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Vibration Fatigue Evaluation on Solder Joints of Under-Filled BGA

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Abstract
A previously developed ball grid array (BGA) solder joint vibration fatigue life prediction model, which was experimentally validated by Test Vehicle One (TV1) test data for the BGAs with and without under-filled materials, has been used to determine the solder joint integrity of BGAs. However, the newly obtained TV2 test results show that this previously developed life prediction model has a tendency to under estimate the fatigue life of BGA solder joints. Therefore, there is a need to re-validate the previously developed life prediction model and it then becomes the objective of the present study.

A TV2, on which various sizes of BGA daisy-chained packages with/without under-filled materials (including non-reworkable and reworkable) are soldered, is designed, fabricated and subjected to random vibration tests with continuously monitoring the solder joint integrity. Based on the measurement results, a destructive physical analysis is conducted to further verify the failure locations and crack paths of the solder joints. The previous developed life prediction model combined with a finite element analysis is re-calibrated by the TV2 test results. This updated model is then recommended to serve as an effective tool to determine the solder joint integrity of the BGAs (with/without under-filled materials) during vibration. The determination of the relationship between the BGA solder joint fatigue life and the elastic modulus of under-filled material is illustrated. The analysis results show that BGA fatigue life exponentially increases as the elastic modulus of under-filled material increases to a certain threshold value and this relationship can be used to select the under-filled material for improving BGA solder joint vibration fatigue life.

Introduction
An experimentally validated ball grid array (BGA) vibration fatigue life prediction model, calibrated by Test Vehicle One (TV1) test data,[12, 13, 14, 15] was developed to evaluate the effects on the durability/reliability of the 1.27 mm-pitch BGA with/without under-fill materials. However, the use of a finer pitch (less than/equal to 1 mm) BGA in electronic package design becomes more popular due to their significant reduction of substrate interconnect area. The smaller the pitch, the smaller the BGA solder ball. This condition can further reduce the already-less compliant interconnect between the BGA component and the substrate and could result in a higher failure risk in the BGA solder joint over vibration environments. To further study this risk, Test Vehicle two (TV2), on which various sizes of BGA daisy-chained packages (with 0.8 mm, 1.0 mm, and 1.27 mm pitches) are soldered, was designed, fabricated and subjected to random vibration tests. A destructive physical analysis was then followed to verify the failure locations and crack paths of the solder joints. The TV2 test results[16] were summarizes, which show that a 580-pin BGA (whose pitch is 1 mm) solder joint can survive vibration test. However, a previously developed life prediction model[15] indicates that the solder joint failure of this package would occur under the vibration test. This model is also used to predict the vibration fatigue life of 313-pin PBGA (with 1.27 mm pitch) in TV1. The predicted life is less than the test observation[15] and both of them are summarized in the 1st two columns of Table 1. Therefore, this model has as a tendency to under estimate the fatigue life of the BGA solder joints; hence, there is a need to re-calibrate the previously developed life prediction model and it then becomes the objective of the present study.

Some understanding of other solder joint vibration fatigue and life-predicting capabilities can be obtained.[2, 5, 6 10] A theoretical background of the random vibration can also be found.[7, 8, 11]

Table 1 – Solder Joint Life of 313-pin PBGA in TV1

Test Data	Prediction from Wong et al. (2000b)	Prediction from Updated Model
67.8 minutes	26.3 minutes	48.6 minutes

Experiment

A TV2 is designed and constructed as shown in Figure 1. The configurations of this test vehicle include the parameters of under-filled materials (no under-filled, reworkable or non-workable under-filled), PWB solder pad sizes (nominal or ±10% nominal), and part rework (no or yes). The parts list is shown in Table 2. The PWB material is high Tg FR-4. Note that the elastic modulus of reworkable is 1.12 GPa. The total of 14 types of TV is used in the present study.

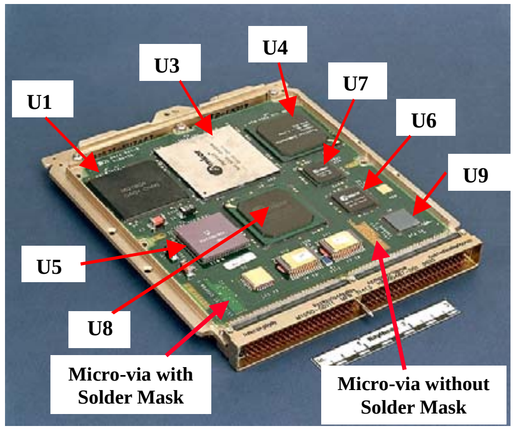


Figure 1 – TV2 Configuration

Table 2 – TV 2 Parts List Spreadsheet[16]

Component	Ref. Des.	Pitch (mm)	Ball Dia. (mm)	Body Size sq. (mm)	Die Size sq. (mm)
TBGA-352	U1	1.27	0.75	35.0	N/A
SBGA-600	U3	1.27	0.75	45.0	N/A
PBGA-313	U4	1.27	0.76	35.0	7.73
CBGA-360	U5	1.27	0.89*	25.0	N/A
flexBGA-280	U6	0.80	0.48	16.0	9.76
PBGA-256	U7	1.00	0.50	17.0	5.13
PBGA-580	U8	1.00	0.63	35.0	20.36
Flip Chip-96	U9	0.46	0.20	12.7	N/A

*** 1.62 mm height**

The setup for vibration test is shown in Figure 2. Nine (9) accelerometers, evenly spaced, are mounted on the surface of the TV2 to measure the dynamic response characteristics of the TV2 (resonant frequencies and transmissibilities)) for the vibration input test profiles shown in Figure 3. A total of 22 modules are subjected to z-axis (normal to PWB) random vibration. Prior to actual testing, each module is subjected to a pre-survey 1 g sine sweep, 10–2000 Hz, and 1 octave/minute. Figure 4 shows a typical sinusoidal vibration response from accelerometer at the center of the TV2. This figure shows that the 1st mode frequency is 573 Hz with transmissibility equal to 36.7. During the vibration test, the TV2 is connected to an Anatec Event Detector and computer to monitor electrical opens. A resistance threshold of 1000 ohms and spike duration of 0.2 microseconds, for fifteen consecutive evidences, constituted a failure. This higher resistance threshold is selected to overcome the noise effects during the vibration.

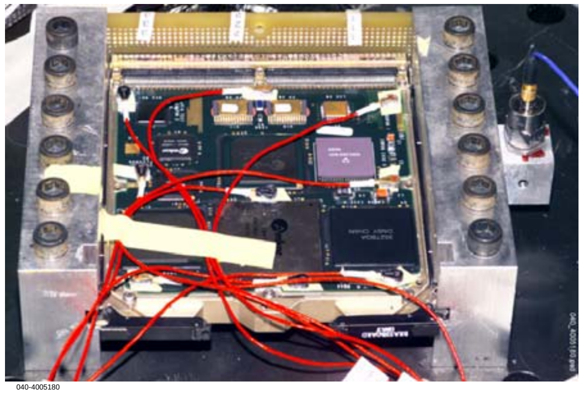
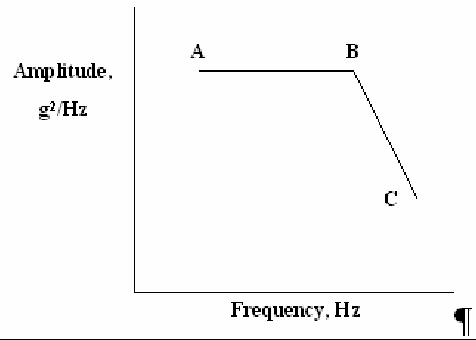


Figure 2 – TV2 Vibration Test Setup



Level	Freq. (Hz)/Amplitude (g²/Hz)			Total Grms	Duration, min.
	A	B	C		
1	50/.04	1000/.04	2000/.01	7.71	60
2	50/.08	1000/.08	2000/.020	10.90	60
3	50/.16	1000/.16	2000/.040	15.41	To failure (120 max.)

