SUMMARY OF THE KFIR FATIGUE EVALUATION PROGRAM

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Abstract

A fatigue life evaluation program (FEP) has been performed to promote fleet safety and economy for Kfir aircraft in service. The main purposes of the program were to identify potentially fatigue critical locations, evaluate their expected lives and correspondingly schedule non-destructive in-service inspections in order to detect cracks before they reach unrepairable or unsafe size. The FEP included durability and damage tolerance analyses, specimen and component testing and the full-scale fatigue test of the aircraft. Fatigue cracks discovered during the test were monitored by NDI and their growth recorded. The test-article passed 4 lifetimes, followed by a residual strength test; no failures occurred during the full-scale test. A limited tear-down inspection of the airframe was performed. Many design improvements were implemented as a result of the FEP. An individual aircraft tracking program was developed in order to monitor and evaluate fatigue damage in individual Kfir aircraft. This tracking program increases safety of operation and reduces maintenance costs for the Kfir fleet.

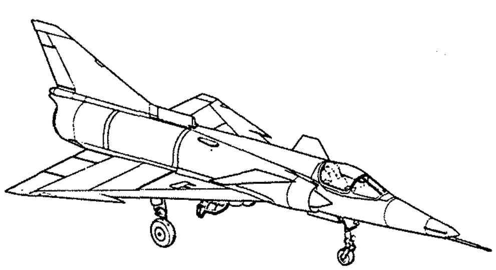


FIGURE 1 : THE KFIR FIGHTER AIRCRAFT

1. Introduction

The Kfir, a canard/delta wing air-superiority fighter, as shown in Figure 1, was designed and built by Israel Aircraft Industries. It is used by the Israel Airforce in one-seat and two-seat versions for both air-to-air, and air-to-ground roles.

It is also used by the U.S. Navy (F-21) in an aggressor role and is in service with several other airforces. The aircraft is powered by a single GE J-79 engine. The Kfir was designed with a service life goal of 4000 hours.

Israel Aircraft Industries has conducted a fatigue evaluation program (FEP) to enhance fleet safety and economy in operation of the Kfir aircraft [1,5]. The main purposes of this program were to identify potential fatigue critical locations, evaluate their expected fatigue lives, and schedule inspections in service in order to detect cracks before they reach an unrepairable or unsafe size.

It should be noted that the Kfir was not originally designed to damage-tolerance requirements. An additional goal of the FEP was to assess the degree to which the aircraft meets the damage-tolerance requirements of MIL-A-83444 and to schedule inspection intervals accordingly.

The FEP contained several steps :

a. Generation of a nominal operating spectrum of the aircraft.
b. Damage-tolerance and durability analyses.
c. Coupon, specimen and component tests.
d. A full-scale test of an entire airframe.
e. Design improvements to extend the useful service life of the aircraft.
f. Development of an individual aircraft tracking program to monitor the accumulation of fatigue damage.
g. Development of an inspection/ maintenance program.

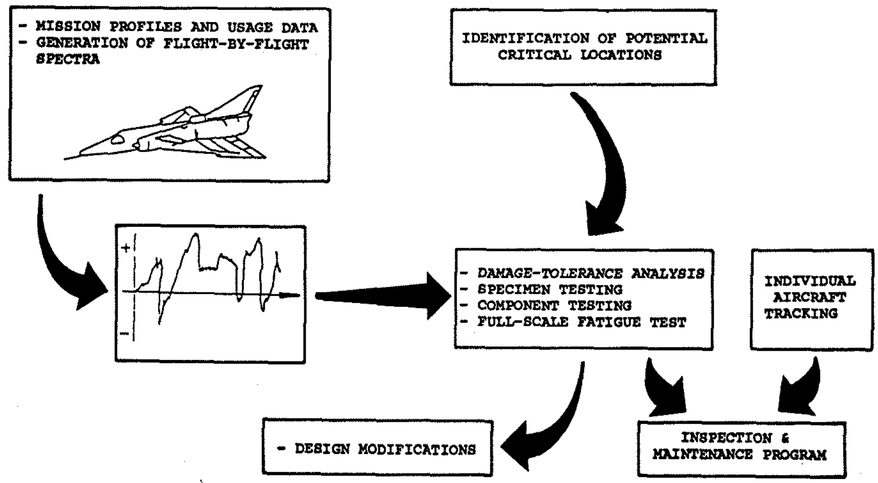


FIGURE 2 : GENERAL DESCRIPTION OF THE KFIR FATIGUE EVALUATION PROGRAM

Figure 2 describes schematically the Kfir FEP and the various steps that it contains.

2. Generation of the Nominal Operating Spectrum

The loading spectrum of the aircraft was developed based on the nominal mission profiles and symmetric maneuver usage data.

