Solder Joint Reliability in Patriot Advanced Capability Missile Electronic Components Using MSC/FATIGUE.

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Abstract

The reliability, or fatigue life, of solder joints is investigated in the Patriot Advanced Capability (PAC-3) missile for various electronic components using MSC/FATIGUE. Frequency response and random vibration analysis is performed using MSC/NASTRAN to extract transfer functions due to 1G accelerations, and RMS stress levels. The suspect joints are modeled using 8 noded brick elements. Acceleration input load PSDs are defined based on measured vibration test and flight worthiness levels. Stress response PSDs are extracted to determine fatigue lives based on S-N methods. The calculated fatigue lives give confidence that the troublesome solder joints will not only endure the various qualification tests, but that there will be enough remaining life to survive actual flight.

Problem Description

The Patriot Advanced Capability (PAC-3) missile contains various electronic equipment and components used for guidance and target acquisition. Most of the electronics are contained in a portion of the missile called the Seeker, near the front of the missile, aptly named for its ability to seek and destroy hostile aircraft and other enemy missiles. The Intermediate Frequency Processor (IFP) is a subassembly of the Seeker, on which is contained the Multi-channel Receiver (MCR). Numerous band pass filters (BPF) and Multi-functional Arrays (MFA) reside on the MCR. Each BPF has an RF (radio frequency) lead connecting to an RF tab. The connections are made using solder.

Although there are many solder joints throughout the PAC-3 electronic assembly, it was decided to concentrate efforts on the more critical areas only. During qualification testing, some of these solder joints connecting the RF leads to the RF tabs on the BPFs proved troublesome, showing either a failure or a degradation of the BPF (not working to specification). The goal was to investigate the fatigue life of these solder joints subjected to the various vibration screening tests and subsequent flight worthiness tests to give confidence that, after testing, sufficient life would be left to survive actual flight. This pre-supposes a defect-free solder joint.

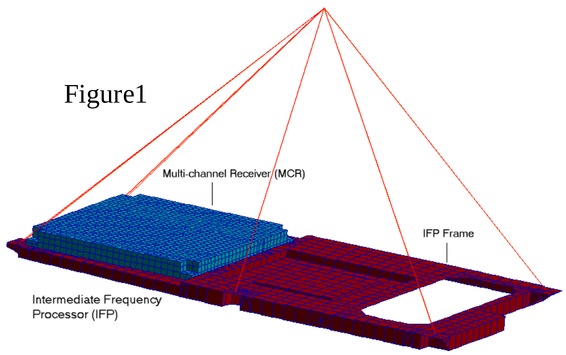


Figure1

Finite Element Model

Only the IFP was actually modeled, along with the MCR, MFA, BPFs, and solder joint connections. The IFP frame itself, made of cast aluminum, was modeled in MSC/NASTRAN entirely of shell elements (CQUAD4). The MCR, made of aluminum also, consisted of both CQUAD4 and CTRIA3 shell elements mostly, and a few solid (CHEXA) elements where it connected to the IFP. The BPFs consisted of both solid and shell elements, the solid elements representing the ceramic portion of the BPF and the shell elements simulating the sheet metal portion. The MFA was modeled entirely of solid elements. Each BPF has an RF lead modeled with shell elements. The RF lead exits the BPF and is then twisted by 90 degrees by the time it reaches the RF tab. The solder joints connecting the BPF to the RF lead and the connection of the RF lead to the RF tab were modeled using solid elements. Refer to *figure 1* through *figure 5*.

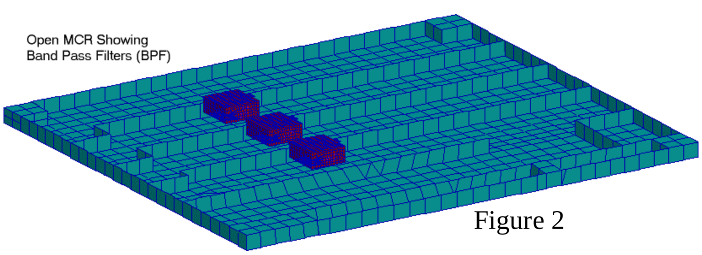


Figure 2

A modal analysis was first performed to determine the natural frequencies of the IFP and componentry. These frequencies were compared to the natural frequencies from the actual component as tested in the laboratory. The model was correlated and updated to bring the first resonant frequency and the damping in line with test values, which occurs at around 260 Hz with about 2.5% critical damping.

