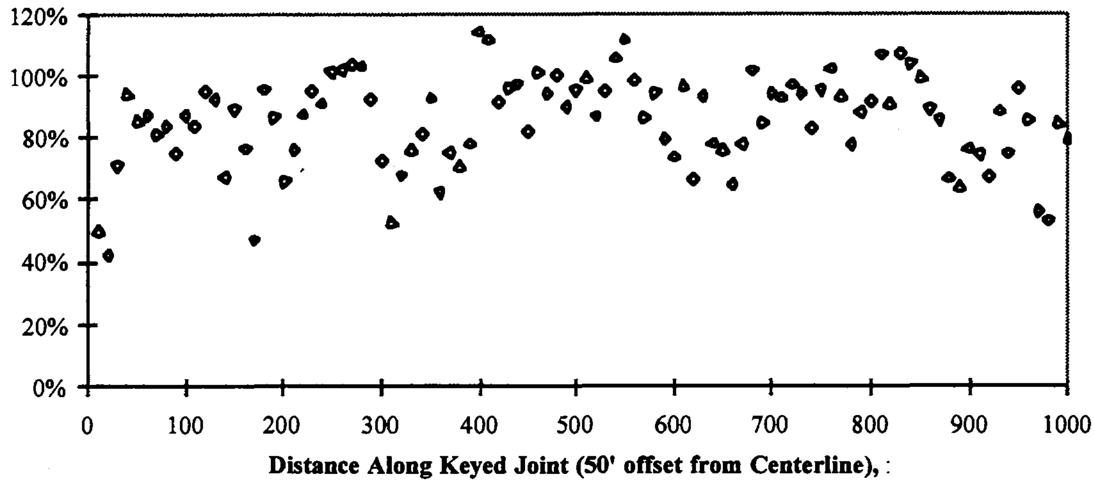

Figure 13. Load Transfer Efficiency of Keyed Joint, North End.

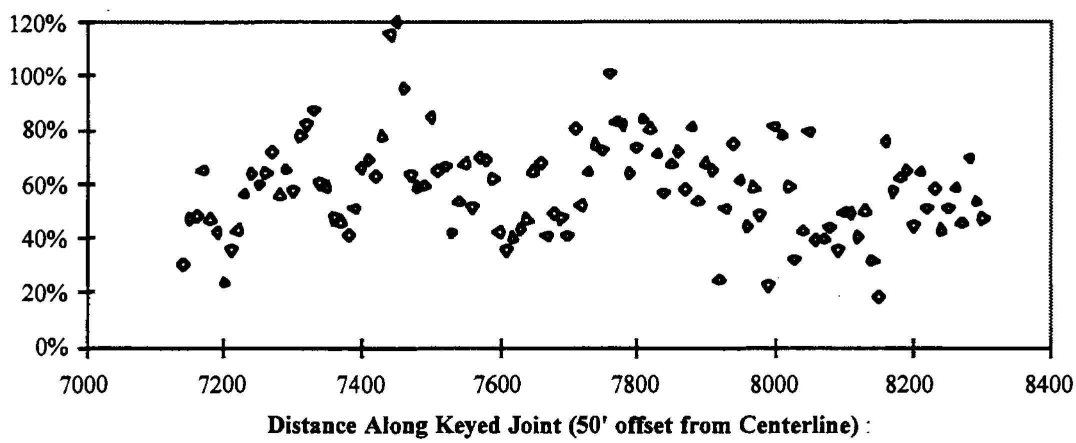

Figure 14. Load Transfer Efficiency of Keyed Joint, Middle of Runway 17R/35L.

This final report illustrates a method of comparing different joints and different joint types. For example, the RDD data was used to compare the relative performance of the centerline joint to the keyed joint 50 feet to the east of centerline. The centerline joint on Runway 17R is keyed and doweled, while the joint at 50 feet from centerline is simply keyed, without dowels. Again, the deflection at the joints produced by the RDD can be compared to obtain the relative performance of these two joints. The process involves simply computing the LTE for each of the joints, and taking the ratio of the two values.