Figure 3 – Random Vibration Inputs and Test Duration

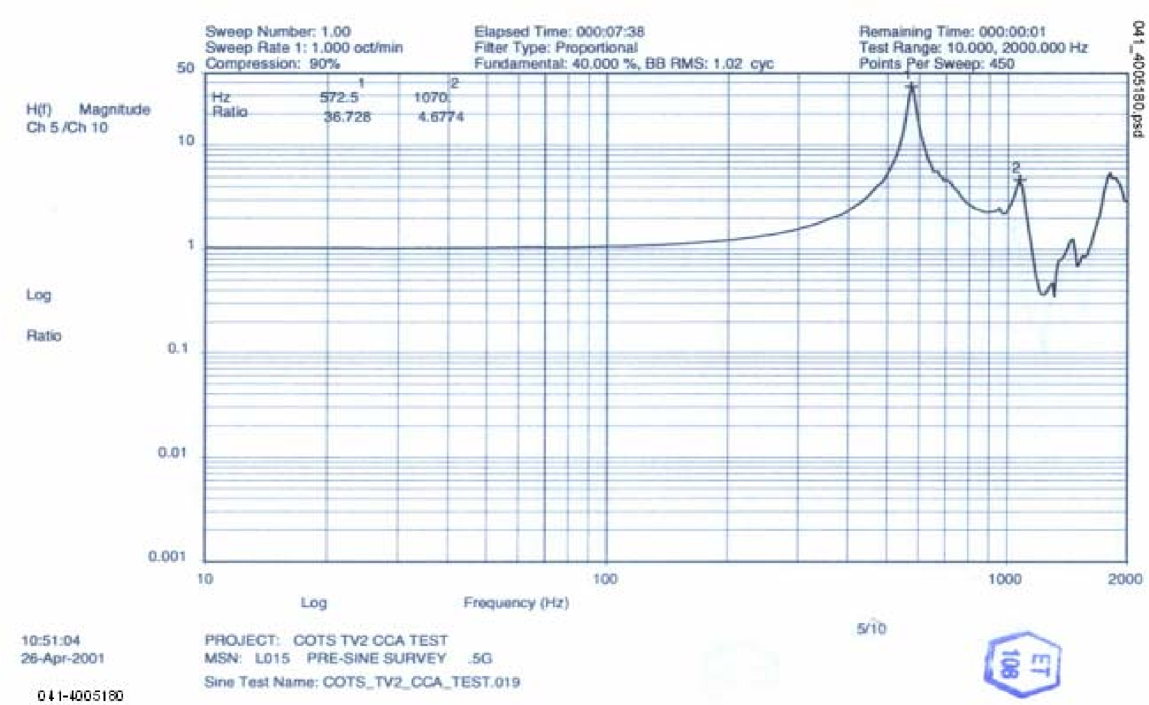


Figure 4 – Typical Transmissibility Plot at the Center of the TV2 during a 1 g Sinusoidal Sweep

The failure map of the random vibration test results is shown in Figure 5. Table 3 shows that the 352-pin TBGA (U1) and 600-pin SBGA (U3) are more susceptible to failure than PBGAs under the same conditions and that the use of under-filled materials (including reworkable and non-reworkable) appears to improve the life expectancy of all the components. The stiffer packages of TBGA and SBGA, which have copper heat spreaders, may account for higher BGA solder joint stress/strain during random vibration tests. A finite element analysis in next section will be conducted to verify this hypothesis. Note that no solder joint failure is observed in finer-pitch BGAs. Due to insufficient data on solder joint failures, the mean-cycle-to-failure cannot be derived.

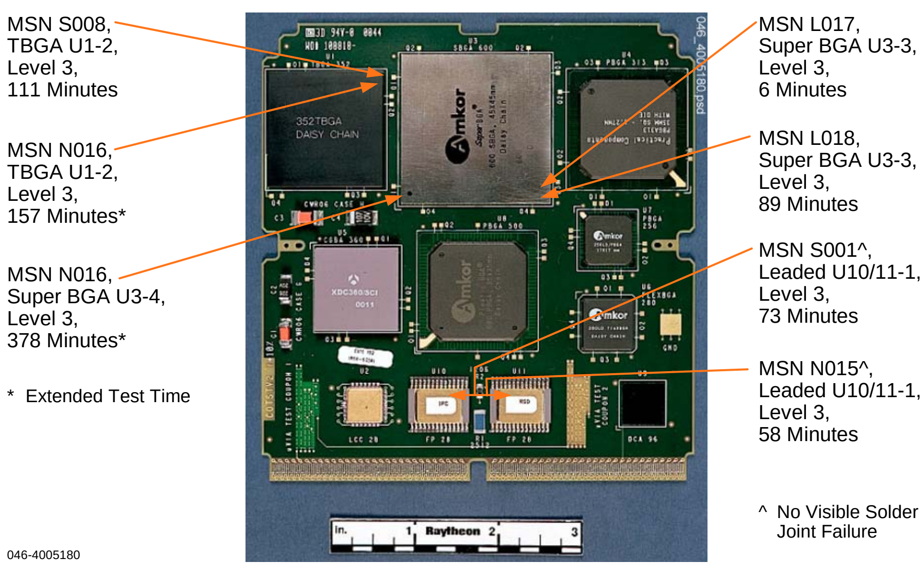


Figure 5 – Failure Map of TV2 Random Vibration Test

Table 3 – Comparison of Failures in Random Vibration Test

Under-filled Material	PWB Solder Pad Size	Rework Parts (U3,5,7)	CCA #	Min.@failure								
				U1:352-pin TBGA				U3:600-pin SBGA				U10/ U11
				1	2	3	4	1	2	3	4	
None	Nominal	No	N016^, N023	*	157	*	*	*	*	*	378	*
		Yes	N007	*	*	*	*	*	*	*	*	*
	+10%	No	L017, L018	*	*	*	*	*	*	6,89	*	*
		Yes	L019	*	*	*	*	*	*	*	*	*
	–10%	No	S018, S019	*	*	*	*	*	*	*	*	*
		Yes	S008	*	111	*	*	*	*	*	*	*
Reworkable	Nominal	No	N015, N019	*	*	*	*	*	*	*	*	58
		Yes	N/A	-	-	-	-	-	-	-	-	-
	+10%	No	N/A	-	-	-	-	-	-	-	-	-
		Yes	N/A	-	-	-	-	-	-	-	-	-
	–10%	No	S001, S012	*	*	*	*	*	*	*	*	73
		Yes	N/A	-	-	-	-	-	-	-	-	-
Non-Reworkable	Nominal	No	N010, N013	*	*	*	*	*	*	*	*	*
		Yes	N021	*	*	*	*	*	*	*	*	*
	+10%	No	L012, L015	*	*	*	*	*	*	*	*	*
		Yes	L021	*	*	*	*	*	*	*	*	*
	–10%	No	S014, S015	*	*	*	*	*	*	*	*	*
		Yes	S010	*	*	*	*	*	*	*	*	*

Note: '157' means solder ball failed under level 3 random vibration (15.4 Grms) at 157 minutes.
*** Testing only performed to 120 minutes, no failure observed.**
^ Denotes module subjected to extended testing.

1	2
4	3

Failure locations at BGA

A destructive physical analysis is conducted to further verify the failure locations and crack paths of the solder joints. The results are consistent with test measurements (by Anatec Event Detector). Figure 6 shows a micro-section of one of the corner solder joints in the 600-pin SBGA. Solder cracks are observed along the PWB solder pad, and at the package side. The detailed information of TV2 configuration, vibration test setup/inputs/results, and DPA results can be found[16] and will be utilized to calibrate a vibration fatigue damage model in next section.

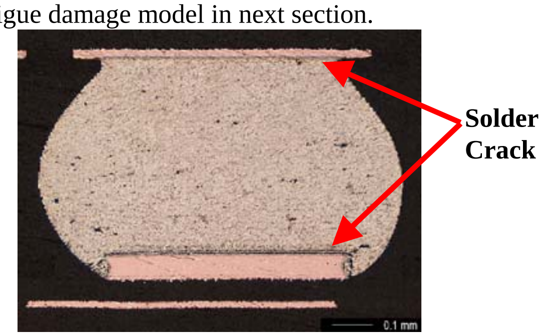


Figure 6 – Microsection of Failed Solder Joint in 600-pin SBGA

Vibration Fatigue Damage

The author[16] describes a methodology to support test validation of BGA solder joint vibration fatigue life prediction model. A 3-D macro/micro modeling technique is used to simulate the random vibration responses of TV. This model is then calibrated with measured fundamental frequencies and their responses. The effective strains of the BGA solder joints using a type of von Mises relationship and a volume-weighted average technique are derived using the calibrated model.

In the methodology development, a random vibration analysis is conducted to obtain the complex frequency response of the six principal components of strain (represented as ε_1, ε_2, ε_3, τ_4, τ_5, and τ_6) to a sinusoidal one gravity input acceleration for each solid element using the analysis code[19]. These strain transfer functions are then utilized to develop the effective strain transfer functions by employing the type of von Mises relationship:

$$\frac{9}{2}|H(\varepsilon_{eff})|^2 = |H(\varepsilon_1) - H(\varepsilon_2)|^2 + |H(\varepsilon_2) - H(\varepsilon_3)|^2 + |H(\varepsilon_3) - H(\varepsilon_1)|^2 + 1.5\left[|H(\tau_4)|^2 + |H(\tau_5)|^2 + |H(\tau_6)|^2\right] \tag{1}$$

This equation is slightly different from Eq. (2)[15]. The rest of calculations to obtain an average effective strain over all the elements in the critical layer, which is expressed in the following equation,[15] (see Eq. (3) through Eq. (9)):

$$\varepsilon = \frac{\sum \varepsilon_{eff,e} V_e}{\sum V_e}, \tag{2}$$

where V_e is the element volume.