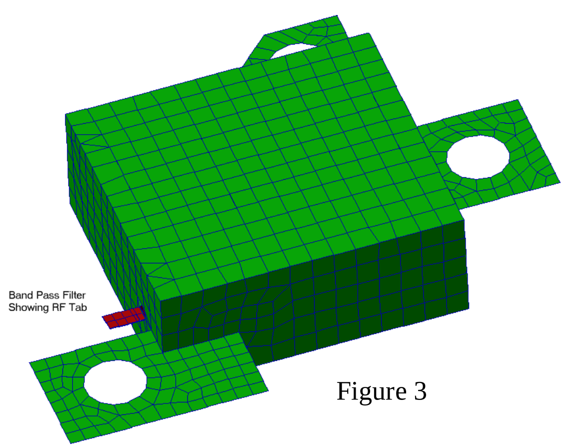


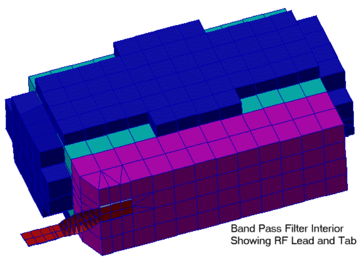
Figure 3

In order to perform a fatigue analysis of the solder joints on the RF lead, three pieces of information are needed. The transfer function(s) (TF) of the system due to a unit load input, the input load power spectral density (PSD) functions, and the cyclic material properties or S-N (stress-life) curve. Each of these is described below.

Frequency Response Analysis

The TFs of the system are obtained by subjecting the IFP to harmonic loads in the same loading direction as that of the vibration screening tests. In all cases, a 1g acceleration was applied at the top of the multi-

Figure 4



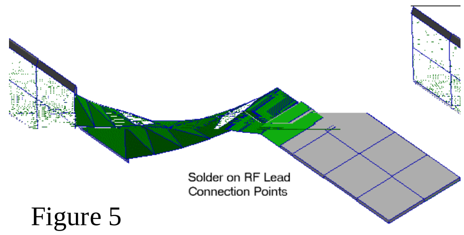


Figure 5

point constraint shown in *figure 1*. In reality, the actual acceleration responses that later define the loading input acceleration PSD levels were acquired at the five mount points on the IFP. The MPC ties these five points to a single seismic mass point from which the 1g acceleration is applied. TFs are determined with the 1g acceleration in the axial direction of the PAC-3 missile as well as the lateral and vertical directions. The TFs (of stress) essentially describe the stess distribution in the IFP, or more importantly, in the solder joints, as a function of frequency. Shown below, in *figure 6* is the TF of stress at one of the critical locations from one of the solder joint elements. It shows clearly the influence of the first natural frequency at around 260Hz.

MSC/NASTRAN was used to calculate TFs of stress using the User Random option and MSC/PATRAN was used to set up the analyses and calculate and view RMS stress levels at critical locations. Care was taken to make sure the frequency content of the TFs was sufficient to fully capture the dynamics of the system, taking into account the natural frequencies of the model and the frequency content of the input load PSDs. If this is not done, the possibility of missing or truncating the response can be significant since interpolation of the TF frequencies to match those of the input PSD currently does not occur in either MSC/FATIGUE or MSC/NASTRAN (1).