The Kfir usage consists of two basic missions :

* Air-to-Air Combat (A-A)
* Air-to-Ground Combat (A-G)

Each mission was subdivided into mission segments :

* Rotation and takeoff
* Combat maneuvers
* Landing on main landing gear
* Landing on nose gear.

A wing fuel tank pressurization cycle was applied at the start of each flight.

The maneuvers during the combat segments, ranging from 8.5g to -2.25g, were defined at several points-in-the-sky representing variations in configuration, Mach number, gross weight, and altitude. Gust loading was not included since a preliminary analysis showed that the gusts contribute an insignificant amount of fatigue damage.

2.1 Spectrum Sensitivity Studies

An experimental sensitivity study was performed to determine the sensitivity of crack initiation and growth life to various spectrum parameters (2). The following parameters were evaluated :

a. Multiple points-in-the-sky vs. a single point-in-the-sky.
b. High load truncation.
c. Negative load truncation to zero.
d. Low load omission.
e. Severe vs. mild usage.
f. Flight-by-flight load sequence vs. full randomization.
g. Introduction of load markers to aid in fractography.

Several of the above spectra are illustrated in Figure 3.

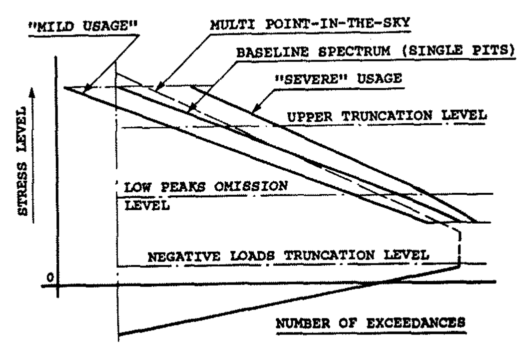
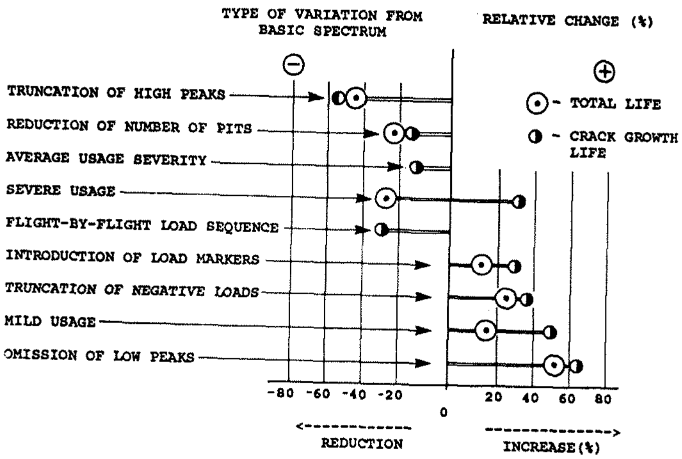


FIGURE 3 : SPECTRUM VARIATIONS USED IN SENSITIVITY STUDY

Variations in the operational use of the aircraft were found to have a pronounced effect on both crack initiation and crack growth lives, as is shown in Figure 4. In the case of "severe usage", the test demonstrated an unexpected increase in crack growth life — above what might be expected on the basis of crack retardation. On the other hand, the "severe usage" reduced the crack initiation life (as expected).

These studies were used to determine to what extent the loading spectra can be truncated without greatly affecting the fatigue life.



NOTE: CHANGES LESS THAN 10% ARE NOT SHOWN ON THE DIAGRAM

FIGURE 4 : TEST DEMONSTRATED SPECTRUM SENSITIVITY EFFECTS

3. Damage-Tolerance and Durability Analysis

Approximately sixty five locations were selected on the Kfir wing, fuselage, and canard for a damage-tolerance and durability assessment.

Damage-tolerance analysis, on the basis of MIL-A-83444, was performed in order to insure structural safety in spite of material flaws that are assumed to exist at the start of service. Durability analysis, which was also performed on the basis of crack growth, was used to insure that the maintenance and life-cycle costs of the aircraft will be minimal and that operational readiness will be maximized.

At several critical locations, inspection intervals were determined on the basis of the damage-tolerance analysis. These intervals were later updated on the basis of the component and full-scale test results.

Both the damage-tolerance and durability analyses were performed using the closure model to describe crack growth and retardation characteristics. (8) Material crack growth properties were determined by specimen testing.

4. Specimen and Component Testing

In order to support the analyses, more than 280 specimens were tested in computer controlled, single channel fatigue machines having load capacities ranging from 10 to 50 tons. Component tests, performed as part of the Kfir FEP, included such items as complete wings, main fuselage frame, main wing spars, engine mounts, main and nose landing gears, etc.

The objectives of the component tests were:

- to identify fatigue critical locations
- to determine the expected fatigue life of potentially critical locations
- to evaluate the effect of design details such as cold working or material thickness (3,7).