A 3-D macro/micro finite element model (FEM) of the electronic module, shown in Figure 7, is constructed to simulate major structural elements and to determine the module dynamic responses when subjected to an excitation normal to the PWB. Five types of BGA packages soldered onto the PWB are shown in this figure. Table 4 lists the material properties of aluminum, polyimide/glass, copper, 63Sn/37Pb solder, dry film solder mask, polyimide tape, alumina, silicon, mold compound, epoxy adhesive, reworkable under-fill, and heat sink adhesive.[1,3,4,9]

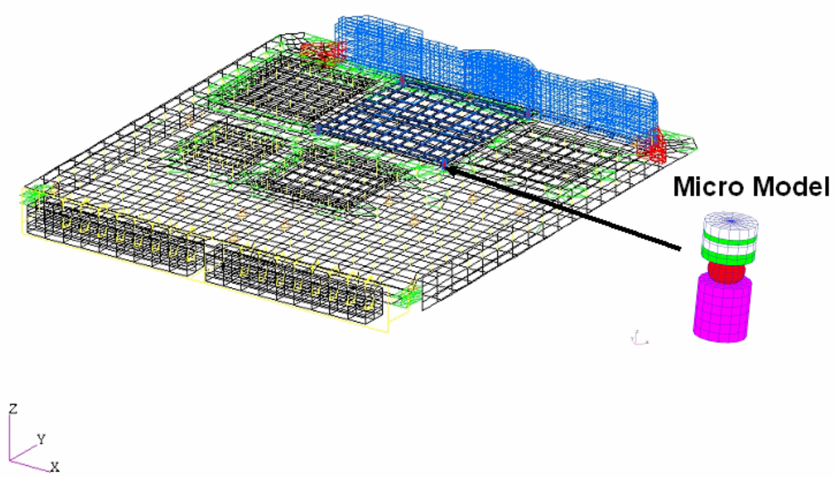


Figure 7 – 3-D Macro/Micro Finite Element Model

Table 4 – Material Properties

Material	*Tensile* **Modules, GPa**	**Shear Modulus, GPa**	**Poisson's Ratio**
Aluminum	**68.9**	**25.9**	**0.33**
FR-4	**16.9 (X & Y)** **7.44 (Z)**	**3.03 (XY)** **2.41 (YZ & ZX)**	**0.129 (XY)** **0.417 (YZ)** **0.183 (ZX)**
Copper	**117**	**44.0**	**0.33**
63Sn/37Pb Solder	**30.2**	**10.8**	**0.4**
Solder Mask	**4.89**	**1.72**	**0.4**
Polyimide Tape	**14.5**	**6.27**	**0.16**
Alumina	**303**	**125**	**0.21**
Silicon	**131**	**50.4**	**0.3**
Mold Compound	**12.5**	**4.82**	**0.3**
Heat Sink Adhesive	**0.00276**	**0.00095**	**0.45**
Reworkable Under-fill	**1.12**	**0.4**	**0.4**

A random vibration analysis is applied in the macro/micro model. This model is then calibrated by matching the analysis results with the vibration test measurements obtained in the previous section, i.e., natural frequencies and their corresponding amplitudes. Note that this modeling calibration is achieved by adjusting the model boundary conditions and the damping for each of natural frequencies. Linear static and dynamic finite element analyses with computer code[19] are conducted to calculate the effective strains of the solder joints. In the calculation process, several in-house developed Fortran programs, in conjunction with the outputs obtained from static[19] and frequency response analyses, are used to perform the required computations. Finally, a previous vibration fatigue life model[15] is used with two unknown parameters, which can be determined by correlating the derived solder effective strains to the TV2 test data. The experimentally validated BGA vibration fatigue life prediction model is described as below.

$$\boldsymbol{k\varepsilon = N_k^{-c}\left(\frac{A_i}{A_D}\right)^{c}} \qquad (3)$$

where k=1, 2 and 3, ε=strain amplitude, N=fatigue cycles, c=0.5128, A_D=0.2555 mm^2, and A_i is the solder crack surface in mm^2. The corresponding number of fatigue cycles of random vibration is obtained by multiplying the times by the maximum of the number of positive zero crossings (N_0^+). Thus, for a total of T hours of random vibration, the number of applied cycles is calculated from the following equations:

$$\begin{aligned} &\boldsymbol{n_1 = N_0^+ T}(3600\sec/\boldsymbol{hr})(.6831) \\ &n_2 = N_0^+ T(3600\sec/hr)(.271)\text{, and} \\ &n_3 = N_0^+ T(3600\sec/hr)(.0433) \end{aligned} \qquad (4)$$

The cumulative damage index (CDI) using Miner's cumulative damage law, assuming a linear summation of damage, can be obtained as

$$CDI = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}. \qquad (5)$$

"Failure" is predicted when the CDI has a value greater than or equal to a critical value, usually chosen as 0.5.

Using the updated fatigue life prediction model, the CDIs of the 352-pin TBGA and 600-pin SBGA with and without reworkable under-filled material are calculated when the TV2 subjected to the random vibration input, and the CDIs along with predicted and tested fatigue lives are summarized in the last three columns of Table 5. This table indicates that: 1) the predicted fatigue lives are reasonably consistent with the tested observations; 2) the use of the reworkable under-filled material can improve BGA fatigue life; 3) the fatigue life of 600-pin SBGA is less than that of 352-pin TBGA; and 4) the 1st failure location of 352-pin TBGA is predicted at the lower-right corner solder ball, which is inconsistent of test observation (this inconsistency could be due to the varied configurations in the solder joints induced by manufacturing process, package warpage, etc.). The effect of the under-filled stiffness impacts on the BGA fatigue life is also evaluated and the predicted result for 600-pin SBGA is shown in Figure 8. This figure indicates that: 1) the solder joint vibration fatigue life increases as the elastic modulus of under-filled material increases; and 2) the fatigue life would significantly increase when the elastic modulus of the under-filled material is larger than 7 GPa. Therefore, the updated fatigue life prediction model can be used to select the under-filled material for improving BGA solder joint vibration fatigue life. In addition, the vibration fatigue life of the 313-pin PBGA in TV1 is estimated using the updated life prediction model and is summarized in the last column of Table1. This table shows that the prediction life from the updated model is less conservative than that from the previous model.[15]

Table 5 – Predicted and Tested Vibration Fatigue Life Comparison

Package	Solder Ball Location	CDI	Predicted Fatigue Life, hours	Tested Fatigue Life, hours
TBGA 352 without Underfill	1	0.167	1.91	1.85
	2	0.203		
	3	0.524		
	4	0.142		
TBGA 352 with Reworkable Underfill	1	0.086	7.94	> 2 (No failure observed)
	2	0.126		
	3	0.055		
	4	0.016		
SBGA 600 without Underfill	1	0.122	1.25	1.48
	2	0.101		
	3	0.743		
	4	0.803		
SBGA 600 with Reworkable Underfill	1	0.070	1.74	> 2 (No failure observed)
	2	0.055		
	3	0.513		
	4	0.567		

Note: under level 3 random vibration (15.4 Grms)

1	2
4	3

Failure locations at BGA

Figure 8 – 600-pin SBGA Solder Joint Vibration Fatigue Life vs. Elastic Modulus of Under-filled Material

Summary and Recommendation

Linear dynamic and static analyses, combined with TV2 test results, are conducted to support the re-calibration of the previously developed vibration fatigue damage model[15] for BGA solder joint assembly (with/without under-filled material). A TV2, on which various sizes/pitches of BGA daisy-chained packages are soldered, is first constructed and subjected to random vibration tests with continuously monitoring the solder joint integrity. Based on the measurement results, a destructive physical analysis is then followed to further verify the failure locations and crack paths of the solder joints. Next, a 3-D modeling technique is used to estimate the strains of the BGA solder joints, resulting from the exposure of electronic modules to the random vibration environments. This technique is implemented by the utilization of the several in-house developed Fortran computer programs, which, in conjunction with the outputs obtained from MSC/NASTRAN™ static and frequency response analyses, perform the required computations. The Fortran computer codes allow the users to obtain the average effective strains of the BGA solder joints.

The previous developed vibration fatigue damage model of BGA solder joint with 1.27 mm pitch,[15] combined with a three-band technique and the derived solder effective strains, is used to predict the BGA solder joint survivability/durability. This prediction is compared to TV2 test results (including finer-pitch BGAs) to re-calibrate the previous vibration fatigue damage model. The analysis results, obtained from the updated model, show that: 1) the predicted fatigue lives are reasonably consistent with the tested observations; and 2) the use of the under-filled material can improve BGA fatigue life. Since this updated fatigue damage model has been qualitatively validated by test, this model could be used and is recommended to serve as an effective tool to determine the solder joint integrity of BGAs (with/without under-filled materials) during vibration. In addition, the relationship between the BGA solder joint fatigue life and the elastic modulus of under-filled material is evaluated. The analysis results show that BGA fatigue life exponentially increases as the elastic modulus of under-filled material increases to a certain threshold value and this relationship can be used to select the under-filled material for improving BGA solder joint vibration fatigue life.