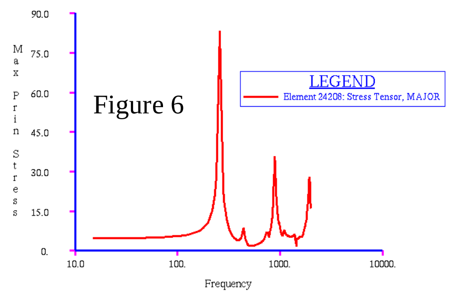


Figure 6

Input Load PSDs

Various load input PSDs are provided from acceptance test acceleration data. Since the data are acquired at the mount points, an envelope of the acceleration data from all mount points is used as a single PSD input for each test. This avoided the necessity of having to perform multi-input random vibration

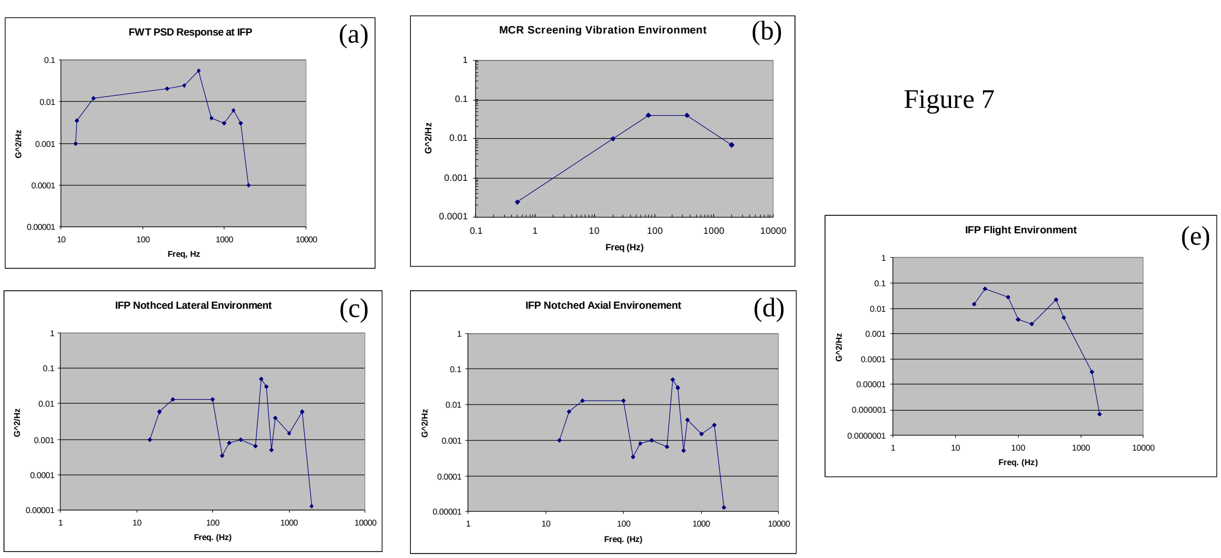


Figure 7

analyses, which would have proved difficult since no cross-correlation terms (relating one input load to another) were readily available. The four input PSD loads are shown in *figure 7*.

The Seeker Flight Worth vibration test (*7a*) is done once for all three axes (axial, lateral and vertical) with a duration of 2 minutes per axis to a maximum level of $0.02g^2$/Hz. These tests are done with the IFP assembly attached to the Seeker. The IFP Flight Worthy vibration test is an identical test to the Seeker Flight Worth vibration test and uses the same input loads. The difference is that only one of the lateral direction is investigated and the IFP assembly is not attached to the Seeker. It also has the same duration and g level. The PSD used in the analysis represents the envelop of acceleration data from all the mount points from these tests.

The MCR Vibration Screening environment (*7b*) is applied in a lateral direction only and is applied to the MCR only (no IFP bracket). Thus, a FE model of only the MCR (and its components) was used. The MCR is tested alone, mounted on a titanium block. The duration of this test is 9 minutes to a maximum of $0.04g^2$/Hz in the one axis.

The other tests done (*7c & 7d*) are the same as the Seeker Flight Worth tests where the IFP assembly is mounted to the Seeker, again applied all axis directions. The PSDs used however, are referred to as "notched" because the resonate frequency at 260 Hz is purposely reduced, which is more representative of reality. These "notched" tests have the same duration and g levels as the "un-notched" tests. Thus, they should prove less damaging than the "un-notched" tests.

Figure 7e represents the actual flight environment PSD to which we wish to know how much life remains after testing.

Each acceleration load input PSD was exported from an Excel spreadsheet in the form of a text file and easily imported into the MSC/FATIGUE loading database manager.