Several of these tests were performed on the basis of damage tolerance with initial flaws introduced at potential critical locations.

4.1 Main Spar Test

Since the Main Wing Spar has been identified as fatigue life limited, a substantial amount of testing has been performed on this component.

Several spars were mounted to a fixture and were loaded by two independent channels which simulate the spar root bending moment and aft flange fastener load-transfer in the root area. A flight-by-flight load spectrum was applied randomly. This test was used to check the effectiveness of main spar design improvements, in particular cold-working of fastener holes. The results indicated that a significant improvement in fatigue life can be expected by employing cold-working either as a design improvement or as a retrofit change.

4.2 Wing Fatigue Test

A fatigue test of a complete Kfir wing was performed as is shown in Fig. 5. The wing was mounted to a rigid fixture and loaded by six independent channels which simulated the internal loads in the wing root area. Spectrum loading was applied in a flight-by-flight randomized manner using 500 hour blocks. Marker loads, which contain the highest spectrum loads, were applied at the end of each 500 hour block, in order to aid in post-test fractographic analysis. The wing was instrumented with strain and crack gages in order to monitor the progress of the test. Potential critical locations were inspected using NDI techniques at preselected intervals.

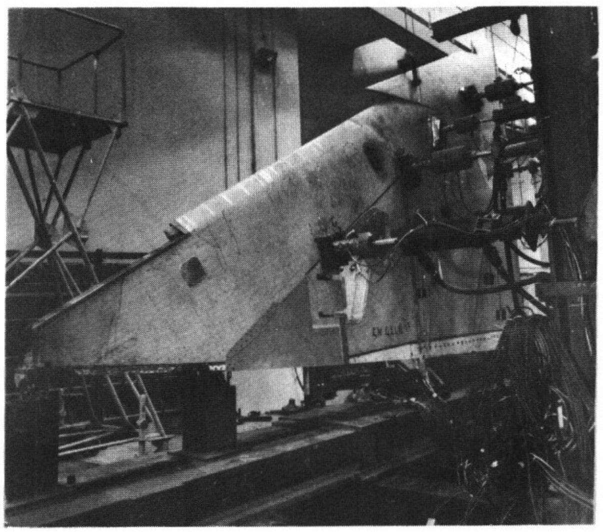


FIGURE 5 : GENERAL VIEW OF THE WING FATIGUE TEST

Only two significant cracks were detected during the wing test. A main spar fastener hole crack was repaired by reaming and subsequent cold-working. A lower skin crack was repaired by means of a metallic patch. Both repair schemes successfully arrested further crack growth in these areas.

The test terminated after 3.5 lifetimes with the failure of the main spar lug, due to a fatigue crack in the center of the bore. This failure was not considered to be representative of service aircraft since the test-article had been left outdoors, and was exposed to the weather for enough time for corrosion damage to develop at the lug bore. Nevertheless, this location is inspected periodically in aircraft in service. No cracks, to date, have been detected in this area in service aircraft.

4.3 Main Fuselage Frame Fatigue Test

Two main frames were fatigue tested under flight-to-flight spectrum loading. The main frame, mounted to the test rig, is shown in Figure 6.

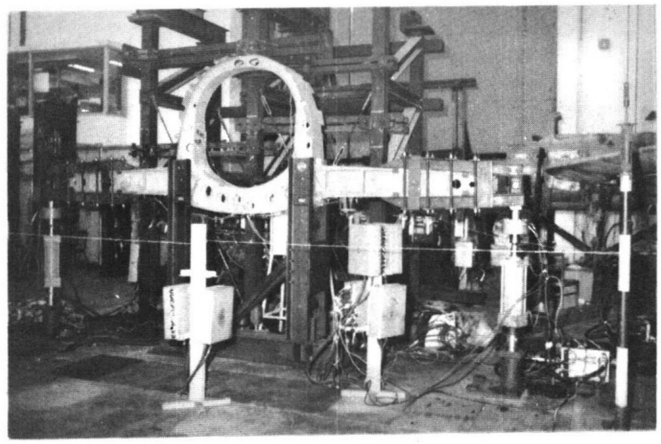


FIGURE 6 : GENERAL VIEW OF THE MAIN FRAME FATIGUE TEST

Fatigue cracking of the web and flange in the upper portion of the frame occurred in both tests.

A residual strength test, performed with the upper portion of the frame badly cracked, revealed that the remaining lower part was capable of carrying at least limit load. This indicated that this component has a high degree of residual strength.

