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# Numerical simulation and fatigue life estimation of BGA packages under random vibration loading

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ABSTRACT

This work investigates finite element (FE) simulation and fatigue life prediction of ball grid array (BGA) under random vibration loading. The printed circuit board (PCB) assemblies are tested under random vibration loadings. The center displacement responses of PCB assemblies and the time to failure are recorded. A three-dimensional FE model of the PCB assembly is established using ABAQUS software, and spectrum analysis specified for random vibration is performed numerically to obtain the response power spectral density (PSD) of the PCB assembly. Simulation results show good correlation with experimental data in terms of center displacement responses in actual random vibration testing, validating the effectiveness of the proposed FE model. In particular, the root mean square (RMS) values of the maximum peeling stress under different loading conditions are calculated and compared. Different pre-tightening force levels and vibration intensities are applied to study their influence on solder joint reliability. Finally, the fatigue life of BGA solder joints under random vibration loading is determined in terms of Miner's rule and random vibration theory, and it is experimentally verified that the predicted fatigue life of BGA solder joints matches the experimental results with reasonable accuracy. It is concluded that solder joints at the four outermost corners of BGA packages have higher peeling stress values than others, especially at the both sides of solder joints near PCB and BGA. The stress responses of critical solder joints increase with the increase of vibration loading. BGA packages would be more prone to damage and failure when the screws became looser. This research will provide a guide for investigating the dynamic characteristics and optimization design of PCB assemblies, and predicting the fatigue life of BGA solder joints.



## 1. Introduction

Electronic systems are often required to operate under different mechanical shock and vibration loadings for commercial, industrial, and military applications. Although vibration loading is commonly encountered in the service life of electronic packaging, the characteristics of the stress history caused by vibration loading cannot be directly obtained experimentally. In this respect, finite element (FE) numerical simulation is a very effective tool for the analysis and optimization of integrated circuit (IC) package design. In particular, numerical simulation in terms of the vibration reliability of PCB assemblies has been much used to simulate the dynamic behavior.

An effective FE analysis will help to detect potential failure and to predict the reliability of the solder joints. To evaluate the reliability of PCB assemblies under vibration and shock loading, different modeling technologies, e.g. a sub-model method, have been applied to perform dynamic response analysis [1–4]. For instance, Che and Pang [5] developed a sub-model approach to conduct quasi-static and harmonic response analyses. Researchers have also combined vibration tests and FE simulation analysis to predict the fatigue life of solder joints [6–8]. Chen [6] combined vibration testing with FE analysis to predict the fatigue life of ball grid array (BGA) components, using a three-dimensional modeling technique to simulate the vibration responses of BGA solder joints on a printed wiring assembly. The use of various package sizes, solder ball configurations, and vibration profiles for further calibration was recommended. A rapid life-prediction approach for BGA solder joints under combined thermal cycling and vibration loading conditions has been developed [9]. Cinar et al. [10] used a global–local modeling technique to calculate the stress magnitude of solder joints due to harmonic excitation.

Most electronic systems used in vibration environments are subjected to random vibration loading instead of harmonic excitations. More researchers have been concerned with the failure mechanisms and fatigue life prediction models under random vibration loading. Barker et al. [11,12] proposed analytical methods to estimate the vibration fatigue life of leaded surface mount components. Wong et al. [13] adopted a three-band technique and developed a vibration fatigue life prediction model for the BGA solder joints. Li [14] presented a methodology of failure analysis and fatigue prediction of lead/solder joints under automotive vibration environment. Tang et al. [15] studied the effect of

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different structural parameters on stress distribution under random vibration. Wu [16] developed a rapid assessment methodology that can determine the solder joint fatigue life of BGA and chip scale package (CSP) under vibration loading. In a previous study [17], it was found that the failure locations of lead-free BGA solder joints would change with different failure modes from fatigue crack to brittle crack when subjected to vibration loadings with different acceleration PSD amplitudes. The failure mode under large amplitude vibration loading was similar to that in drop impact loading.

In this study, based on modal test and modal simulation, a FE model was established to further investigate the dynamic characteristics and failure mechanism of BGA solder joints. The results of random vibration simulation were validated by the experimental data of random vibration tests. The effects of pre-tightening forces and random vibration intensities on solder joint reliability were investigated. Miner's rule and random vibration theory, which was generally used to predict the fatigue life of mechanical structures, were innovatively applied to assess the fatigue life of BGA package, benefiting the design optimization of PCB assemblies.

## 2. Experimental procedures

The PCB assembly is an eight-layer round FR4 board of 160 mm diameter and 1 mm thickness. The PCB assembly consists of package, solder mask, sub-core, copper pad, solder ball, and PCB. Eight BGA packages are centro-symmetrically mounted on the PCB. The dimensions of the BGA package are 11 mm × 13 mm, and there are 103 solder balls for every BGA package. The lead-free solder is 96.5Sn3.0Ag0.5Cu, and the pitch of the solder balls is 0.80 mm. All the material properties of the PCB assembly at room temperature are given in Table 1.