In general, the performance of the joints in the runway and the taxiway is good, with the exception of the 2000 foot extension, which may need further analysis to determine proper rehabilitation action. It must be noted, though, that the measurement shown in Figure 12 is for the centerline joint only, and an evaluation of the other joints should be made before implementing any rehabilitation strategy. In addition, the centerline joint between 2000 and 8000 feet from the north end should be reevaluated in approximately 5 years to estimate the rate of deterioration of the joint's performance. If, at that time, the joint performance has deteriorated significantly, a rehabilitation plan should be prepared to correct the problem, and to prevent further deterioration of the joint.

REMAINING LIFE

From the completed analyses, the remaining life was calculated for five failure modes. The remaining life was estimated in years to a caution zone and years to dangerous zone. Any pavement in the danger zone will require additional inspection and maintenance to keep the runway or taxiway operational. Emergency runway closures are likely in the danger zone.

Due to Runway Roughness

The Boeing Corporation has performed detailed studies that produced a correlation between vertical accelerations and relative fatigue damage to aircraft. A vertical acceleration of 0.45g, or 0.45 times the acceleration of gravity, would cause over 30 times as much damage relative to a 0.35g acceleration. An acceleration of 0.55g would cause 1000 times more damage as a 0.35g acceleration. Another way to look at this effect is to say that runway roughness that causes a 0.45g vertical acceleration during a takeoff or landing operation would cause as much damage to the aircraft as 30 operations on a smooth runway which produces an acceleration of only 0.35g. At a vertical acceleration level of 0.4g, , the effects on aircraft can become detrimental. In addition, vertical accelerations greater than 0.45 begin to have adverse effects on pilots and passengers.

Vertical acceleration values were calculated for Runway 17R/35L and Taxiway L using the elevation profile and the computer programs TAKEOFF and LANDING, which were produced by Mr. Tony Gerardi and APR Consultants. These computer programs calculate the vertical accelerations at the pilot station and at the center of gravity as well as the related loads on the pavement due to the vertical accelerations at the nose gear and the main landing gear. The University of Texas and APR Consultants each performed computer analysis of the runway profiles.

The end result of the analyses was that Runway 17R/35L and Taxiway L are within acceptable ride quality limits and have no excessive vertical accelerations. There is small hump at the south of end of Taxiway L which could be a problem if aircraft were taxiing in excess of 40 knots. Taxiway L should not be used for high speed taxiing or for emergency takeoffs or landings at the south end without a change in elevation profile. The remaining life for runway roughness of the runway and taxiway are estimated to exceed 10 years. However, a regular inspection of profile roughness should be conducted about every three years for a major runway or after any significant repairs. The most common cause of induced runway roughness is a result of repairs made to the runway because the long wavelength roughness is not considered. If runway or taxiway reconstruction takes place, careful attention should be paid to the maximum deviation from planned grade lines so that roughness does not become a problem.

The performance of Runway 17R/35L from the standpoint of roughness would be considered excellent when compared to other surfaces constructed on the swelling clays at the airport. The primary reason for this is the construction sequencing used on the original runways and taxiways. For these original units the lime stabilized layer was placed approximately one year prior to the stabilized bases. The impervious cover resulted in the swelling occurred during this period. The roughness was then graded out prior to placement of the subbase and concrete pavement. Thus, we recommend the airport authority take note of the difference in runway and taxiway performance from a roughness standpoint when considering construction sequencing. A guide would be developed for future construction and reconstruction.

Due to Fatigue Cracking

Fatigue cracking is a serious problem at the north end of Runway 17R/35L and Taxiway L. The analysis of the visual inspection revealed that 90% of the slabs in the keel section (center 50 ft) of the runway and taxiway have fatigue cracking. Using a special inspection technique, it was observed that the fatigue cracking is more severe in the north ends where aircraft trafficking is heaviest. The cracks are more numerous, more closely spaced and more cracks travel the length of the slab. If this runway and taxiway were not reinforced they would have reached failure already. The only thing keeping these crack widths narrow is the steel reinforcement.