4.4 Damaged Wing Residual Strength Test

Several service aircraft have had cracked wing rib segments found during routine inspections (see Figure 7). Although finite-element analyses have shown that cracked ribs do not affect the flight safety of the aircraft, it was decided to perform a residual strength test of an entire Kfir wing. After completion of the full-scale fatigue test (see Section 5), the right wing, which had undergone four lifetimes of fatigue loading, was selected for testing. Virtually all the rib segments were disconnected from the wing. The wing was then loaded to well above limit load. Up until the maximum load, no buckling of the upper wing skin or any other failure occurred as a result of the lack of support of the wing ribs.

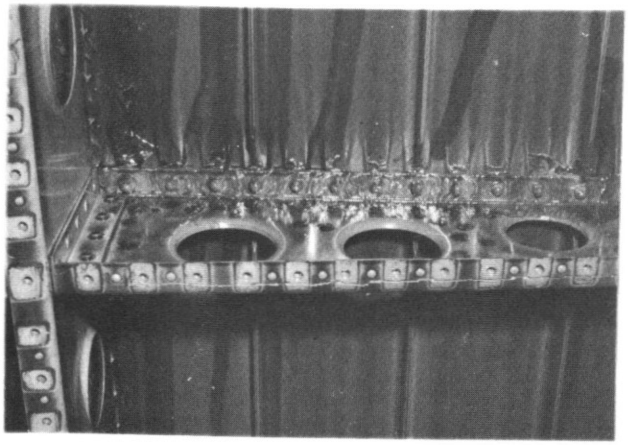


FIGURE 7 : CRACKED WING RIBS

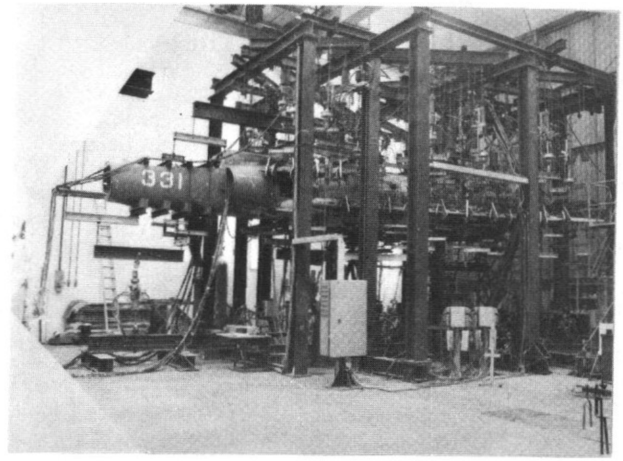


FIGURE 8 : KFIR AIRFRAME DURING THE FULL-SCALE FATIGUE TEST

This test, therefore, verified that cracking of wing ribs does not affect flight safety, and repair of cracked ribs may be performed at the convenience of the operator. A special design modification has been prepared to reinforce the wing ribs to be more fatigue resistant.

5. Kfir Full-Scale Fatigue Test

The Kfir full-scale fatigue test (FSFT) was the highlight of the fatigue evaluation program. Virtually an entire airframe was fatigue tested in order to verify potential critical locations and to establish, as accurately as possible, crack growth rates. The FSFT was also aimed at validation of modifications to improve particular details and at development of suitable in-service methods of non-destructive inspection.

5.1 Test Setup and Loading

The test article consisted of a fuselage, both wings and both canards that had been taken from the normal production run. Configurations were chosen to be representative of early production, that is, without the implementation of design improvements. The fuselage was mounted to the test fixture at the nose landing gear attachment fitting and at the engine rear-mount fittings. The test-article mounted in its fixture is shown in Figure 8.

Optimization and error-analysis studies were performed using a constrained least-square technique which minimizes the errors of the most important parameters, in order to obtain the loading values simulating those occurring in service, for the various flight conditions. A total of thirty independent loading zones and command channels were selected to adequately describe the loading of the aircraft. These channels were distributed as follows :

a)	wing loading	19 channels
b)	fuselage loading	6 channels
c)	canard loading	3 channels
d)	main landing gear loading	1 channel
e)	wing fuel tank pressure	1 channel

Figure 9 describes the loading zones and actual loading points for the wing and canard.