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19. MSC/NASTRAN™

Vibration Fatigue Evaluation on Solder Joints of Under-filled BGA

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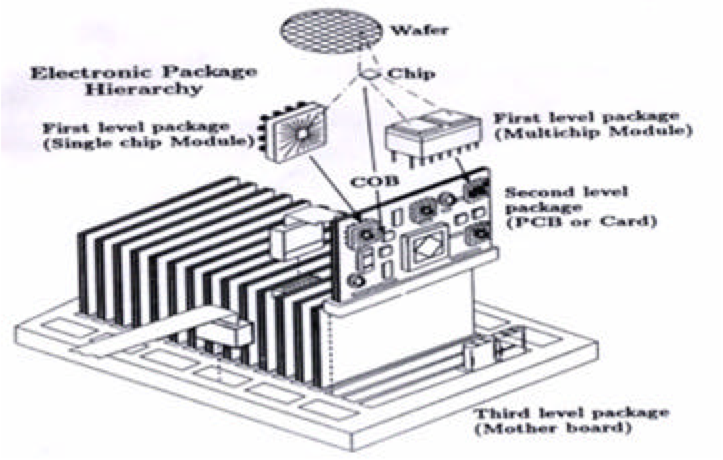
Outline

Raytheon

- Background
- Objective & Approach
- Experiment
- Vibration Fatigue Damage
  - Methodology Development
  - Finite Element Analysis
- Summary & Recommendations

Background

- **Various surface mount electronic parts are soldered on a printed wiring assemble (PWA), which is a printed wiring board (PWB) adhered to an aluminum plate**
  - **Parts include various types of ball grid array (BGA) components, chip scale package (CSP), flip chip, lead flat pack, and leadless capacitors**
- **Vibration environments of military usage are significantly higher than those of commercial applications**
- **Relative motion occurred between the package and the PWA during vibration would produce high-cycle fatigue damage in the solder**
  - **No compliant interconnect (except flat pack) is available to reduce the solder stress/strain**
  - **BGAs with underfill have been used to minimize the solder ball stress/strain**
- **Only rudimentary reliability data, usually supplied by the vendor, exists**



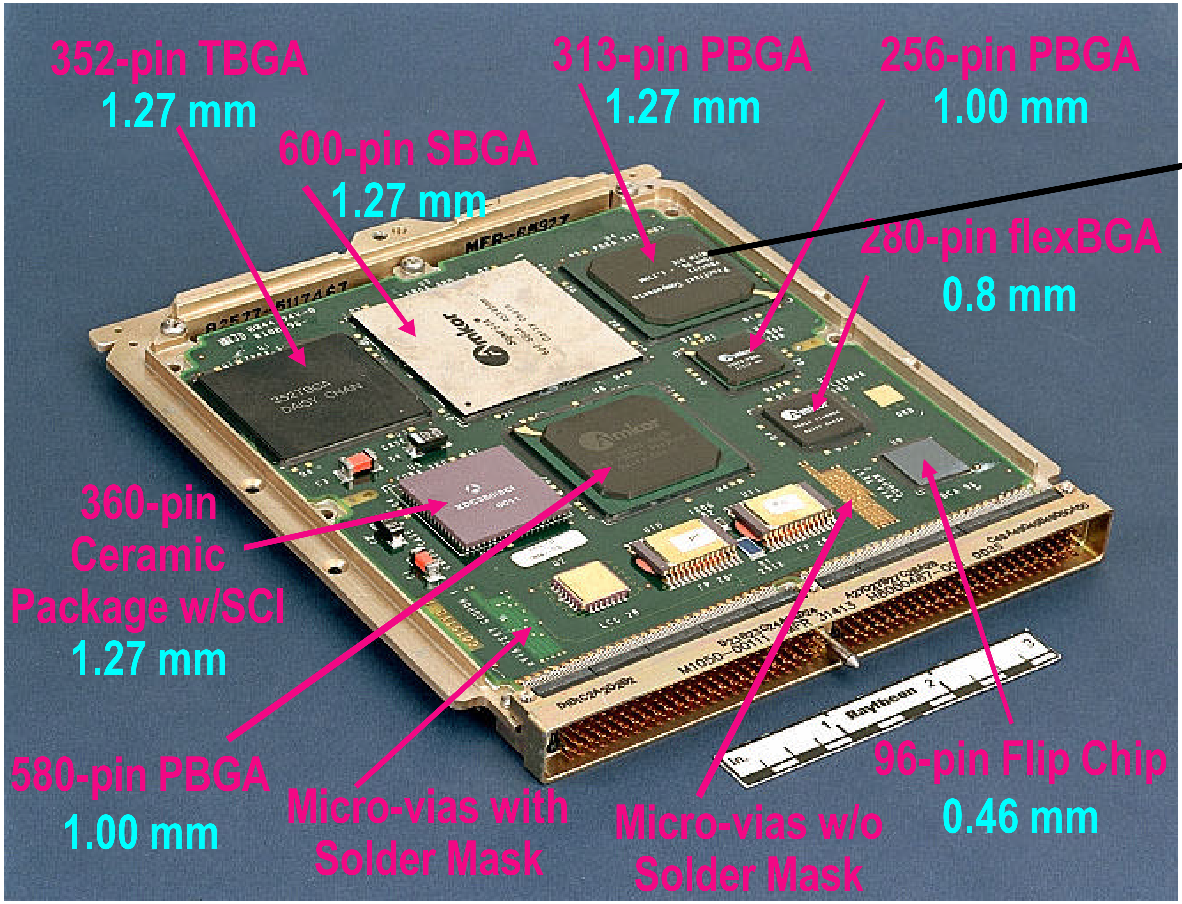
Objective & Approach

Raytheon

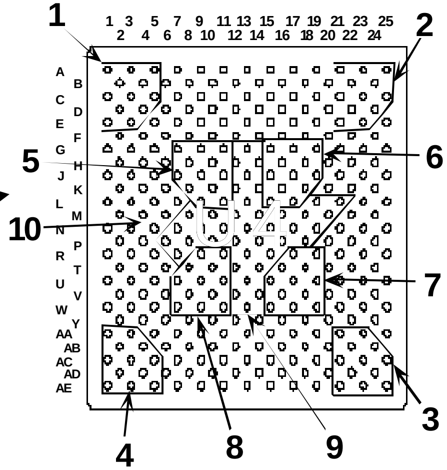
- **Objective: Develop an experimentally validated vibration fatigue damage model for under-filled BGA solder joints**
- **Approach**
  - **Obtain test vehicle (TV) response and BGA solder joint fatigue test data**
    - » **Design and fabricate a TV, mounted with BGA packages with/without under-filled materials**
    - » **Conduct sine sweep and vibration fatigue tests with continuously monitoring solder joint integrity**
  - **Methodology development to calculate solder joint strains during vibration**
    - » **A 3-D macro/micro modeling technique is used to simulate the vibration responses**
    - » **Correlate this model with measured fundamental frequency and its response**
    - » **Derive the effective strains of the BGA solder joint using a type of von Mises relationship and a volume-weighted average technique**
  - **Establish a vibration fatigue damage model**
    - » **Evolved from an empirically derived formula of universal slopes (based on high-cycle fatigue test data)**
    - » **Predict solder joint survivability/durability using a three-band technique and Miner's cumulative damage law**
  - **Calibrate the proposed vibration fatigue damage model by tests**

Experiment

- **Test vehicle and parts lay-out configuration**
  - **Only one side of aluminum heat sink bonded with a single-side circuit card assemblies (CCAs)**