In the north section of the runway the fatigue cracking will increase in severity under additional aircraft loading. As the cracking increases and map cracking appears, punchouts and load related spalling will result. We estimate that under the current loading conditions the north end of the taxiway and runway will require significant maintenance actions to keep this pavement operational for the next 3-8 years.

Due to Surface Distress

Surface distresses other than fatigue cracking are not a significant threat to remaining life. The pattern of joint and corner spalling will continue as it is unrelated to load. Maintenance efforts should continue to repair these small spalls with patches if maintenance resources exist. However, joint spalls of less than 2 feet with no debris are not an operational hazard and need not be repaired.

CONCLUSIONS ON REMAINING LIFE OF RUNWAY 17R/35L AND TAXIWAY L

1. The prediction of remaining life of Runway 17R/35L and Taxiway L are shown in Figure 15 for five different modes of failure. The most severe mode of potential failure is due to concrete fatigue. It is in the caution zone already as evidenced by the high degree of fatigue cracking on the north end of the runway and taxiway. It is predicted that concrete fatigue will become a dangerous problem in 2 to 3 years at the north ends of both the runway and taxiway. As the fatigue continues, surface distress will become a problem as the longitudinal fatigue cracking observed becomes closer together and transverse cracking leads to block cracking and eventually punchouts.

