Full Scale Structural Durability Test Spectrum Reduction by Truncation Coupon Testing

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Abstract - *The ability to accurately predict damage to an aircraft is one of the essential functions of the F-16/F-22 Integrated Fighter Group Service Life Analysis Team. An important supporting element for analytical modeling is laboratory simulation of the operational loads that the aircraft is expected to experience during its lifetime. This element is known as the full-scale durability test. Prior to the full-scale durability test, truncation tests were performed to verify that low amplitude cycles in the spectrum contribute little or no damage to the structure and that they could be removed from the spectrum used for the full-scale durability test without significantly affecting the full-scale durability test results. Removing these cycles from the test spectrum reduces test time and cost without significantly affecting the outcome of the test. Choosing an appropriate truncation level balances two factors:*

1. Selecting a high enough value that removes enough cycles to reduce test time

2. Selected value is not so high that the resulting cycles in the spectrum are damaging, leading to an un-conservative analysis.

The selected truncation level used for the coupon testing was calculated to, if used, significantly reduce the test time. A comparison of crack lengths from coupon testing between truncated and un-truncated spectra showed similar results. It was concluded that the selected truncation level was appropriate for the full-scale durability test spectrum.

Keywords: *Truncation Test, Full Scale Durability Test, Coupon Testing, Spectrum,*

1 Introduction

The F-16 Block 50 Full-Scale Durability Test (FSDT) is being conducted to support extension of the service life of USAF's Block 40/42/50/52 fleet. The service life of certain areas of the aircraft is determined by predicting how large a crack will form in those areas. This determines how often these areas on the aircraft are examined. For that reason, examining how cracks grow is an important aspect of determining aircraft service life. This is the third full scale durability test that has been conducted on the F-16 aircraft, with the most recent full scale durability test completing in the early 1990's for the F-16 Block 30 C Model. For this test, as it was for the previous tests, it is desirous to simplify the spectra as much as possible while maintaining the predictive accuracy of the test. The method used to reduce the number of load cycles in the spectrum

Figure 1 Full Scale Durability Test Aircraft in Fixture

during the F-16 Block 30 Full-Scale durability test was spectrum truncation. This method removes the smaller values in the stress cycle under a certain chosen limit. The limit selected for the Block 50 FSDT is based upon the limit used in the F-16 Block 30 FSDT. Verification of this spectrum truncation level was done by means of coupon testing. The steps taken to conduct this coupon testing are detailed in this paper. This particular paper applies to the F-16 Block 50 full-scale durability test, but the principles contained here can be applied to other aircraft and aircraft components.

Once this truncation level is established from coupon testing, the truncated spectrum will be used in predictive crack-growth software for various control points across the F-16 airframe. These control points have more complex geometry than can be simulated using coupon testing. These control points have been determined from previous analyses to be areas with short service lives. That is, cracks grow in these control point areas more quickly than other parts of the aircraft. If the crack growth rates using the truncated spectrum are similar to the rates using the un-truncated spectrum for the control points evaluated, the truncated spectrum can be applied to the Full-Scale Durability Test aircraft.

2 Pre-Coupon Test Considerations

Before preparations for the truncation test set-up are conducted, there are other considerations that are not related to the set-up which should be defined. Among these are how the control points are selected, the stresses at those control points, and the spectra which are used for the truncation test.

2.1 Control Point Selection Criteria

Part Number	Control Point Description	Loads	Material
16B1115 (1)	Longeron BL 19, FS 186 – FS 247, Bolt Hole at FS 189	FS189BM	7475-T7351
16B1115 (2)	Longeron BL 19, FS 186 – FS 247, Bolt Hole at FS 242	FS267BM	7475-T7351
16B5111 (3)	Longeron BL 8, FS 279 – FS 341, Upper Leg Fastener Hole at FS 334	FS341V, FS341BM, FS341T	2024-T62
16B5303 (4)	Upper Fuselage Skin, Bolt Hole in Refuel Well Area at FS 314, BL 8	FS293V, FS293BM	2024-T62
16W1102 (5)	Lower Wing Skin, Bolt Hole at FS 309, BL 50, Common to WAF Hole #25	WRBM, WRV, WRPM	7475-T7351
16W1102 (6)	Lower Wing Skin, Fastener Hole near Pylon Cutout at BL 120	WV120, WBM120, WPM120, WV157, WBM157, WPM157	7475-T7351
16B6224 (7)	Upper Bulkhead at FS 479, Upper Flange Bolt Hole at BL 23 (ECP 4085 Configuration)	LHTV_z, LHTM_x, LHTM_y,RHTM_x, VTV, VTBM, VTT	FMS 4097 (Aluminum Lithium)
16T7225 (8)	Vertical Tail Rear Spar, Shear Web Hole	VTBM, VTT	2124-T851