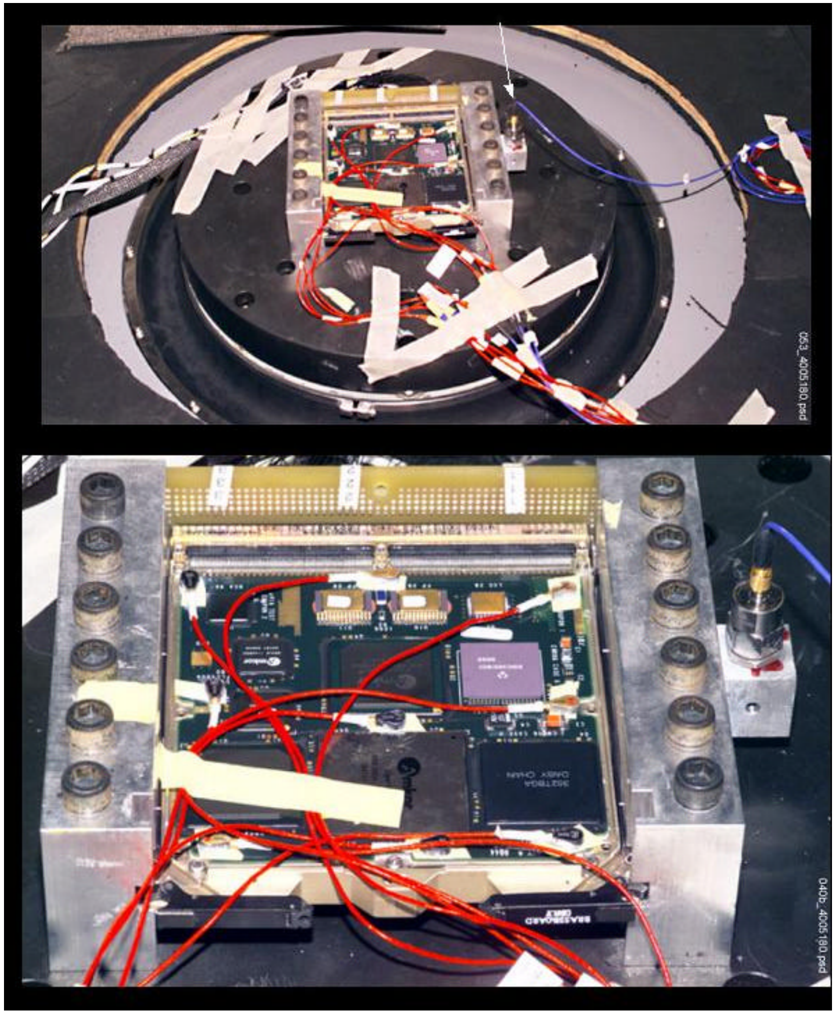


313-pin PBGA daisy chain pattern



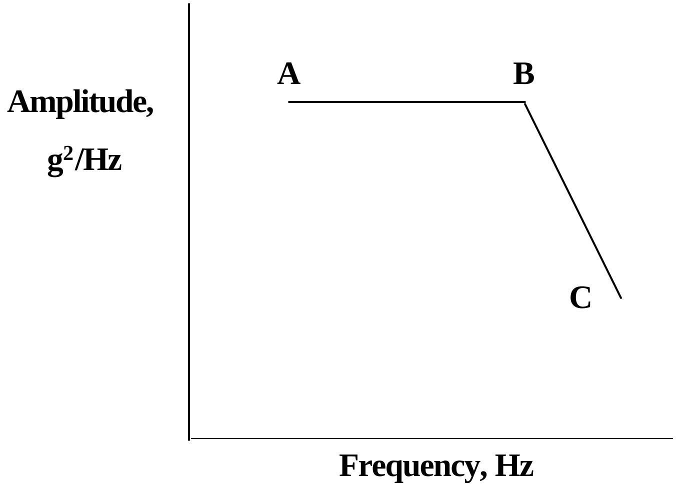
Experiment

- **Vibration fixture and test setup**



Experiment

- **Random vibration inputs (normal to the PWA) and test duration**

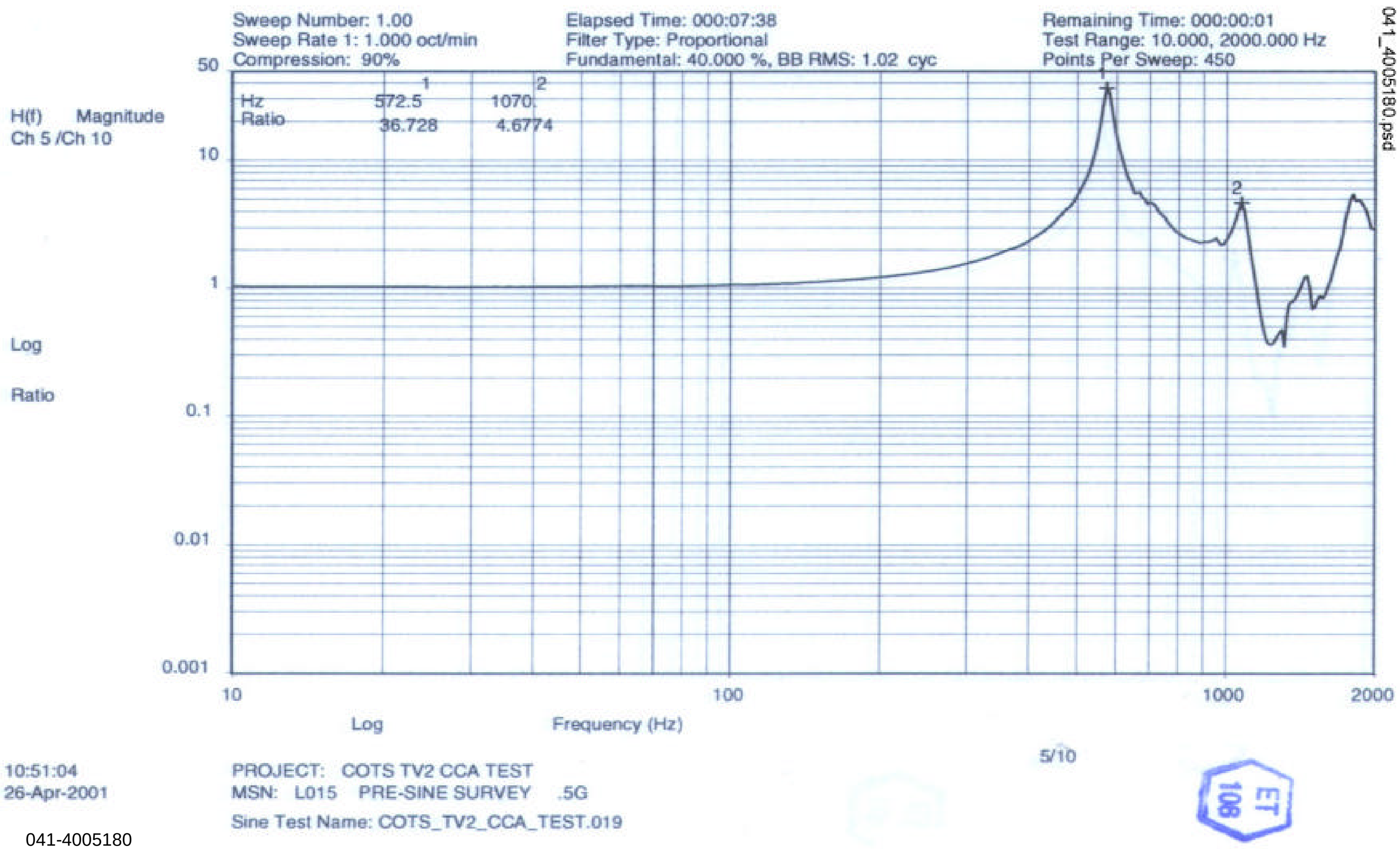


Level	Freq. (Hz)/Amplitude (g^2/Hz)			Total	Duration,
	A	B	C	Grms	min.
1	50/.04	1000/.04	2000/.01	7.71	60
2	50/.08	1000/.08	2000/.02	10.90	60
3	50/.16	1000/.16	2000/.04	15.41	To failure (120 max.)

- **The total number of test samples is 22**
- **The electrical failure is defined as a resistance change of 1000 ohm within 0.2 microsecond**
  - **The higher resistance change is selected for overcoming the noise effects during the vibration test**

Experiment

- **Sinusoidal vibration response from acc. #5 (in the middle of the PWA)**
  - **1st mode of TV natural frequencies is about 573 Hz with transmissibility equal to 36.7**



041-4005180

Experiment

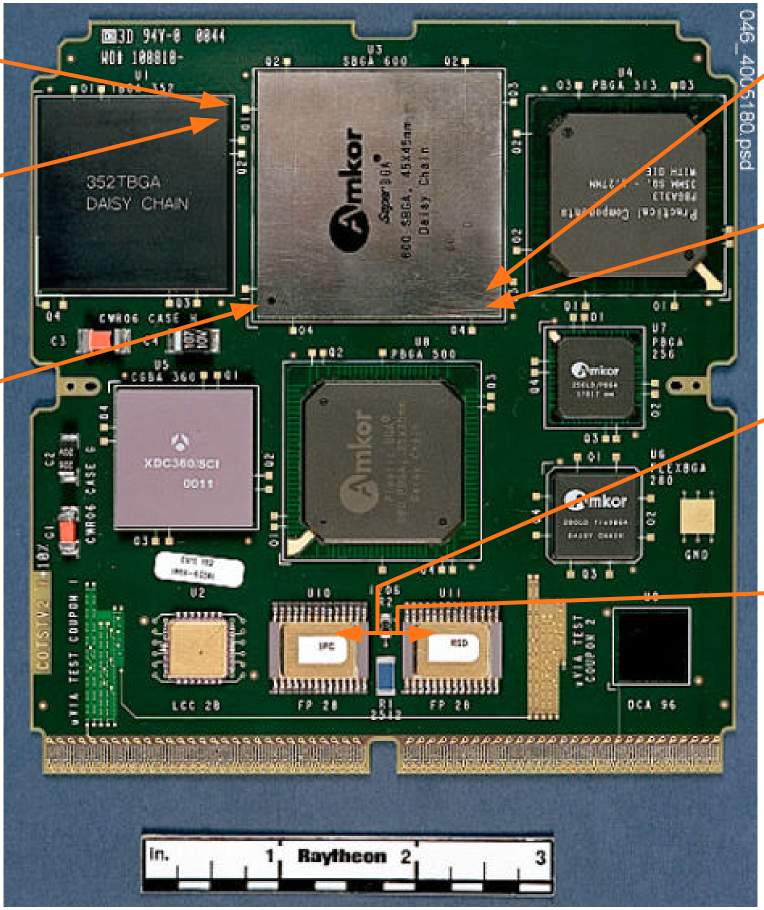
- **Failure map of random vibration test**