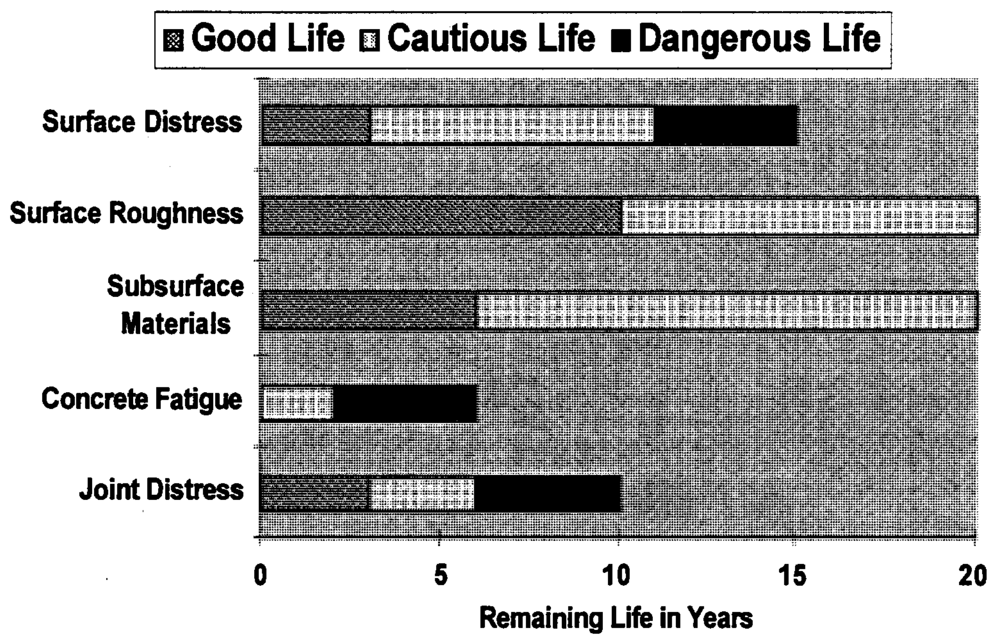

Figure 15. Remaining Life of Runway 17R/35L in years

2. Joint deterioration is not a problem now but the loss of load transfer efficiency from the RDD data and cross-hole testing indicates that most doweled joints are not performing well. There will continue to be joint spalling even in the untrafficked slabs due to environmental factors.
3. The end result of the surface roughness analyses were that Runway 17R/35L and Taxiway L are within acceptable ride quality limits and have no excessive vertical accelerations. There is small hump at the south of end of Taxiway L which could be a factor if aircraft were taxiing in excess of 40 knots. Taxiway L should not be used for high speed taxiing or for emergency takeoffs or landing at the south end without a change in elevation profile.
4. We recommend the airport authority consider using the original construction sequencing used with Runway 17R and Taxiway L for future construction because of roughness concerns..
5. There is a distinct pattern of corner spalling and joint spalling that has been repaired with very small patches (most less than 2 ft long) which mostly occurs outside the trafficked portion of the runway. Much of this distress is associated with the free longitudinal joint restricted only with a keyway .
6. Figure 16 shows that the subsurface deterioration could be a problem in the future. Cross-hole seismic testing indicated that the base and subgrade layers under the joint were approximately 50% lower in stiffness than those under the midslab. Figure 16 also shows the percent reduction in layer stiffness in the runway and taxiway due to aircraft trafficking as measured by comparative cross-hole seismic testing. If the total layer loss of stiffness in trafficked areas were compared to the untrafficked sections, it would theoretically account for 50 to 70 percent greater reduction in pavement life.

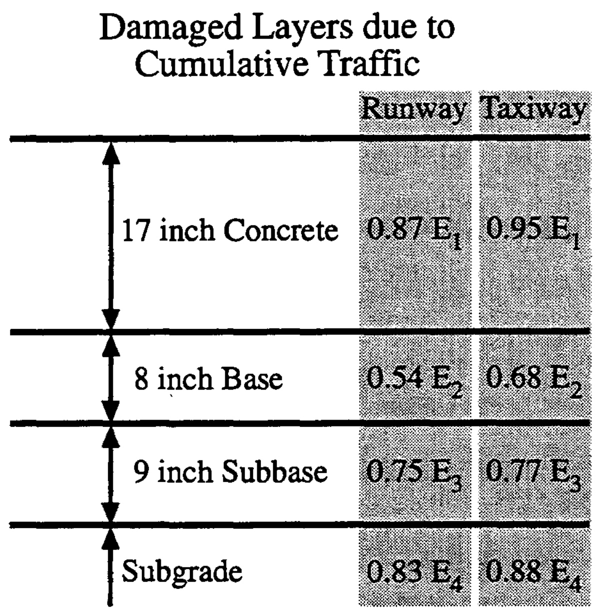

Figure 16. Loss of Stiffness in Layers

From the cross-hole seismic analysis the average in-situ modulus values were calculated for the runway and taxiway in certain locations both in the trafficked area and adjacent to the trafficked area. Comparison of the results shows that the loss of stiffness (reduction in modulus) is most pronounced in the cement treated base layer. As shown in Figure 16, both the runway and taxiway had reduced stiffness in all layers due to trafficking. This data represents midslab measurements and even greater reductions are evident in the subsurface layers when measured under a joint. The significance is that combined loss of stiffness for all layers results in higher stress due to loading and therefore a reduced service life.

RECOMMENDATIONS FOR EVALUATING DFW AIRPORT PAVEMENTS

One of the objectives of this report is to make recommendations on how the remaining runways and taxiways should be evaluated. This research project employed a test plan which was based upon applying new technology developed for the highway sector that had not yet been applied to airport pavements. During the proposal phase, we suggested some testing which we later decided was not feasible or necessary. Spectral Analysis of Surface Waves (SASW) testing was one proposed test that was abandoned because the thickness of the concrete pavements would not provide adequate information about the subsurface materials. The cross-hole seismic test was used directly to measure the required parameter. Dynamic Cone Penetrometer tests were also deemed not useful. The success of the RDD testing and the lack of success with the heavyweight deflectometer has led us to conclude that future HWD testing would be pointless.

For the evaluation of the remaining runways and taxiways, we recommend a two phase program of data collection and analysis as described in the following sections.

Data Collection

We recommend that a data collection effort be developed for all pavements that encompass use of the rolling dynamic deflectometer (RDD), cross-hole seismic testing, fatigue cracking inspection, and mapping of pavement distress. In areas where runway roughness is apparent, profilometer measurements should be obtained. In the following subsections a brief description is provided for the recommended testing.