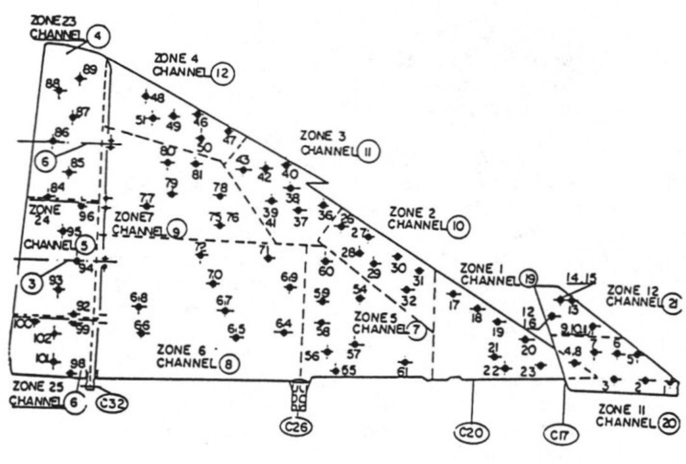


FIGURE 9 : WING AND CANARD UP-LOADING ZONES, KFIR FULL-SCALE FATIGUE TEST

The loads were applied through 52 hydraulic jacks which loaded approximately 800 rubber loading pads through a system of whiffle-trees. These loading pads were mounted to the various surfaces of the aircraft. Air pressure was used to simulate fuel pressure in the wing tanks during flight. Approximately 300 channels of strain gages and deflection transducers were used to monitor key structural parameters.

A multi-redundant safety system was incorporated in the loading system. It provided high accuracy of loading application under normal test operation and the protection of the test-article in the event of a malfunction. The safety functions are distributed between the SEL 360 computer, servo-controller, peripheral-system panel switches, jack limit switches, and emergency push buttons. A schematic representation of the control system is shown in Figure 10.

The test aircraft was subjected to the nominal maneuver loading spectrum as was described in Section 2.

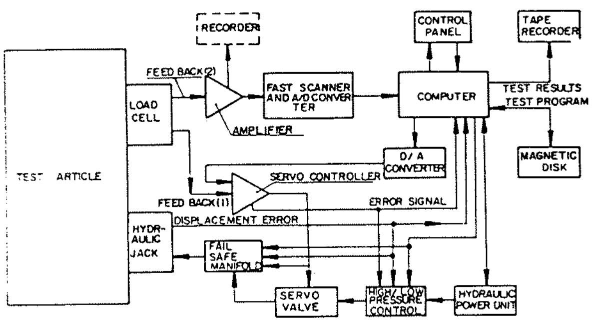


FIGURE 10 : KFIR FULL-SCALE FATIGUE TEST CONTROL SYSTEM

The sequence of loads was selected randomly from a statistical data-bank which contained all the load excursions corresponding to a 500 flight-hour loading block. Three levels of randomizing were employed : randomization of missions within a 500 hour loading block, randomization of flights within a given number of missions, randomization of events within a flight, making each flight within a block unique. The scheme of randomization of the fatigue loads is presented in Figure 11.

Load markers, corresponding to the highest spectrum loads were applied at the end of each block in order to assist in post-test fractography.

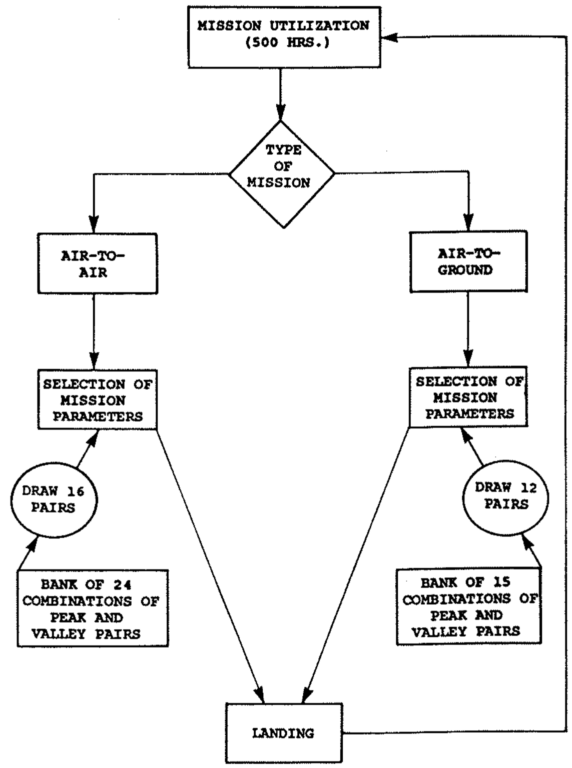


FIGURE 11 : SCHEME OF GENERATING A FLIGHT-BY-FLIGHT KFIR SPECTRUM

5.2 Test History

The test started in March 1983, and was completed in July 1985. The test-article reached 4 lifetimes of fatigue loading. The fatigue test was followed by a residual strength test that reached 120% of limit load. No failures occurred.

The test was interrupted for coldworking of main spar fastener holes after half a lifetime and for minor repairs after two and after three lifetimes.

Several fatigue cracks were discovered during the test, but none of them caused a fatigue failure. Some of the cracks were repaired in order to check possible repair schemes.

Fatigue critical areas of the wing where fatigue cracks appeared during the full-scale test are presented in Figure 12. Types of repairs are shown in brackets.

The majority of cracks were not repaired. The crack grcwth data obtained by NDE revealed that crack growth in the structure was usually slower than predicted. The majority of discovered cracks (38 out of 49) appeared after the first lifetime.