Table 1 List of Selected Control Points

Eight control points from across the airframe were selected to perform truncation test studies and determine, by means of coupon testing, the effect of truncating the spectrum at the chosen stress level. Control point selection was determined by the following criteria:

1. Geometry that could easily be replicated in a dog-bone test coupon

2. Control point location primarily loaded axially

3. Stresses driven by various applied loads to capture a variety of primary loads on the airframe.

4. Representative of materials used on the F-16 airframe

The selected control points, primary loads parameters, and materials are listed in Table 1. The approximate locations of the control points on the airframe are shown in Figure 2.

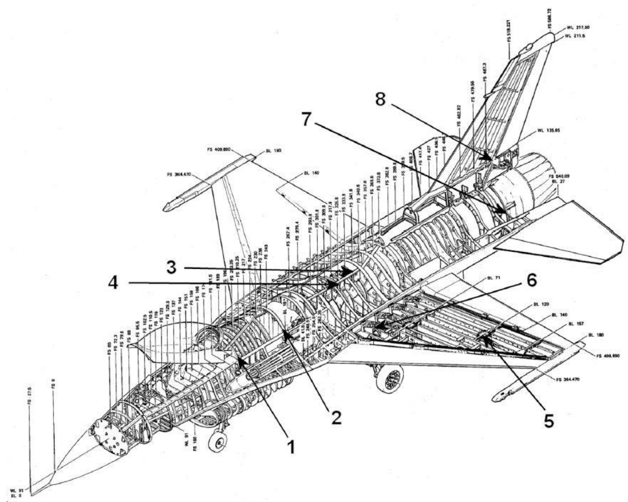

Figure 2 Approximate Locations of the Control Points on F-16 airframe (Corresponds to Table 1 Part Numbers)

2.2 Stresses

Using the control point stress levels without bolt load transfer resulted in extremely long test time for some of the selected control points. For this reason, stresses were increased to obtain crack growth data in a decreased amount of test time. Because the purpose of this test was not to predict life at the control point, but rather examining the effect of truncating the spectrum, this was deemed to be acceptable.

2.3 Full-Scale Structural Durability Test Spectra

An examination of available F-16 Block 50/52 spectra was performed in order to select a test spectrum. Because the F-16 Block 50 Durability Test is being performed to extend the service life of United State Air Force's Block 40/42/50/52 fleet, the test spectrum needs to reflect current fleet usage while at the same time be considered representative of future aircraft operations. This differs from previous F-16 durability tests that were performed to certify that the aircraft met a specified service life contractual requirement or had the goal to examine a specified usage.

After examination of the available spectra, Lockheed Martin Aeronautics recommended that the F-16 Block 50 2000 Fleet Management Update (FMU) Fleet Average UV1N (Baseline) spectrum be used as the test spectrum. It was believed that this Baseline spectrum provided a good representation of Block 50 operations based on the volume of recorded flight data used to develop it [3].

The United States Air Force wanted to accelerate the test by means of using a more severe spectrum. Lockheed Martin Aeronautics then recommended the use of the Fleet Average Most Severe (UV1M) spectrum used as one of the variations in the Individual Airplane Tracking program. This spectrum is more severe than the Baseline spectrum but retains the same mission mix as the Baseline spectrum [3].

Spectra used for the truncation tests were based on the USAF F-16 Block 50 2000 FMU UV1M (average most severe) loads spectrum. This spectrum contains several hundred thousand load points. This is also the number of load points that a full untruncated spectrum would contain. Running a test with numerous coupon specimen and this many load points, would take a great amount of test time.