Rolling Dynamic Deflectometer (RDD)

The use of the RDD for evaluating thick concrete pavement systems proved invaluable. Our initial test results on Runway 17R/35L were quite revealing, especially when comparing the new construction of Runway 17L/35R with the heavily trafficked Runway 17R/35L. Our findings indicate that the influence of the joint affects the deflection profile as much as 8 feet away. As a result of our analysis, we would move our longitudinal test line closer to the center of the slab for future tests. We have only begun to fully appreciate the wealth of information that the RDD can provide for nondestructive analyses of airport pavements. We would strongly recommend that the RDD be used to evaluate the remaining runways and taxiways and aircraft parking aprons by collecting the following data:

1. Longitudinal deflection profiles along the runway or taxiway with one in the trafficked area and one in the non-trafficked area.
2. More transverse profiles in areas identified from the longitudinal deflection profiles to better evaluate the relative effect that trafficking has had on the pavement.
3. The RDD be configured with sensors at several spacings to permit back calculations of layer moduli using a deflection basin.

Cores and Cross-hole Seismic Testing

Cross-hole seismic testing was very successful in the application to DFW airport pavements. Its use permitted detailed evaluations of the individual layers and the damage beneath joints. It may be feasible in the future to reduce the amount of cores which are taken and to rely more heavily on the cross-hole test. It is also possible that these results may be used to calibrate with the RDD results so that fewer cross-hole seismic tests will need to be performed. We would, however, recommend that a limited number of cores be taken and some cross-hole seismic tests be conducted for each major area of the airport. The cross-hole testing locations should be determined after a review of the deflection data. The cross-hole locations would be selected using the following guidelines:

1. A set of cross-holes would be located in the wheel path and in a non-traffic area along the same transverse line.
2. Several sets would be located longitudinally along the runway at areas of highest and lowest deflections as well as in any other unusual areas.

Fatigue Cracking Inspection

The conclusion of the analysis is that concrete fatigue is the critical mode of failure of Runway 17R/35L and Taxiway L. We would expect this to be consistent with the remaining runways and taxiways. The PCI method of distress identification and recording is not sensitive to fatigue cracking for analysis of remaining life. Therefore we would recommend changing the PCI method for future inspections. The change needs to be formally defined, but in the absence of a better standard, the procedures developed for this project have proven adequate.

Fatigue cracking will present the most significant inspection problem for operations and maintenance personnel on Runway 17R/35L and Taxiway L. Currently the north half of the runway has slabs with more than five cracks extending the length of the slab. In the future, as cracking becomes more closely spaced, transverse cracking will occur between the longitudinal cracks and eventually punchouts may occur. Fortunately, the increased design slab thickness of 17 in. over the original FAA recommended thickness of 14 in. has extended the expected 20 year life and the steel reinforcement is keeping the fatigue crack widths small. Without reinforcement, the concrete would most probably already have failed due to punchouts.

Mapping of Pavement Distress and Test Data

We would recommend a method of fatigue cracking inspection which records all cracking that is found in a graphical format. We would suggest the development of a MicroStation based database of cracking, patching and other distress that can be updated in the field from daily inspections rather than using either the videotape system or hiring a consultant every five years. CTR has proposed the development of a differentially corrected global positioning system (D-GPS) for field use in Operations and Maintenance vehicles to collect this information. A proposal was submitted to the Airport in June 1996 but has not yet been approved.

DATA ANALYSIS

The data collected will be analyzed to develop the following output from a network planning and design guidelines standpoint.

Network Planning

1. A plan of predicted times, including when deterioration will start, approach failure, and require major repair, will be developed for each runway and taxiway.
2. The information from item 1 will be compiled for a twenty year projected plan of major rehabilitation for all pavements on the airside of the airport.
3. The plan can be periodically updated.

Design Guidelines

1. The load transfer capabilities of all joints will be ascertained along with the deterioration rates. This information can then be used to revise the design details.
2. Determination of the proper amount of longitudinal and transverse reinforcement to provide 100% level transfer as originally intended.
3. Longitudinal joints that provide excellent load transfer, thus eliminating the problems being experienced at some longitudinal joints.