MSN S008,
TBGA U1-2,
Level 3,
111 Minutes

MSN N016,
TBGA U1-2,
Level 3,
157 Minutes*

MSN N016,
Super BGA U3-4,
Level 3,
378 Minutes*

* Extended Test Time



MSN L017,
Super BGA U3-3,
Level 3,
6 Minutes

MSN L018,
Super BGA U3-3,
Level 3,
89 Minutes

MSN S001^,
Leaded U10/11-1,
Level 3,
73 Minutes

MSN N015^,
Leaded U10/11-1,
Level 3,
58 Minutes

^ No Visible Solder Joint Failure

046-4005180

1	2
4	3

Failure location at BGA devices

Experiment

Raytheon

- **Comparison of failures in random vibration test**

Underfilled Material	PWB Solder Pad Size	Rework Parts (U3,5,7)	CCA #	Min.@failure								
				U1:352-pin TBGA				U3:600-pin SBGA				U10/
				1	2	3	4	1	2	3	4	U11
None	Nominal	No	N016^, N023	*	157	*	*	*	*	*	378	*
		Yes	N007	*	*	*	*	*	*	*	*	*
	+10%	No	L017, L018	*	*	*	*	*	*	6,89	*	*
		Yes	L019	*	*	*	*	*	*	*	*	*
	–10%	No	S018, S019	*	*	*	*	*	*	*	*	*
		Yes	S008	*	111	*	*	*	*	*	*	*
Reworkable	Nominal	No	N015, N019	*	*	*	*	*	*	*	*	58
		Yes	N/A	-	-	-	-	-	-	-	-	-
	+10%	No	N/A	-	-	-	-	-	-	-	-	-
		Yes	N/A	-	-	-	-	-	-	-	-	-
	–10%	No	S001, S012	*	*	*	*	*	*	*	*	73
		Yes	N/A	-	-	-	-	-	-	-	-	-
Non-Reworkable	Nominal	No	N010, N013	*	*	*	*	*	*	*	*	*
		Yes	N021	*	*	*	*	*	*	*	*	*
	+10%	No	L012, L015	*	*	*	*	*	*	*	*	*
		Yes	L021	*	*	*	*	*	*	*	*	*
	–10%	No	S014, S015	*	*	*	*	*	*	*	*	*
		Yes	S010	*	*	*	*	*	*	*	*	*

1	2
4	3

Failure location at BGA devices

Note: '157' means solder ball failed under random vibration (15.4 Grms) at 157 minutes.
*** Testing only performed to 120 minutes, no failure observed.**
Denotes module subjected to extended testing.

Experiment

Raytheon

- Test results show that
  - 352-pin TBGA and 600-pin SBGA are more susceptible to failure than plastic BGAs under the same conditions
    - » Stiffer packages of TBGA and SBGA, which have copper heat spreaders, may account for higher BGA solder joint stress/strain during vibration
  - The use of under-filled materials appears to improve the life expectancy of all the components
  - Only a limited number of electrical opening are observed, which indicates that the test modules are robust enough to survive the random vibration inputs
    - » One possible reason is that the test modules are very stiff and the curvature changes of the test modules are minimal, which result less solder joint stresses due to smaller relative motion between the package and the PWB
  - Due to insufficient data on solder joint failures, the mean-cycle-to-failure cannot be derived

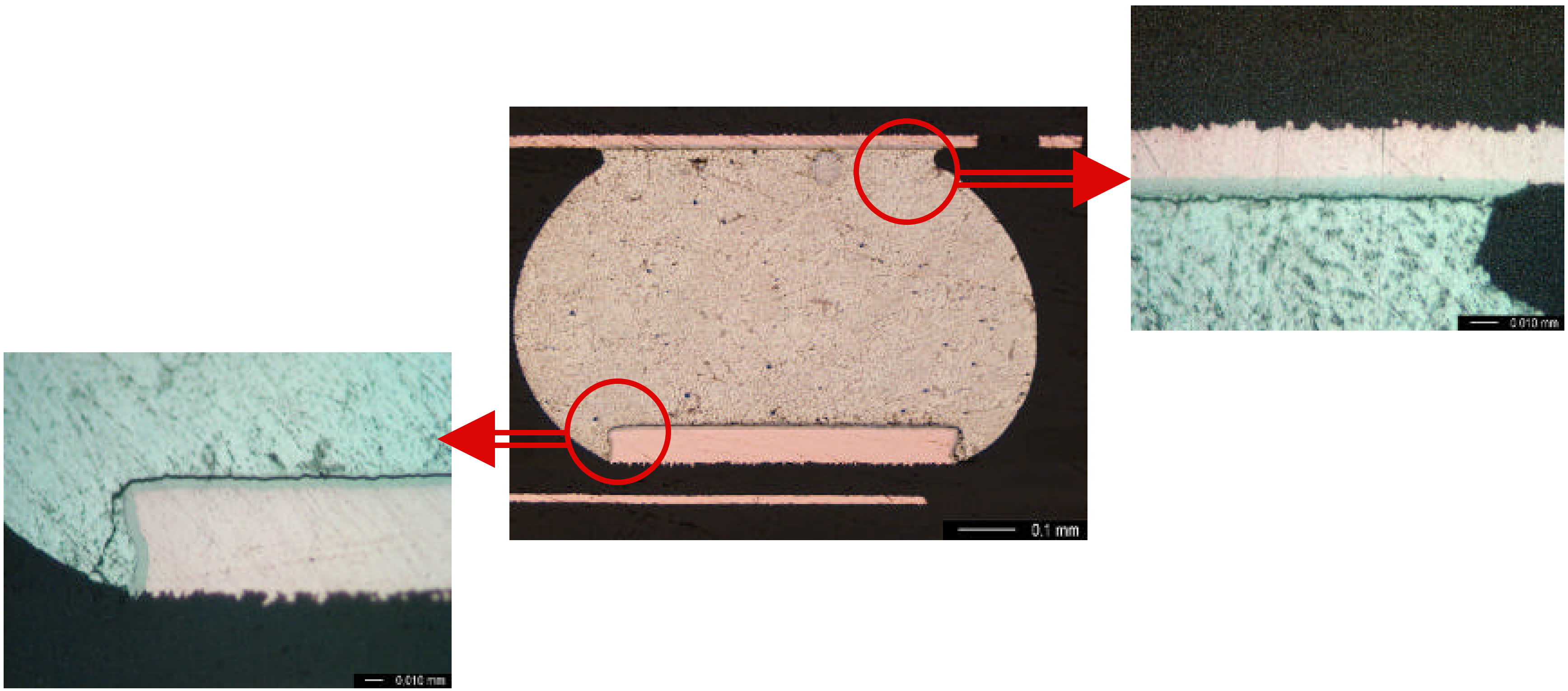
Experiment
(Destructive Physical Analysis)

- **Post-random vibration failure analysis methodology**
  - **Modules with electrical openings during vibration tests are selected for cross-sectioning**
  - **Components are selected based on early first occurrence of failures**
  - **The outer rows of the nets would be sectioned**
  - **Complete cracking across the width of the bump is considered to be confirmation of the failure**
  - **If no confirmation of failure is seen, then additional rows are sectioned**
- **The selected DPAs are: L017 (U3 600-pin SBGA), L018 (U3-600pin SBGA), and S008 (U1-352 pin TBGA)**
- **No visible solder joint failure is observed in flat packs (U10/U11) and a DPA is conducted to further exclude the solder joint failure mode**
- **DPA results confirm electrical openings measured from testing equipment and hand-probing**

Experiment
(Destructive Physical Analysis)

Raytheon

- **Solder cracks are observed along the PWB solder pad, and also at the package side**

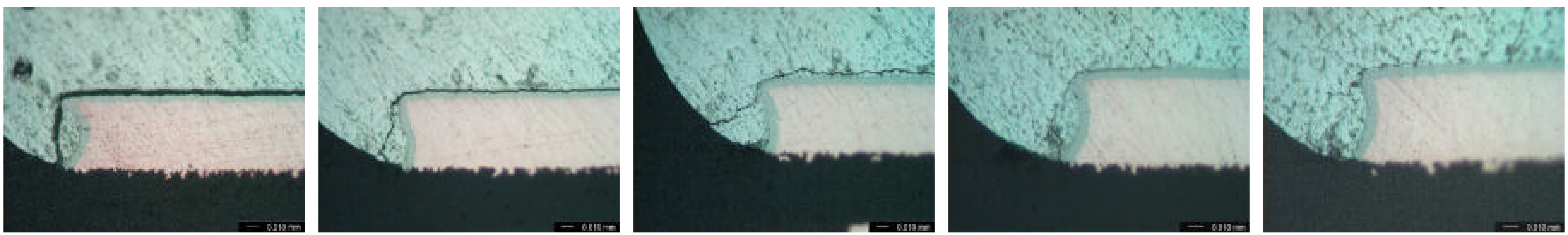


Experiment
(Destructive Physical Analysis)