Cyclic Material Properties

Cyclic material properties of the solder are shown in *figure 8*. The material is a eutectic (ordinary) solder with 63% tin, 37% lead makeup (4). The S-N curve shown is the damage curve used to look up damage once damaging stress cycles have been identified through a procedure called rainflow cycle counting. This curve was easily defined in MSC/FATIGUE's material database manager

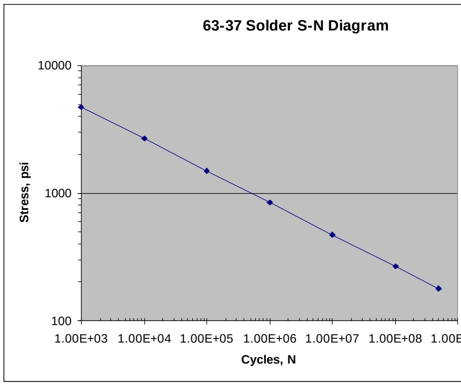


Figure 8

Vibration Fatigue Analysis

With the three major inputs to the fatigue analysis defined, it is a relatively straightforward task to perform the life calculations. Once the TFs have been calculated by MSC/NASTRAN, they are imported into the MSC/PATRAN database where the FE model resides. The acceleration load input PSDs are imported to the MSC/FATIGUE loading database. The S-N curve is defined in the MSC/FATIGUE materials database. The interface to MSC/FATIGUE is fully accessible through MSC/PATRAN and allows for specification of the S-N curve and the acceleration input PSDs can be associated to the appropriate TFs. When the analysis is requested, MSC/FATIGUE actually does the random vibration analysis by multiplying the TFs by the input load PSDs to calculate the stress response PSDs.

MSC/FATIGUE gives you the ability to select the stress invariant that you would like to use in the fatigue calculation. This can range from a single stress component such as the x, y, or z-direction or a combination parameter such as absolute maximum principal or von Mises. MSC/FATIGUE has the ability to determine these invariant stresses from the component stresses of the complex TFs taking into account the phase. The reader is referred to the MSC/FATIGUE User's Guide for more details on these calculations (3). The maximum absolute principal was used in these calculations, although a comparison to von Mises was also done. Either of these gives slightly more conservative answers than selecting the worst case component direction. Some of the output stress response PSDs due to the various PSD inputs are shown for the same element location as the previous TF plot in *figure 9*.

In addition, the user has various fatigue analysis options from which to chose from in the actual life calculation. Three of them are mentioned here. The first is the traditional Narrow Band method. This method presupposes that the output response PSD is narrow band in nature (one dominant frequency). If the response is wide or broad band in nature (more than one dominant frequency), then the answers will tend to be on the conservative side, sometimes to an extreme. A narrow band signals, when viewed in the time domain, appears to have a single frequency where the outside envelope oscillates slowly in the same fashion on both the positive and negative sides. In other words, a narrow band signal tend to have a negative peak (or valley) of roughly the same magnitude as the previous positive peak through out the entire signal. The reason the approach is sometimes overly conservative is that if the signal is not truly narrow band, but is tending towards wide band, it essentially converts the wide band signal to a narrow band signal by assuming there is a negative peak of roughly the same magnitude as the previous positive peak and creating an artificially large number of damaging stress cycles.