In order to reduce the time it takes to run the coupon test, the 'untruncated' spectra was modified using a truncation level of 1.7% of maximum spectrum stress for the 16T7225 Spar and 1% of the maximum spectrum stress (221-421 psi) for the remaining 7 locations.

These modified 'untruncated' spectra took an average of 32% of the test time compared to the original UV1M spectrum. Analysis directly comparing full spectra and the test 'untruncated' spectra showed no difference in the predicted crack growth lives for the specimens. Also, the ranges of stress used to reduce the number of load points in the spectra were all within the loading accuracy of the testing machines.

3 Coupon Test Set-Up

In order to assure the accuracy of the experiment is maintained, certain processes regarding the test specimen used were taken into account. It was important that the material used was within specification, the measurements of the specimen were within drawing tolerances, and that the flaw type used in testing was promoted reasonable crack growth during the coupon testing. Other considerations taken into account are that the specimen was properly placed in the fixture, loaded correctly and that the measurements of the cracks were accurately measured and recorded. The proceeding sections describe these processes.

3.1 Coupon Test Material Preparation

Test coupons were machined from 7475-T7351 Aluminum (FMS-3004), 2024-T62 Aluminum (QQ-A-250), aluminum lithium (FMS-4097), and 2124-T851 Aluminum (FMS-3002). All the coupons used for this truncation test were procured to the appropriate Lockheed Martin Aeronautics material specification. Certification of the heat treatment and material were confirmed by measuring hardness and conductivity prior to coupon manufacturing. All of the test coupon materials meet the NDTS-1500 requirements for hardness and conductivity.

3.2 Coupon Test Specimen Geometry

As previously mentioned, all of specimens were open-hole, dog-bone type specimens as to reflect the geometry, particularly hole diameter and edge distance, in the control point area and to assure the simulation of axial loading found in that area. Thicknesses were increased for some of the control points as a result of a load increase and/or to prevent buckling of the specimen. An example of a specimen is found in Figure 3 below.

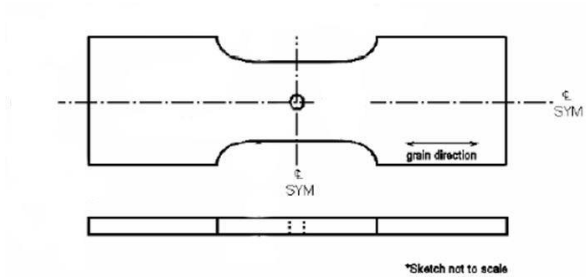

Figure 3 Sample Coupon Specimen

Each test coupon was measured prior to testing. Each test coupon was measured as follows:

1. 3 measurements across the width of the test area (depending on the size of the coupon).

2. 4 hole diameters at 0^0, 45^0, 90^0, and 135^0.

3. 6 thickness measurements (depending on the size of the coupon).

4. Edge distance on the left and right side.

5. Length of the test area on the left and right side.

The results of the measurements revealed the coupons were manufactured within engineering drawing requirements. These coupon measurements were used to calculate the applied loads so that stress levels were maintained at each control point.

3.3 Specimen Flaw Description

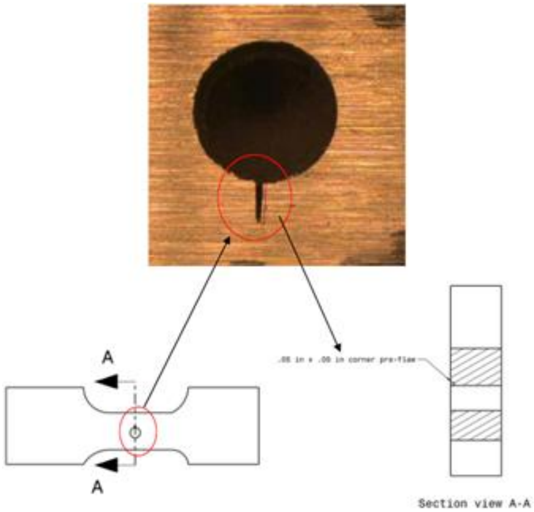

Figure 4 Notch Illustration

The integration of a corner notch was included with the specimen in order to initiate the cracking at the coupon holes. Figure 4 above contains a photograph and drawings of the corner flaw added to each coupon after machining. After measurements were confirmed, each coupon was scribed using a height gage to determine the center of the coupon within 0.001 inch. The scribe lines assisted in aligning the coupon during the installation of the coupon in the test fixture.