Raytheon

- The severity of the solder crack gradually decreases from the package corner toward the inside of the package, which indicates that
  - The solder crack is initiated at the corner solder joint

Package Corner → **Inside of Package**

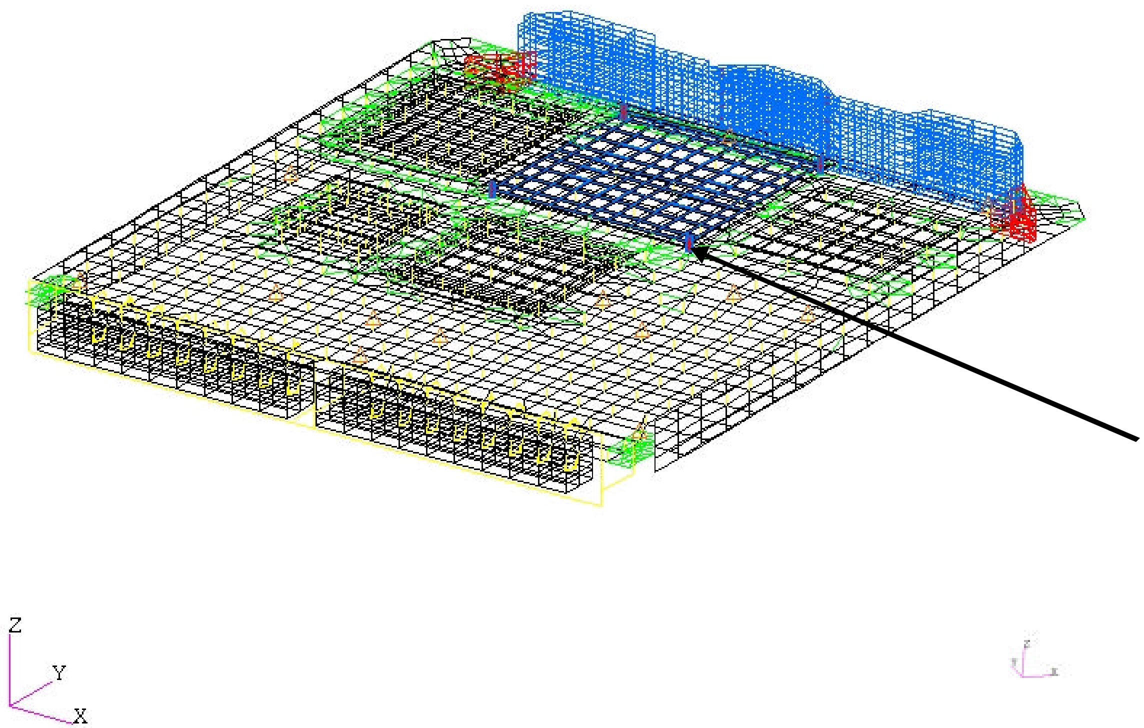


Note: solder cracks at the left end of the PWB solder pad

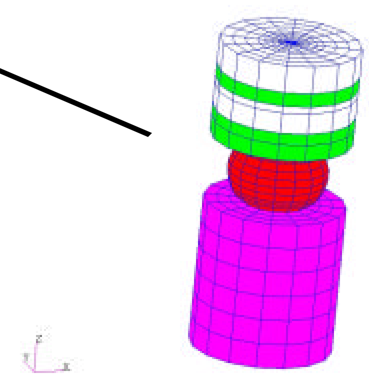
Vibration Fatigue Damage
(Methodology Development)

- **Create 3D macro/micro finite element model with/without under-filled material**

Macro Model



Micro Model



Vibration Fatigue Damage
(Methodology Development)

- **Verify model integrity by means of static analysis, equilibrium check, etc.,**
- **Conduct modal analysis to obtain**
  - **Fundamental frequency and its modal response at the locations of nine accelerometers**
  - **Damping ratio through modal response correlation by test data**
- **Conduct random vibration analysis to obtain complex frequency response of the six principal components of strain to a sinusoidal one gravity input acceleration for each solid element**
- **Derive the effective strain transfer function by employing the type of von Mises relationship**

$$\frac{9}{2}|H(e_{eff})|^2 = |H(e_1) - H(e_2)|^2 + |H(e_2) - H(e_3)|^2 + |H(e_3) - H(e_1)|^2 + 1.5\left[|H(t_4)|^2 + |H(t_5)|^2 + |H(t_6)|^2\right]$$

- **Calculate the power spectrum density (PSD) of the response by the formula**

$$S_o(w) = |H(e_{eff})|^2 \times S_i(w)$$

where S_i(?) is the input PSD of the source excitation

Vibration Fatigue Damage
(Methodology Development)

Raytheon

- **Calculate the power spectral of the response quantity for each element**

$$PS_e = \int S_o(w) \times dw$$

- **The effect strain of each element is derived as**

$$e_{eff,e} = \left| (PS_e)^{0.5} \right|$$

- **Compute an average effective strain over all the elements in the critical layer**

$$e = \frac{\sum e_{eff,e} V_e}{\sum V_e}$$

where V_e is the element volume

- **Number of positive crossing (or the measure of the average frequency) is derived as**

$$f_{+x} = \left| \frac{FS_e}{PS_e} \right|^{0.5}$$

where $FS_e = \int F_o(w) \times dw$ **and** $F_o(w) = (\frac{w}{2p})^2 \times S_o(w)$

- **Several in-house developed Fortran programs, in conjunction with the outputs from MSC/NASTRAN static and frequency response analyses, are used to perform the required computations**

Vibration Fatigue Damage
(Finite Element Analysis)

Raytheon

- Analysis characteristics
  - Construct a 3-D macro/micro finite element model (FEM) to simulate the major structural elements of the study case
  - Conduct a linear static analysis to verify FEM integrity
  - Perform a dynamic analysis with an excitation normal to the PWA
  - Loading & boundary conditions
- Material properties

Material	Tensile Modules, GPa	Shear Modulus, GPa	Poisson's Ratio
Aluminum	68.9	25.9	0.33
FR-4	16.9 (X & Y) 7.44 (Z)	3.03 (XY) 2.41 (YZ & ZX)	0.129 (XY) 0.417 (YZ) 0.183 (ZX)
Copper	117	44.0	0.33
63Sn/37Pb Solder	30.2	10.8	0.4
Solder Mask	4.89	1.72	0.4
Polyimide Tape	14.5	6.27	0.16
Alumina	303	125	0.21
Silicon	131	50.4	0.3
Mold Compound	12.5	4.82	0.3
Heat Sink Adhesive	0.00276	0.00095	0.45
Reworkable Under-fill	1.12	0.4	0.4

Vibration Fatigue Damage
(Finite Element Analysis)

Raytheon

- 3-D FEM is calibrated by matching the analysis results with the vibration test data obtained from accelerometer measurements
  - Natural frequencies and their corresponding modal response
- 3-D FEM is subjected to level 3 random vibration
- The average effective strains (four outer most corners) of 600-pin SBGA

600-pin SBGA without under-filled

Solder Ball Location	Positive Crossing, N_0 (Hz)	Solder Strain, 10^{-4}	
		Solder/ Package	Solder/ PWB
Upper-left	586	3.66	3.26
Upper-right	669	1.30	1.15
Lower-right	688	1.17	1.03
Lower-left	589	3.51	3.11

600-pin SBGA with reworkable under-filled

Solder Ball Location	Positive Crossing, N_0 (Hz)	Solder Strain at Solder/Package, 10^{-4}
Upper-left	582	3.07
Upper-right	673	0.98
Lower-right	702	0.84
Lower-left	585	2.91

Vibration Fatigue Damage
(Finite Element Analysis)

- The average effective strains (four outer most corners) 0f 352-pin TBGA

352-pin TBGA without under-filled

Solder Ball Location	Positive Crossing, N_0 (Hz)	Solder Strain, 10^{-4}	
		Solder/ Package	Solder/ PWB
Upper-left	577	1.31	0.57
Upper-right	595	1.40	0.63
Lower-right	629	1.51	0.68
Lower-left	577	2.56	1.11

352-pin TBGA with reworkable under-filled

Solder Ball Location	Positive Crossing, N_0 (Hz)	Solder Strain at Solder/Package, 10^{-4}
Upper-left	613	0.42
Upper-right	595	1.00
Lower-right	628	1.18
Lower-left	768	0.69

Vibration Fatigue Damage

Raytheon

- **Analysis characteristics**
  - **Vibration fatigue life prediction model, empirically derived formula (with some modifications) of universal slopes based on high-cycle fatigue test data)**

$$e = \frac{\Delta e}{2} = \frac{3.5 S_u}{2E} N^{-.12} \left(\frac{A_i}{A_D} \right)^{.12}$$