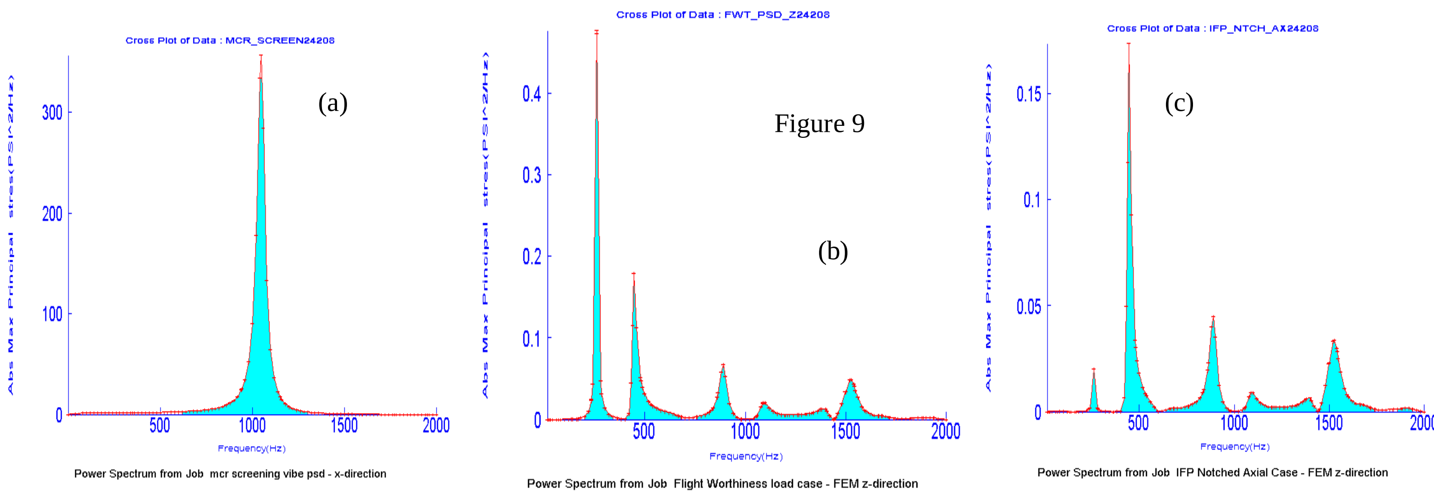


Figure 9

The next method is the Steinberg method, commonly used in electronic fatigue calculations. This method uses the three-banded technique and assumes a Gaussian distribution for the probability density function (PDF) of rainflow cycles. This is actually a crude guess at the actual PDF of rainflow cycles, which, in fact, is not Gaussian. All stress cycles falling within 1σ of the rms level are grouped in the first band and given a probability of occurrence. Correspondingly, any cycles falling in the 2σ or 3σ ranges of the rms level are grouped into the second and third bands respectively with their corresponding probabilities of occurrence. Any cycles above this are ignored. Generally this will tend to give conservative answers, but because the higher stress levels being ignored, it could also lead to non-conservative answers.

The final method, and the one considered in the analysis of the PAC-3 is the Dirlik method. It can handle any type of signal, from narrow to wide band and is generally applicable. The PDF of rainflow cycles is an empirical fit based on the observation of many signals. For this reason it makes to best fit to most any response PSD and gives more realistically close answers to reality as opposed to be overly conservative.

Three fatigue analyses are performed corresponding to the three Flight Worthy test environments in the three principal axis directions. Three more are performed, equivalent to the Flight Worthy test (FWT) environments, except that the resonate frequency is purposely reduced. This can be seen in the response PSDs in *figure 9b* and *9c* where the first contributing frequency at around 260 Hz *9b* is considerably attenuated from that in *9c*. Also, it would be expected that the analyses using the "notched" input load would be less damaging than the "un-notched," which is generally the case as shown in *table 1*.

Another analysis is that of the MCR Vibration Screening environment. Because of the g levels attained in this test, it is expected that this should be the most damaging event. Again this is confirmed by the analysis results.

The final analysis is that of the actual flight environment. There is no corresponding test to this analysis. In *table 2*, a comparison between the three above mentioned analysis methods is made. Note that the MCR Vibration Screening environment test appears to be fairly narrow band in nature. This would suggest that perhaps either three of the methods would give close answers. The results confirm this. But because the other responses are in no way narrow band, answers from the methods other than Dirlik are out by a factor of two at least on the conservative side. The "notched" and "un-notched" Y-direction runs show close correlation between the three methods, but this is because if you look at the responses, they are fairly narrow band, but not quite. Perhaps this explains why the "notched" is more damaging than the "un-notched," since there was very little frequency content at the notching frequency to begin with. The procedure used to notch the frequency content must have added more energy somewhere else.