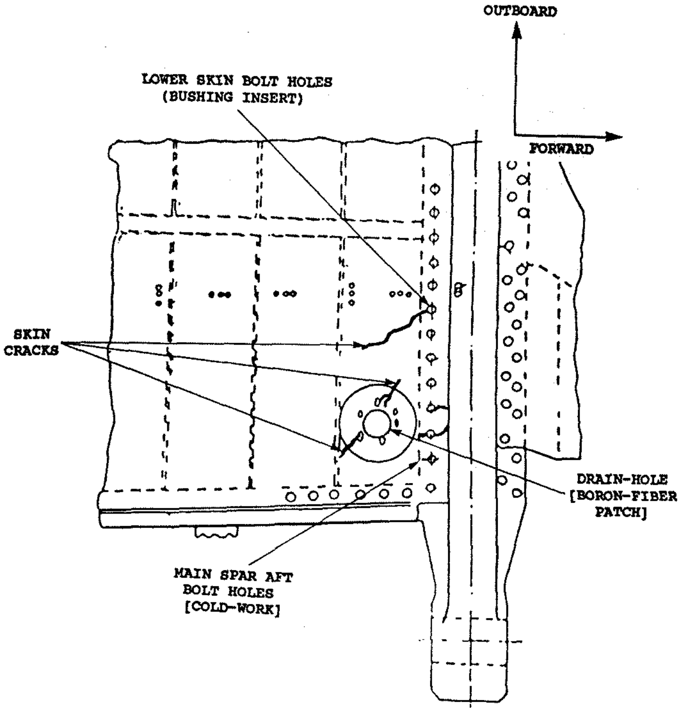


FIGURE 12 : KFIR LOWER WING ROOT AREA CRACK LOCATIONS DISCOVERED DURING THE FULL-SCALE FATIGUE TEST

Fatigue critical areas of the main frame where fatigue cracks appeared during the full-scale test are presented in Figures 13 and 14.

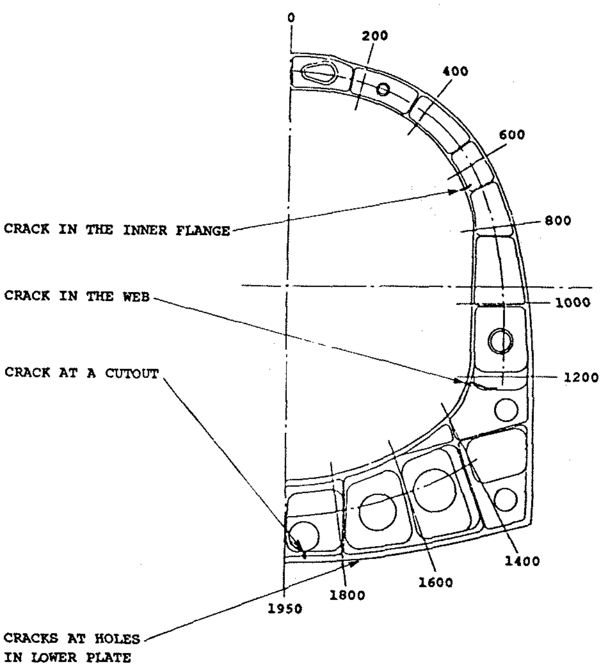


FIGURE 13 : AREAS OF FATIGUE CRACKING IN THE MAIN FRAME DURING FULL SCALE TEST

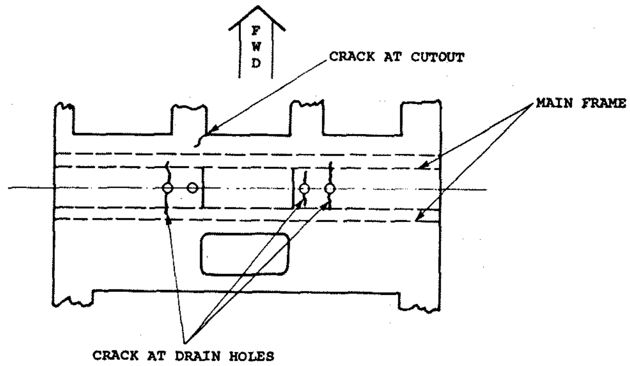


FIGURE 14 : AREAS OF FATIGUE CRACKING IN THE LOWER PLATE OF THE MAIN FRAME DURING THE FULL-SCALE TEST

5.3 Non-Destructive Evaluation

A variety of non-destructive evaluation (N.D.E.) methods were used in the full-scale test including : visual inspections, eddy-current, fluorescent penetrant, X-ray, and magnetic particles.