Non-contact TV laser holography technology was firstly employed to perform experimental modal test, so as to get natural frequencies and mode shapes. Then, narrow-band random excitation was carried out. Its center frequency was the first order natural frequency, and the input acceleration PSD amplitude was a constant value (such as 60 $(m/s^2)^2/Hz$). The vibration test system was shown in Fig. 1. Through eight screws, the test vehicle was mounted on a solid fixture which was screwed to the vibration shaker (LDS V8-640T). Torque wrench was used to determine the pre-tightening force on the eight screws. In particular, the pre-tightening force in random vibration test was the same as that in modal test. Thus, the same boundary condition may be adopted in modal simulation and random vibration simulation. LMS instrument (④) was used to perform feedback control of the shake table. A laser displacement sensor ( ) was adopted to determine the center dynamic response of the PCB assembly. Daisy chain loops were monitored simultaneously by Sony data acquisition instrument (⑨). The detailed experiment procedure has been reported in reference [17].

The vibration fatigue tests under four different kinds of acceleration PSD amplitudes were carried out. The four acceleration PSD amplitudes were 60 $(m/s^2)^2/Hz$, 80 $(m/s^2)^2/Hz$, 120 $(m/s^2)^2/Hz$, and 160 $(m/s^2)^2/Hz$, and their center frequencies and bandwidth were the first natural frequency and 20 Hz, respectively. The mean time to failure was 1830.00 s, 1509.75 s, 1202.21 s and 720.31 s, respectively. In addition, the vibration test was preformed when the acceleration PSD amplitude is 5 $(m/s^2)^2/Hz$ and the frequency band range was between 50 Hz and 500 Hz. The center displacement responses under different vibration loadings were measured by the laser displacement sensor.

**Table 1**
Material properties of PCB assembly.

| | Cu | Package | PCB | SM | Sub-core | Solder |
|---|---|---|---|---|---|---|
| Density ($kg/m^3$) | 9000 | 1035 | 2680 | 1000 | 1570 | 8410 |
| Modulus (GPa) | 110 | 27 | 22.5 | 5 | 21 | 42.5 |
| Poisson's ratio | 0.34 | 0.3 | 0.12 | 0.467 | 0.25 | 0.4 |

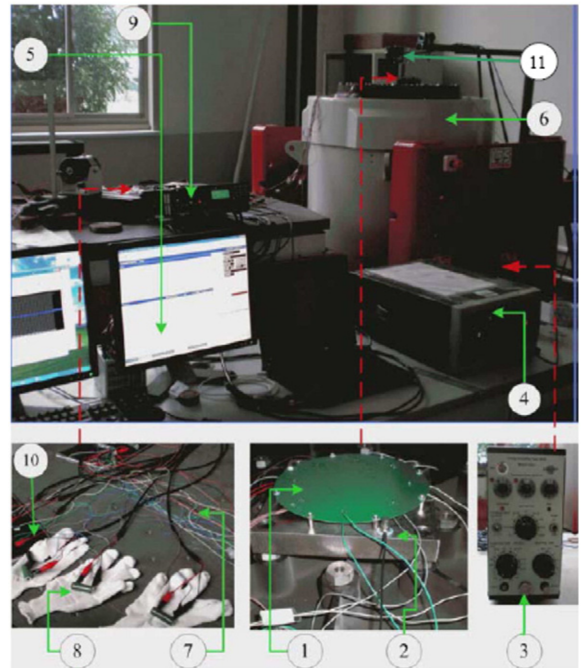


**Fig. 1.** Spot picture of random vibration test.

The center displacement histories of PCB assembly were obtained. To analyze the experimental data, given that $\hat{x}(t)$ is a sample function of ergodic stationary random process $X(t)$, the RMS of variables $x(t)$ is

$$\hat{x}_{RMS} = \sqrt{E\left(\hat{x}^2(t)\right)} = \sqrt{\int_{f_s}^{f_e} 2S_{XX}(f)df} = \sqrt{\int_{f_s}^{f_e} G(f)df} \tag{1}$$

where $f_s$ and $f_e$ are the upper and lower bounds of the frequency range (i.e. 50–500 Hz in this study), respectively; $E(\cdot)$ is the expectation; $S_{XX}(f)$ is the auto PSD function; $f$ is frequency; $G(f)$ is a one-sided PSD function. Note that Eq. (1) is also valid for stress/displacement evaluation to obtain the stress RMS and standard deviation values.

## 3. Finite element simulations

### 3.1. Modal simulation

On the basis of the experimental modal analysis, an effective equivalent model could be established, which was presented by Liu [18]. Following this modeling method, ABAQUS software was adopted to establish a three-dimensional FE model, and the C3D8R solid element type was selected. The FE model of the PCB assembly and a one-fourth unit assembly of solder balls were shown in Fig. 2. The FE model consisted

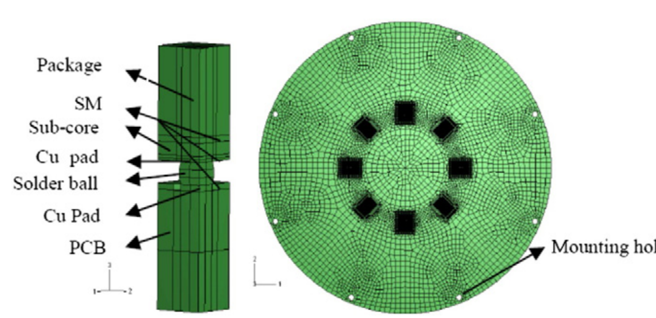


**Fig. 2.** FE model of circular PCB assembly.