4.0 Test Execution

All coupon tests were conducted on five MTS Systems Corporation (MTS) servo hydraulic load frames. Each frame had a maximum load capacity. Which frame was used was based on the predicted maximum load at the control point, and therefore the maximum load coupon would be subjected to. Cyclic testing was conducted after each coupon was properly aligned and secured in the test frame. Cyclic testing was performed using a load rate that accurately achieved spectra end points. Time (seconds), displacement (inches), force (lbs), count (segments), and force command (lbs) were collected for each block of each coupon configuration. In this case, a block is a set of spectra end points used to simulate a certain number of flights. Upon completion of each block, the cyclic testing was stopped so that crack measurements could be obtained and recorded. The block by block crack length measurements were recorded and saved for crack growth analysis. These measurements are done with calibrated optic lenses on the front and rear of the coupon. The process was repeated until the coupon failed. After coupon failure, the depth of the initial notch and the length of the final crack were measured and recorded using a Keyence VHX-500 digital microscope.

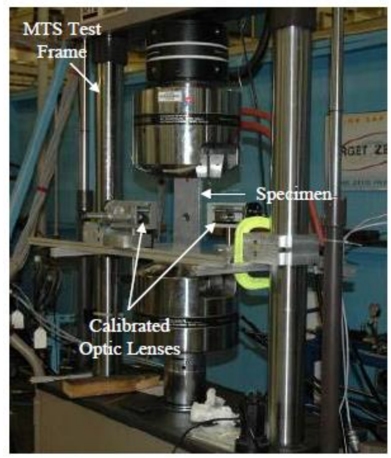

Figure 5 Test Frame

5.0 Data Analysis

For each of the 8 control points selected for the tests, 3 specimens were to be tested with the untruncated spectrum (specimens identified as “UN”), and 3 specimens were to be subjected to the truncated spectrum (specimens identified as “TR”) to have a comparison of the effect of truncating the spectrum at a certain, pre-determined stress level. Of the 8 control points represented by this coupon testing, 7 control points used six specimens for testing. The remaining control point which represented the 16B6224 used 7 specimens for coupon testing. Therefore a total of 49 coupons were actually tested.

5.1 Coupons Removed From Results

There were 44 of the planned 49 test specimens that were included in the results. One coupon that represented a control point on 16T7225 and one coupon that represented a control point on 16W1102 BL 50 were not included in the results because the spectrum was different from the others used. Three coupons that represented the control point on 16B6224 were not included because the wrong loads were used in the coupon testing. Despite these coupons that were not included in the results, the results are believed to have enough coupons to draw reasonable conclusions regarding the results.

5.2 Coupon Test Results

Crack length measurements obtained by visual inspection via calibrated optic lenses for each of the specimens are shown in Figures 6 through 13. These figures represent normalized data. Normalized data shows crack growth beginning at a size that common to all of the coupons in that data set. Normalization of the data allows comparison of crack growth by reducing or eliminating the effects of varying EDM notch geometry on crack initiation.

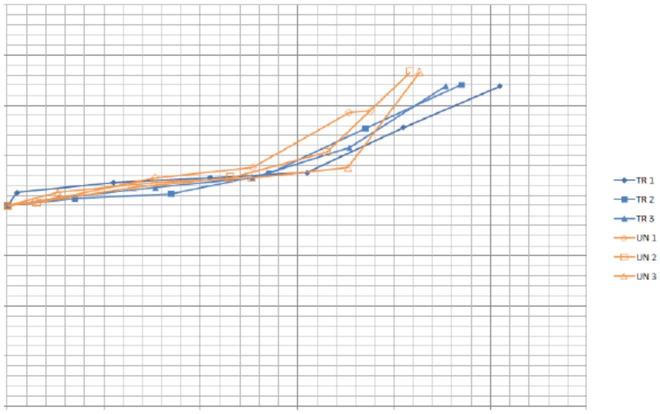

Figure 6 16B1115 Longeron, Bolt Hole at FS 189

The results shown in Figure 6 for the bolt hole at FS 189, show small differences in the crack growth results between the specimens using the truncated and the untruncated spectra.