Table 1 Fatigue Analysis Results for Top 3 Damaged Elements

Element	Damage/sec	Life (Minutes)	Irreg. fact	Root M0 (PSI)	Log damage	Log life
Flight Worth Environment Un-notched, FEM x-direction						
27820	6.673E-7	25,000	0.3636	72.69	-6.1757	6.1757
24208	5.274E-7	31,600	0.3672	67.05	-6.2779	6.2779
26373	1.462E-7	114,000	0.4509	47.79	-6.8349	6.8349
Flight Worth Environment Notched, FEM x-direction						
24208	2.496E-8	668,000	0.6412	25.97	-7.6028	7.6028
27820	1.704E-8	978,000	0.5727	24.79	-7.7685	7.7685
26373	9.982E-9	1,670,000	0.6945	20.71	-8.0008	8.0008
Flight Worth Environment Un-notched, FEM y-direction						
27820	1.26E-5	1,322	0.9262	108.4	-4.8995	4.8995
24208	8.444E-6	1,974	0.9272	97.99	-5.0735	5.0735
26373	4.608E-6	3,617	0.9256	84.46	-5.3365	5.3365
Flight Worth Environment Notched, FEM y-direction						
27820	1.99E-5	837	0.9688	117.6	-4.7011	4.7011
24208	1.323E-5	1,260	0.969	106.2	-4.8785	4.8785
26373	6.891E-6	2,418	0.9677	90.41	-5.1617	5.1617
Flight Worth Environment Un-notched, FEM z-direction						
27820	5.802E-11	287,000,000	0.6882	6.685	-10.236	10.236
24208	2.568E-11	649,000,000	0.632	5.821	-10.59	10.59
26373	2.172E-11	767,500,000	0.7335	5.545	-10.663	10.663
Flight Worth Environment Notched, FEM z-direction						
27820	5.53E-12	3,013,000,000	0.7754	4.421	-11.257	11.257
24208	2.146E-12	7,768,000,000	0.7242	3.861	-11.668	11.668
26373	1.752E-12	9,513,000,000	0.7843	3.735	-11.756	11.756
MSC Vibration Screening Environment, FEM x-direction						
24208	6.649E-5	250	0.9733	173.2	-4.1772	4.1772
27820	2.669E-5	624	0.9733	137.9	-4.5736	4.5736
26373	2.523E-5	660	0.9733	135.9	-4.5981	4.5981

Table 2 Comparison of Fatigue Analysis Methods – Element 24208

Life in Minutes	Dirlik	Narrow Band	Steinberg
FWT Un-notched X-dir.	32,650	9,185	8,615
FWT Notched X-dir.	670,000	316,000	296,000
FWT Un-notched Y-dir.	1,978	1,643	1,542
FWT Notched Y-dir.	1,263	1,171	1,098
FWT Un-notched Z-dir.	650,000,000	305,000,000	271,000,000
FWT Notched Z-dir.	7,786,000,000	4,643,000,000	4,690,000,000
MSC Vib. Screen X-dir	251	237	223

Damage Summation

The final task is to sum the damage from all events to ensure that the solder joints on the IFP assembly can withstand all tests to which they are subjected. Table 3 shows three actual test sequences (histories) in which three separate Seeker/IFP/MCR assemblies were tested. For example, the first row indicates that the Seeker with serial number 14 and MCR serial number 19 was subject to three MCR Vibration Screening tests, on "un-notched" FWT test (in each of the three axes), and one "notched" FWT test (in each of the three axes). Obviously row two is the worst case. The percentage of remaining life (for most critical element) is also indicated based on the analyses performed which is simply Miner's constant less the total summed damage. This is explained in more detail.

Table 3 Seeker/MCR Vibration Test History

Seeker Serial #	MCR Serial #	# of MCR Vib. Tests	# of IFP Vib. Tests	# of SKR Vib. Tests Un-notched	# of SKR Vib. Tests Notched	Percentage Life Remaining
14	19	3	0	1	1	89%
15	11	5	1	6	2	81%
16	14	5	0	1	1	82%

The IFP Vib. Test is the same as an Un-notched test in the lateral (FEM x-direction) only.