Inspections were scheduled on a regular basis during the FSFT, generally at 1000 hour intervals. It was shown that service cracks can be successfully detected at an early stage of their formation using a "directed inspection". This was particularly true at locations where analysis or previous testing had shown that cracking is likely. As soon as a crack was detected, its length and depth were systematically monitored during the regularly scheduled inspections.

Direct measurements of cracks at holes included not only measurements of surface length but also estimates of the crack depth into the material. The latter measurement was obtained by precalibrating the eddy-current signal on known crack depth specimens. This permitted a "real-time" estimate of crack depth to be made throughout the test.

An example of such a "real-time" estimate is shown in Figure 15. Both the length along the bore (c) and penetration (a) of the crack were estimated both by eddy-current (real-time) and later measured by fractography.
The results show good correlation for the the crack length along the bore, (c), but indicate that the eddy-current method of NDE consistently overestimated the crack penetration (a).

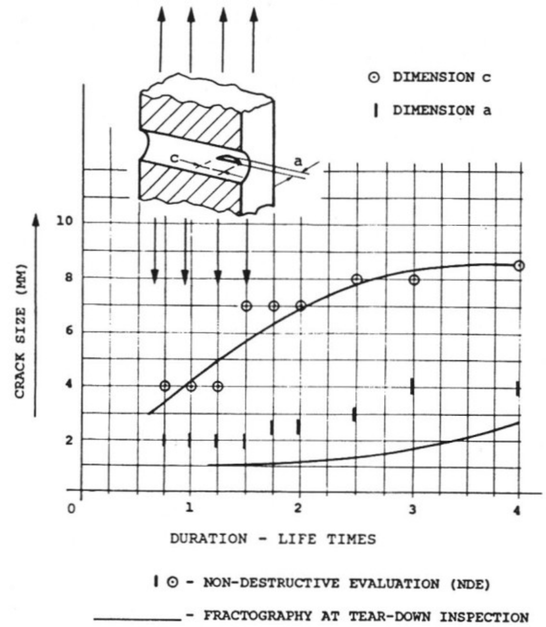


FIGURE 15 : "REAL-TIME" NDE MEASUREMENT OF CRACK GROWTH IN THE WING MAIN SPAR COMPARED TO FRACTOGRAPHY RESULTS

Two new NDE techniques were developed and applied during the FSFT, through-the-bushing inspection of cracks and video-documentation of cracks.

Application of Video Technique for Documentation of Cracks

Cracks in holes are usually inspected by eddy-current or visually, by means of a boroscope. These methods do not ensure a direct documentation of the discovered crack.

The video technique was used by connecting an "Olympus" boroscope to a video system. This gave the possibility to observe the form, size, and the exact location of the flaws and cracks that were detected in the holes. This allowed for a detailed study of the nature of the various flaws. Video inspection of cracks in holes was successfully used in the Kfir full-scale fatigue test. An example of video recording of a crack is shown in Figure 16. It should be noted that in many cases the cracks emanate from a skin-spar interface where eddy-current detection of cracks is usually difficult. In such cases the use of the Video Technique offers a unique opportunity of crack identification.

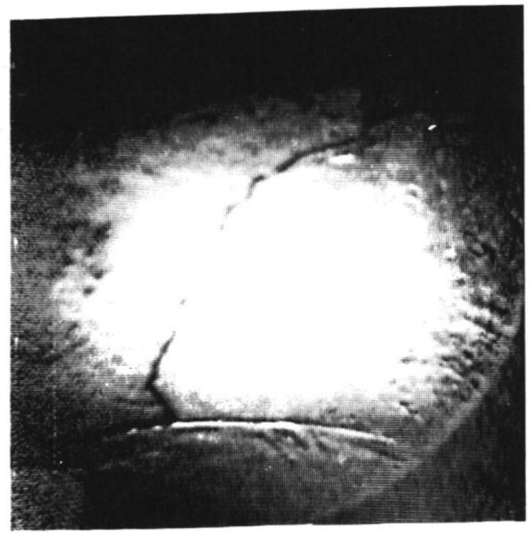
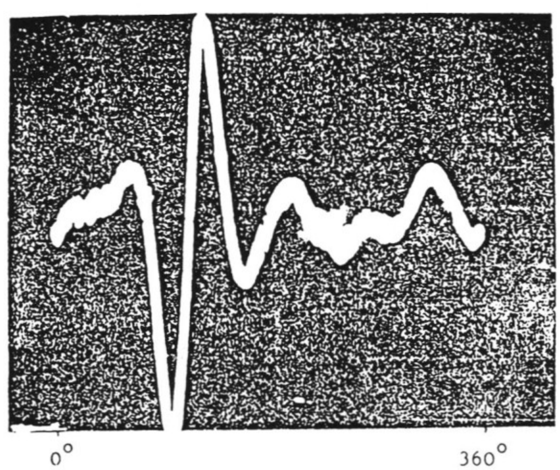


FIGURE 16 : A VIDEO RECORD OF A SKIN CRACK AT A COUNTERSUNK HOLE

Through-the-Bushing Detection of Cracks

Detecting cracks at a bushed hole is generally impossible without removing the bushing. The removal is time consuming and often damages the hole. A special low-frequency dynamic eddy-current procedure, using "Defectomat" equipment, was developed for this purpose and was used in the Kfir full-scale fatigue test. The results showed that cracks can be detected through nonmagnetic steel bushings having wall thicknesses as much as 3mm (6)



Angle of the Defectomat probe rotation within the hole.