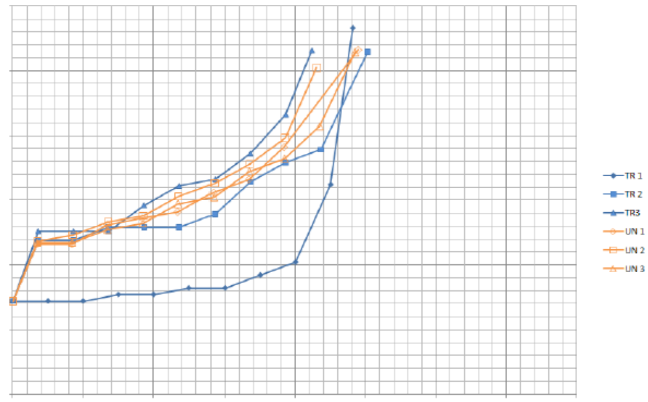

Figure 7 16B1115 Bolt Hole at FS 242

The results shown in Figure 7 for the bolt hole at FS 242 show similar crack growth rates for all the specimens with the exception of the truncated # 1 (TR 1) test specimen. This specimen had a much smaller EDM notch (initial flaw size) than the other specimens, which resulted in a much slower initial crack growth rate. However, the final crack size and the life to failure for this specimen was similar to the results of the other specimens.

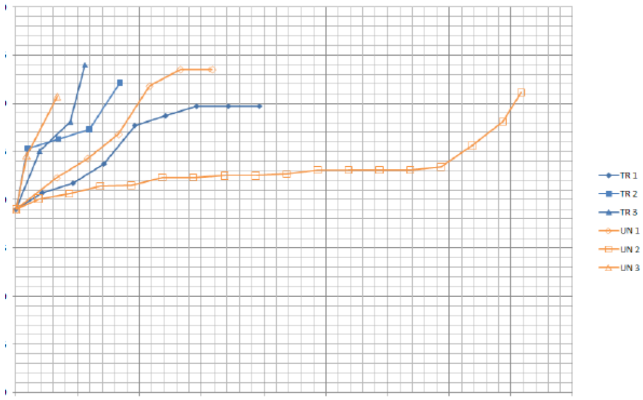

Figure 8 16B5111 Longeron at BL 8, Upper Leg Bolt Hole at FS 334

The results included in Figure 8 show a much longer crack growth life for the untruncated #2 (UN 2) specimen than for the other specimens. Closer examination of the fracture surface of this specimen shows two distinct cracks growing for some time before merging. This is different than the crack growth exhibited by the other specimens, which consisted of multiple crack initiation sites which quickly coalesce into a single crack. The growth of the two cracks in the untruncated #2 specimen is believed to be the reason for the much longer life of this specimen

The crack growth curves of untruncated # 1 (UN 1) and truncated # 2 (TR 2) show decreasing crack growth rates toward the end of the test. This is an unusual behavior because the crack growth rate typically increases as the crack gets larger. Close examination of a spare specimen revealed that the specimen was bowed. The specimen was loaded in a test fixture and with the use of a displacement gage, out of plane movement was observed when loads were applied to the specimen. Lockheed Martin Aeronautics believes that the EDM notch in such a thin specimen (0.080 in.) may have resulted in the bowing and the out of plane bending may have affected the crack growth results.

Despite these anomalies, the results of the truncated spectrum test specimens are intermixed with the results of the untruncated test results.