The damage from each test can be summed using the Palmgren-Miner linear damage summation rule which states:

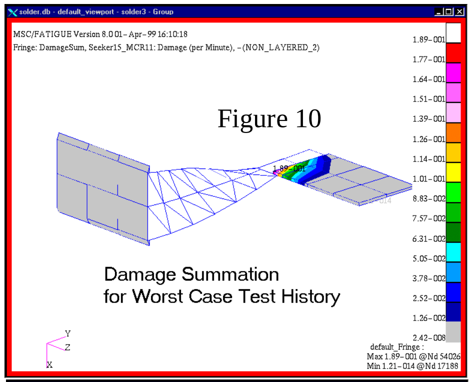
$$\Sigma(D_i) = \Sigma(n_i/N_i) \geq C$$

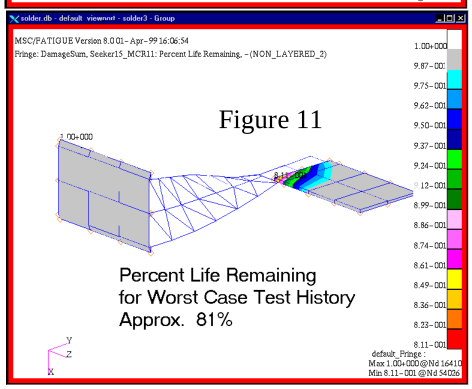
The damage (D_i) from any one event (test) is equal to the ratio of the actual time of the test divided by the total time to failure, determined by each fatigue analysis. When the sum of these ratios equals the Miner's constant C, usually defined at 1.0, failure is said to have occurred. Miner's constant can take on values from 0.5 to 2.0 depending on how conservative (or non-conservative) you wish to be. The procedure take was:

1. Determine the total time the solder is subjected to each test. Defined by *table 3*.
2. Determine the total life due to each test environment using MSC/FATIGUE.
3. Divide the test time by the total life for each test. This gives the n_i/N_i in Miner's rule (and thus the damage) corresponding to each test, i.
4. Sum the damage from each test ($\Sigma n_i/N_i$). This gives the total damage for each test history in. (On a side, if you take the reciprocal of this number, it indicates the total life that the solder joint lasts if you continually subjected it to the same test history.)
5. Subtracting the total damage from Miner's constant gives the percentage life remaining.
6. The analysis done using the flight vibration environment is the total life the solder lasts if only subjected to this environment. Multiplying the percentage of remaining life by the predicted life due

to the flight vibration gives the life remaining if only subjected to the flight vibration from that point on.

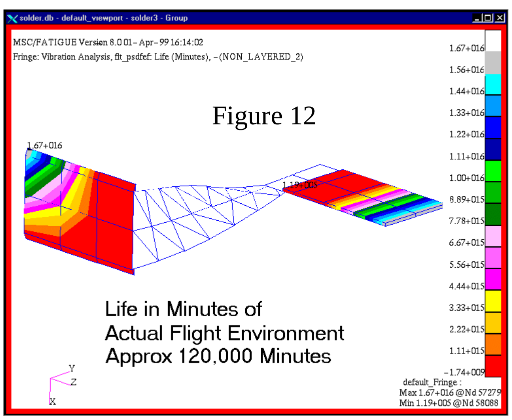
Although seven separate fatigue analyses were performed, it is simple to sum the damage from each using the Results application in MSC/PATRAN. Results from each of the fatigue runs are read into the MSC/PATRAN database for all elements of the solder joints. A linear summation of damage (damage/sec) is done with each individual damage result case being scaled by the appropriate time duration of each test as per *table 3*. This gives the total damage. This is done for each vibration test history. A graphical plot of damage/min. (summation) for the worst case test history is shown in *figure 10*. To convert damage/min. into $\log_{10}$ values of life in minutes, each new result case of summed damage was modified according to the equation LOG (1/damage)/60). This was done using PCL (PATRAN Command Language) within the Results application. This is not of particular interest to us though since all it will tell us is how long a particular test history might be repeated.