FIGURE 17 : INDICATION OF A 0.9MM DEEP FATIGUE CRACK THROUGH A 1.5MM THICK STAINLESS STEEL BUSHING

The results also showed that cracks having a depth of 1mm can be reliably detected through bushings with a 1.5mm wall thickness. Figure 17 shows an example of readings obtained while detecting a 0.9mm deep crack through a 1.5mm thick stainless steel bushing.

5.4 Teardown Inspection and Fractography

A selective teardown inspection (TDI) was performed immediately after completion of the four lifetimes of fatigue loading of the FSFT. The scope of the TDI and fractographic description of the discovered cracks is shown in the following Table :

GENERAL RESULTS OF THE SELECTIVE TDI

Aircraft Part	Number of Holes Cracked			
	Total Inspected	Found Cracked	NDE	Fracto-graphy
Left Wing	1722	52	52	24
Right Wing	1722	50	50	
Left Canard	2			
Right Canard	90			
Fuselage	1351	68	68	12
Total :	4937	170	170	36

During the TDI additional cracks, which were not detected during the test, were discovered and were analyzed by fractography. This gave additional data that was used to prepare the maintenance and inspection program for the aircraft.

As was stated in Section 4.4, several service aircraft have had cracked wing ribs found during routine inspections. (See Figure 8). These cracks were previously attributed to buffeting of the wing at certain flight conditions.

Unexpectedly, the teardown inspection revealed that similar cracking had occurred at the wing ribs of the full-scale test-article. Since buffeting loads were not simulated in the F.S.F.T., it was concluded that the wing pressurization cycle, that occurrred one per flight, was responsible for the cracking in the F.S.F.T. It was also concluded that fuel tank pressure cycles are one of the primary causes of rib cracking that was found in service.

Section 4.4 describes the residual strength test that was performed in order to prove that these cracks do not affect the flight safety of the aircraft.

6. Design Improvements

As a result of the component and full-scale fatigue tests, the critical locations of the aircraft were identified and suitable design improvements were made in order to extend the useful service life of the aircraft.

Several of these improvements were incorporated during the production run of the aircraft. Others were implemented as retrofit changes.

These improvements include :

a. Cold-working and installing interference bushings in potentially fatigue critical holes in the wing and fuselage.
b. Redesigning the main spar by increasing its strength and eliminating several undesirable design features such as blind-holes and unnecessary rivet holes.
c. Strengthening the wing lower skin and elimination of undesirable design features.
d. Relocation of wing drain-hole to a lower stressed region and applying a boron reinforced patch at the original drain-hole.
e. Redesigning the wing ribs to provide a more fatigue resistant design.

These improvements together with the inspection program, are expected to extend the useful service life of the Kfir aircraft to beyond the design service life goal of 4000 hours.

7. Individual Aircraft Tracking

One of the main aims of the Kfir fatigue evaluation program was to provide sufficient information to monitor the accumulation of fatigue damage on individual Kfir aircraft in service. In order to perform this function, an individual aircraft tracking program was developed. Each Kfir aircraft is provided with a counting accelerometer system which records load-factor exceedance levels at the aircraft's center-of-gravity. It is conservatively assumed that several critical locations of each aircraft have initial fatigue cracks. A computer program was developed that tracks the growth of these assumed cracks as a function of the severity of usage of the specific aircraft. Whenever these assumed crack lenghts reach a predetermined value, the aircraft is inspected and repaired as required. The computer program takes into account the various configurations of the aircraft as well as the design improvements and retrofit operations that were performed at each location for each specific aircraft.

Individual aircraft tracking enhances fleet safety for the entire service life of the Kfir while minimizing the maintenance costs.

8. Concluding Remarks

The Kfir fatigue evaluation program has been completed. Fatigue critical locations were identified, design improvements were implemented and an inspection program was developed. As a result, the Kfir aircraft is expected to have a useful service life beyond the design goal of 4000 hours. An individual aircraft tracking system was developed to enhance flight safety and the economy of operation. New NDE techniques developed by I.A.I. enable the implementation of "directed inspections" to assist in detecting cracks, and thereby promoting flight safety.

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