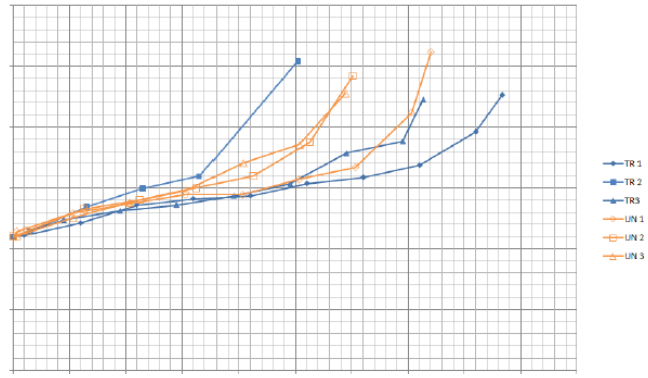

Figure 9 16B5303 Upper Fuselage Skin, Bolt Hole in Refuel Well Area FS 314, BL 8

Results included in Figure 9 for the bolt hole in the refuel well area show substantial differences for the crack growth data between the truncated spectrum specimens and the untruncated spectrum specimens. However, the crack growth curves are intermixed and show that using the truncated spectrum produces similar crack growth results to the untruncated spectrum.

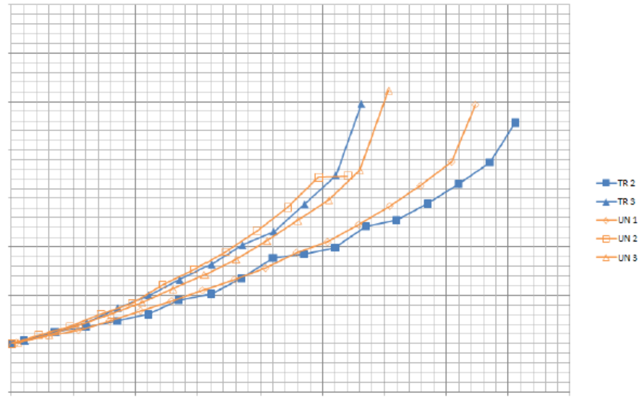

Figure 10 16W1102 Lower Wing Skin, Bolt Hole at FS 309, BL 50

Results included in Figure 10 for the bolt hole at BL 50 show slightly larger differences between the truncated spectrum results, but overall, the figure shows similar crack growth results for both the truncated and the untruncated spectra.

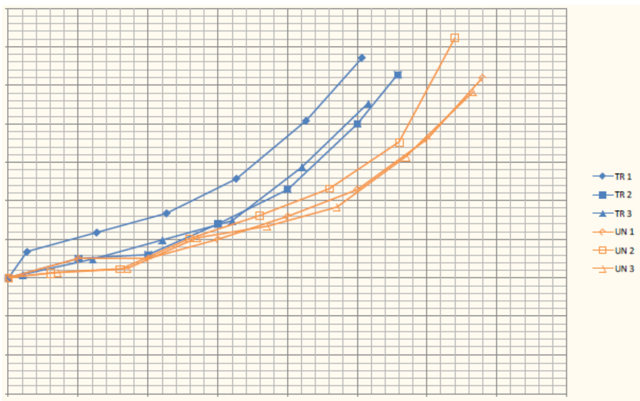

Figure 11 16W1102 Lower Wing Skin, Bolt Hole near Pylon Cutout, BL 120

Results included in Figure 11 for the bolt hole at BL 120 show that the truncated spectrum specimens have slightly longer crack growth lives when compared to the untruncated spectrum specimens. However, the results for the untruncated spectrum specimens and the truncated spectrum specimens are still fairly close to one another. This shows that for this set of data truncating the spectrum did not produce a significant effect.

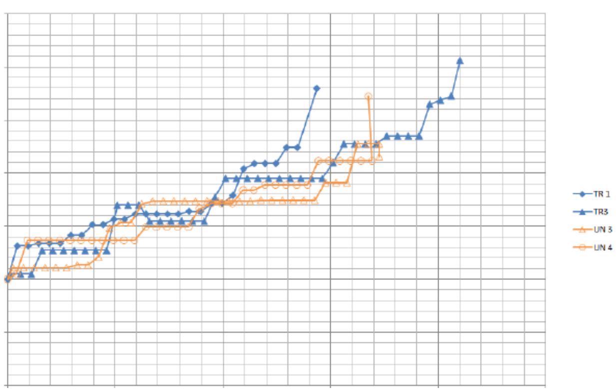

Figure 12 16B6224 FS 479 Bulkhead, Bolt Hole at BL 23

Results included in Figure 12 show different crack growth curves for the test specimens as compared to the curves which represent the other control points. This behavior is due to the grain structure of Aluminum-Lithium material which causes the crack to change directions as it grows.