N=solder fatigue life

S_u=ultimate tensile strength=37.9 MPa

e **= strain amplitude**

E=modulus of elasticity=30.2 GPa

De **= total strain range**

A_i=solder crack surface in mm^2

A_D=characteristic area in mm^2 and will be determined from test results

  - **Modified vibration fatigue life prediction model**
    - » **The values of c and A_D are determined to be 0.5128 and 0.25548 mm^2, respectively**

$$e = N^{-c} \left(\frac{A_i}{A_D} \right)^{c}$$

Vibration Fatigue Damage

Raytheon

- **A three-band technique**
  - **Vibration fatigue life with** 1σ, 2σ, and 3σ **strains**

$$ke = N_k^{-c}\left(\frac{A_i}{A_D}\right)^c,$$

where k=1, 2 and 3

  - **Number of applied cycles for T hours of random vibration**

$$n_1 = N_0^+ T\,(3600\ \text{sec/hr})(.6831)$$

$$n_2 = N_0^+ T\,(3600\ \text{sec/hr})(.271)$$

$$n_3 = N_0^+ T\,(3600\ \text{sec/hr})(.0433)$$

Where N_0^+: Number of positive zero crossings

  - **Cumulative damage index (CDI) using Miner's cumulative damage law**

$$\text{CDI} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}$$

» **"Failure" is predicted when CDI has a value greater than or equal to a critical value, usually chosen as 0.5**

Vibration Fatigue Damage

Raytheon

- **BGA CDIs and fatigue lives**

Package	Solder Ball Location	CDI	Predicted Fatigue Life, hours	Tested Fatigue Life, hours
TBGA 352 without Underfill	1	0.167	1.91	1.85
	2	0.203		
	3	0.524		
	4	0.142		
TBGA 352 with Reworkable Underfill	1	0.086	7.94	> 2 (No failure observed)
	2	0.126		
	3	0.055		
	4	0.016		
SBGA 600 without Underfill	1	0.122	1.25	1.48
	2	0.101		
	3	0.743		
	4	0.803		
SBGA 600 with Reworkable Underfill	1	0.070	1.74	> 2 (No failure observed)
	2	0.055		
	3	0.513		
	4	0.567		

1	2
4	3

Failure location at BGA devices

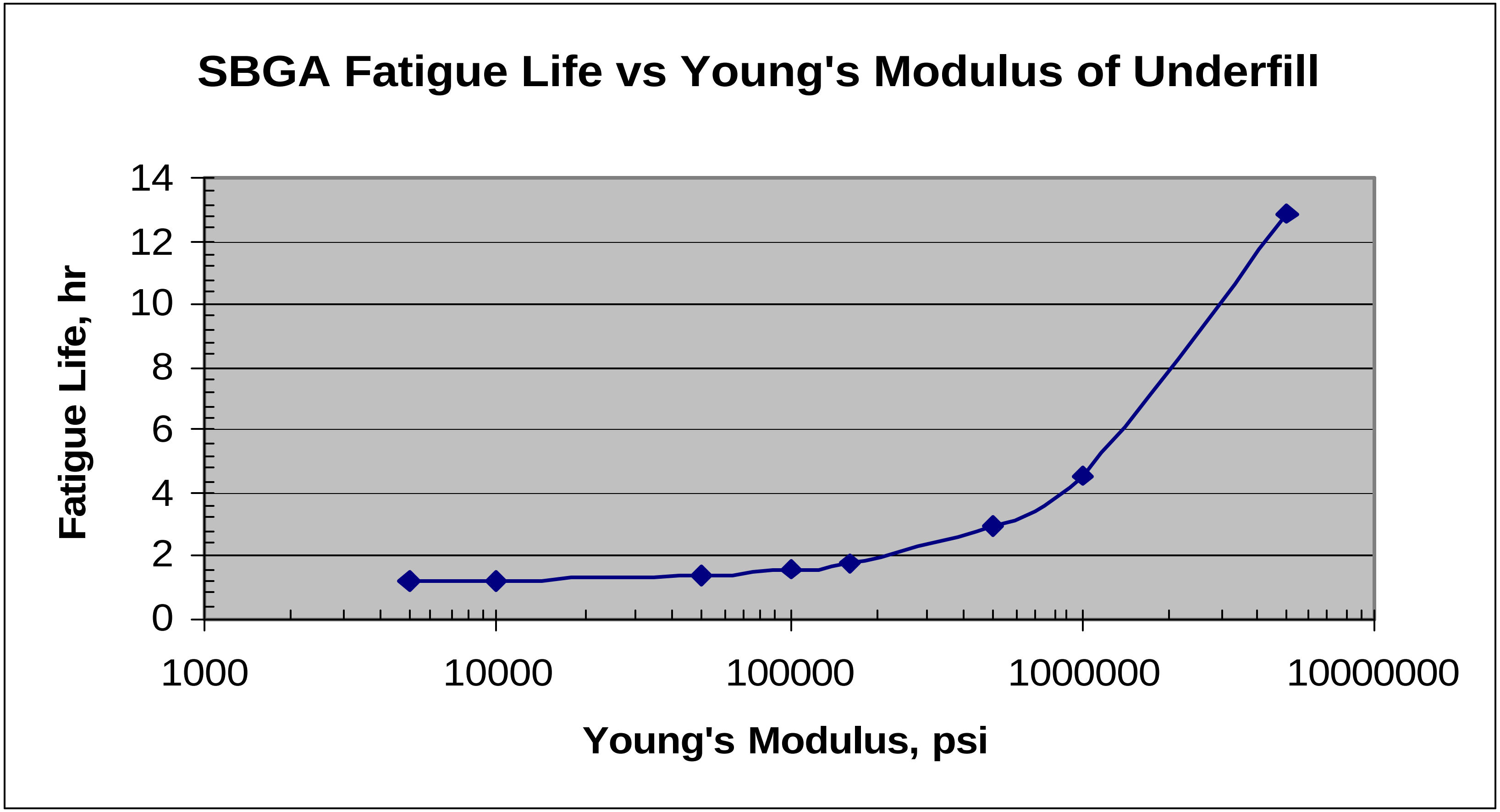
Vibration Fatigue Damage

Raytheon

- For the 352-pin TBGA, analysis predictions show that
  - Solder crack would occur at solder/package interface (larger values of CDIs), which matches with test observation
  - The 1st failure location is at the lower-right corner solder ball (having the largest value of CDI), which is inconsistent of test observation
    - » This inconsistency could be due to the varied configurations in the solder joints (induced by manufacturing process, package warpage, etc.)
  - Reworkable underfill significantly improves 352-pin TBGA fatigue life
  - Predicted fatigue life is close to the test result
- For the 600-pin SBGA, analysis predictions show that
  - The solder joints of this package have shorter fatigue lives than those of the 352-pin TBGA
  - The 1st solder joint failure in this package is at the lower-left corner solder ball, which is partially consistent of test observation
  - Reworkable underfill improves 600-pin SBGA fatigue life
  - Predicted fatigue life is close to the test result

Vibration Fatigue Damage

• **600-pin SBGA solder joint fatigue life increases as under-filled Young’s modulus increases**



Vibration Fatigue Damage

Raytheon

- **Solder joint fatigue life tested data and predictions of 313-pin PBGA in TV1**

Test Data	Prediction from Previous Model	Prediction from Updated Model
67.8 minutes	26.3 minutes	48.6 minutes

- **The prediction life from the updated model is less conservative than that from the previous model**

Summary

Raytheon

- TV (soldered with BGAs) is designed, constructed, and tested under the random vibration environment
- Linear static and dynamic analyses with a 3-D macro/micro modeling technique is used to estimate the effective strains of BGA solder joints during vibration
  - Relative motions between the package and the PWA produce high cycle fatigue damage in the solder
  - Several in-house developed Fortran programs are used to perform the required computations
- Vibration fatigue damage model is established and combined with a three-band technique and Miner's law to predict solder joint survivability/durability
- The experimentally validated model is then used to predict the survivability/durability of all solder joints
  - Analysis predictions match with test observations
    - » Solder crack surface would occur at the solder/package interface for 352-pin TBGA and 600-pin SBGA
    - » Predicted fatigue lives of 352-pin TBGA and 600-pin SBGA are close to their corresponding fatigue lives
    - » The fatigue life of 600-pin SBGA increases as under-filled Young's modulus increases, and their relationship is nonlinear

Recommendations

- Further improvements in the above developed methodology and FEA process, including finer pitch BGA
- Selecting more study cases with various package sizes, solder ball configurations, vibration profiles, etc. to further calibrate vibration fatigue model
- Using the experimentally validated vibration fatigue model as an effective tool to determine the integrity of BGA solder joints during vibration
- Conducting a parametric study to identify critical design factors impacting on the BGA solder joint vibration fatigue life and then seeking an optimum design