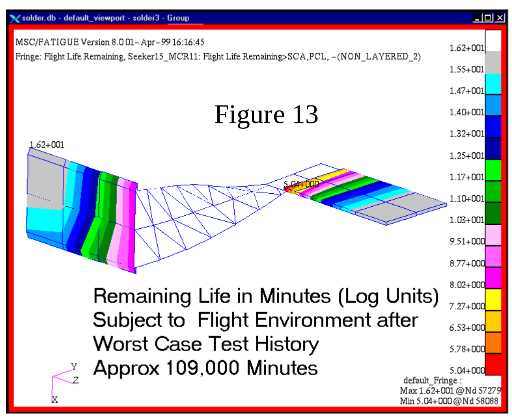


What we want is the percentage of life remaining. This was also done with a PCL equation in the Results application and shown in *figure 11*. The equation used this time was Miner's constant (C) of 1.0 less the damage (C - damage).

The final step was to convert the total life of the flight environment analysis from seconds to minutes (shown in *figure 12*), then to multiply the "percent of life remaining" by the total life of the flight environment. This is shown in *figure 13*. The life has been converted to log units. So the results for the three test histories is summarized in *table 4*. Note that both Elements 27820 and 24208 are listed because it was impossible to tell from any single analysis which would be the worst case. It turns out that Element 24208 has the least amount of life remaining, whereas the other analyses would have lead you to believe that the other element would have been the critical one.



Note: Actual flight time is generally around three minutes or less.



Conclusions

In the exercises performed in this study, it is clear that the solder joints for the IFP assemblies have not expended their useful life. Subjecting them to more vibration in actual flight should not pose any risk. The most damaging event is the MCR Vibration Screening. In fact, the damage from this event alone accounts for roughly 90% of the damage. MSC/FATIGUE was also very handy in identifying the actual critical locations, which is difficult to do by observing the rms stress levels alone. MSC/NASTRAN frequency response analysis together with the visualization capabilities of MSC/PATRAN and the vibration fatigue analysis capabilities of MSC/FATIGUE provide a powerful tool to the engineer. Maximum absolute principal stresses were used as the stress parameter for damage lookup in all these problems. Subsequent analyses using von Mises stresses showed slightly more conservative answers, but not enough to draw different conclusions. All analyses were done using element centroidal stresses. This was done mostly for comparison purposes with other independent investigations into the fatigue life based simply on the rms stresses which are reported from MSC/NASTRAN at the element centroid. Investigation using nodal stresses gives more conservative answers, but again, not to any degree that would alter the conclusions of this study.

MSC/FATIGUE provides an easy and simple method of predicting fatigue life from random vibration analysis. As many electronic components are required to go through vibration screening and flight qualification tests before they are signed off, the goal is to have these tests pass the first time. It is especially useful for determining before hand, whether a given test will pass. This has the potential to avoid costly problems of redesign down the road. MSC/FATIGUE can be used to design electronic components against premature failure when subject to random excitation well before physical assembly such that this goal can be accomplished.

Table 4 – Damage Summation and Remaining Life

SEEKER S/N	MCR S/N	NO. OF MCR VIBE TESTS	NO. OF IFP VIBE TESTS	NO. OF SEEKER VIBE TESTS: UN-NOTCHED x	UN-NOTCHED y	UN-NOTCHED z	NOTCHED x	NOTCHED y	NOTCHED z
14	19	3	0	1	1	1	1	1	1
15	11	5	1	6	6	6	2	2	2
16	14	5	0	1	1	1	1	1	1

		Test Time (Minutes)								Total
14	19	27	0	2	2	2	2	2	2	39
15	11	45	2	12	12	12	4	4	4	95
16	14	45	0	2	2	2	2	2	2	57

	Life (Minutes)								Flight Life (Minutes)
Elem 27820	624	24,976	24,976	1,323	3.E+08	978,091	838	3.E+09	119,000
Elem 24208	251	31,602	31,602	1,974	6.E+08	667,735	1,260	8.E+09	147,000

		Damage Ratios (Elem 27820)								Damage Sum	Life Remaining for Flight (Miners Constant C) 0.7	1.0	1.3
14	19	0.04324	-	0.00008	0.00151	0.00000	0.00000	0.00239	0.00000	0.04722	77,681	113,381	149,081
15													

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