Taking this crack growth behavior into account, the overall trend of the data for the specimens tested with the truncated spectrum is similar to the specimens tested with the untruncated spectrum, indicating no significant effect due to truncation.

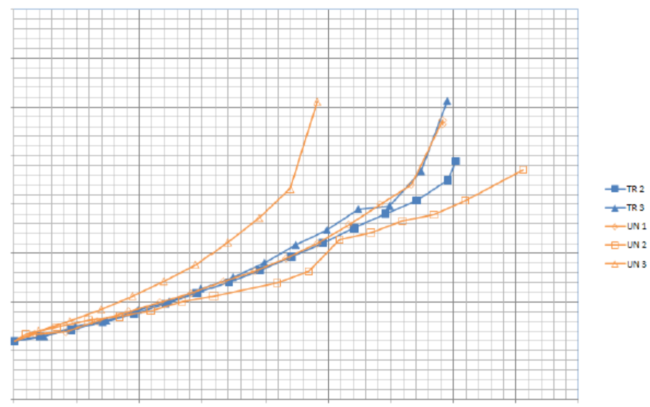

Figure 13 16T7225 Vertical Tail Rear Spar, Shear Web Hole

Results included in Figure 13 show that the crack growth rates for the truncated specimens are similar to the crack growth rates of the untruncated spectrum.

6.0 Conclusion

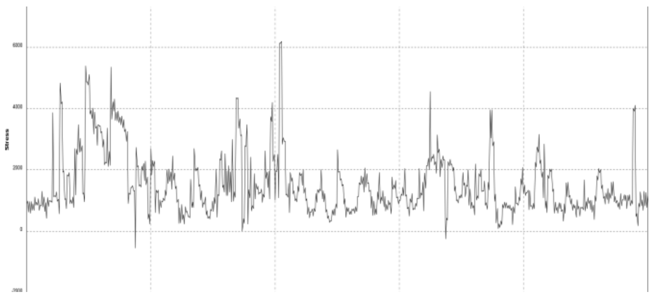

Figure 14 Sample F-16 Block 50 UV1M Un-Truncated Spectrum for a Single Flight

An estimate of how much test time would be saved from spectrum truncation needs to be calculated. For the given truncation level used in this coupon testing, the percentage of load cycles removed is about 82% when comparing the truncated and the untruncated spectrum. The untruncated spectrum had over 680,000 load points.

Using the numbers listed above as an example the number of load points removed from the untruncated spectrum can be calculated by:

Load Points Removed = Percent of Load Points x Load Points

Load Points Removed = 0.82 x 680,000 Load Points

Load Points Removed = 557,600

A typical rate of Load Points that can be run on a full-scale durability test is 15 Load Points/minute means that 37,173 minutes would saved by using the truncation level for this Full-Scale Durability test. Assuming 40-hour work weeks, this equates to about 15.5 weeks saved. Observing the difference in the number of load points between spectra in Figure 14 and Figure 15, it can be seen how a truncated spectra would save test time on the full-scale durability test.

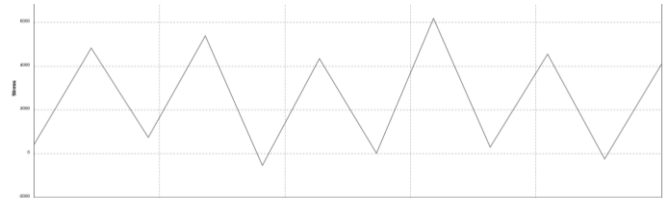

Figure 15 Sample F-16 Block 50 UV1M Truncated Spectrum for a Single Flight

Referring to the normalized cracking results which represent the 8 control points shown in Section 5.2 of this paper, the untruncated and truncated cracking data show similar crack growth rates. From this data, it can be concluded that the chosen stress level is reasonable for reducing the UV1M Analytical Spectrum. The truncated spectrum will be used in predictive crack-growth software for various control points across the F-16 airframe.

Acknowledgment

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