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RESEARCH

Fatigue Life Based Study of Electronic Package Mounting Locations on Printed Circuit Boards Subjected to Random Vibration Loads

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Abstract

Plastic Ball Grid Array (PBGA) packages (chips) mounted on a Printed Circuit Board (PCB) assembly are vulnerable and are more likely to fail when they are subjected to random vibration environmental conditions. The proper positioning of the packages on the PCB also influences the magnitude of the dynamic stresses induced in the vulnerable solder joints of the PCB assembly. In this work, an effort is made to identify the best location for positioning the packages on the PCB, which are subjected to severe random vibration load conditions. Investigations have been carried out by designing and fabricating a multi-chip PCB assembly and several single-chip PCB assemblies (chips mounted at different locations on the PCB) as per JEDEC standards. By subjecting these packages to random white noise input, numerical analysis and experiments were sought to identify the vulnerability of the packages to various mounting locations in a novel way. Based on the response stress PSD on the solder joints, the fatigue life of the PCB assembly was calculated. The results showed that the fatigue life of the PCB assembly with PBGA package at the U6A position is significantly higher when compared with that of a package at the center position of the PCB.

Keywords Plastic ball grid array · Printed circuit board · Random Vibration · Solder joints · Mounting location · Fatigue life

1 Introduction

Electronic products fail over time when they are exposed to extreme vibrating environments. These vibrating environmental loading conditions are inevitable in automobile, machining environments, aerospace, and spacecraft applications. Whenever an electronic product is employed in such severe environmental conditions, it is subjected to extreme fatigue and fails before its estimated life, leading to catastrophic effects [1]. The electronic components used in critical applications are subjected to random vibration loads and induce failure in the vulnerable solder joints. As a result, vibration-induced failure is one of the most serious dependability concerns for these machines with electronic devices [2]. Also, the reliability of solder connections in electronic devices is crucial to the operating performance of electronic systems employed in safety-sensitive applications [3]. "The corner solder joint inter-connection is the most vulnerable part of any electronic assembly, as it undergoes maximum deformation during vibration and hence susceptible to early damage". This deterioration progresses over time, eventually leading to solder joint fracture initiation, crack propagation, and connection failure, which leads to system failure. As a result, the PCB's life estimation is required beforethe product launch to ensure the board's longevity [4]. This also assists manufacturers in reducing scrap and ensuring product reliability. While designing high-reliability electronic packages for critical applications, the fatigue of the solder joints must be considered, as it is an important failure mechanism. In order to predict the fatigue life of the PCB assembly subjected to random vibration loads, various attempts have been made by the researchers and are reported in the literature. To estimate the fatigue life of the PCB assembly, Karthiheyan et al. [5] investigated the dynamic response

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properties of the printed circuit boards (PCB) under random vibration loading. Random vibration tests were done with FEA for the fatigue life prediction of PCB under different service situations, as per JEDEC requirements, and the results for different service conditions were compared. The fatigue life of the PCB was calculated using the Wirsching and Light model with rain flow adjustment for four distinct conditions.

Su et al. [6] developed a model for the fatigue reliability design for Metal Dual Inline Packages under random vibration based on finite element analysis, physics of failure model, and response surface approach. Saravanan et al. [7] investigated the fatigue life of lead-free surface-mounted BGA (Ball Grid Array) packages exposed to random vibration. The Palmgren-rule Miner was employed for random vibration analysis to calculate the cumulative fatigue damage. The permitted acceleration levels that the package can endure were also determined for the selected factor of safety, as well as the cumulative damage incurred by the critical solder junction overtime.

Yusuf et al. [8] investigated on the influence of solder pad size on a FBGA solder joint inter-connections. This investigation was done on a memory modules subjected to harmonic excitation by both global and local modelling techniques. To identify susceptible areas of solder joints under vibration, calculated displacements from the global model were substituted along the established local model's boundary and fatigue life was estimated. It is concluded that the solder pad's geometry is one of the major design variable in estimating the fatigue life through modelling techniques which affects the overall stiffness of the system under vibration. Doranga et al. [9] developed a novel validation technique of the numerically developed PCB assembly to address the issues of signal leakage and improper windowing of the frequency response function (FRF) by a step sine testing procedure. A board level ball grid array package was used to validate the global-local FE model and the resonance based fatigue testing. The volume average Von-Mises stress was used to predict the life of the solder joint and compared with the results of the fatigue testing for validation.

Yu et al. [10] used vibration testing and FEA to establish a method for forecasting the fatigue life of PCBs under random vibration loading. By altering the constant G input excitation, the BGA packages were tested under sinusoidal vibration loading to generate the stress-life curve. The S-N curve was plotted using the stress from FEA and the number of cycles obtained from the sinusoidal vibration test. The Rain-flow cycle counting technique was used to condense a wide range of stress levels into a set of simple stress reversals. The finite elemental model was compared and validated against the vibration test results by correlating with the natural frequencies, damping ratio, mode shapes, and transmissibility function. Chen et al. [11] established a system for calculating electronic component fatigue failure under vibration stress that integrates vibration fatigue failure, finite element analysis, and theoretical formulation. The findings revealed that the numerical model developed is precise enough to forecast fatigue life. The authors concluded that the solder ball stress is maximum near the component's corner, where the real displacements from the vibration test were fed into the FEA model. As a result, the stress versus failure cycles (S–N) curve was generated by connecting the obtained solder ball stresses and the number of failure cycles in the vibration test. When those test components failed, Miner's rule was used to calculate the fatigue damage index.

Various researchers adopted several methodologies to find the fatigue damage caused by varying environmental conditions, especially the random vibration loads. As the PCBs are used in critical applications such as deep tunnel drilling, automobile dashboards, aircraft engines, and so on, they may fail due to high cycle fatigue caused by the random vibration loading during their service. Thus estimating the fatigue life of the critical solder joint in those PCB assemblies is essential. Also, the location of the Plastic Ball Grid Array packages mounted on the PCB majorly affects the life of the solder joint, and it is critical to analyze the orientation of the PBGA on the PCB.

Researchers have made numerous attempts to study the dynamic characteristics of the PCB assembly with surface mount packages at U1A, U5A, U8A, U11A & U15A positions specified by JEDEC standards. However, most of the work reported in the literature had their test vehicle designed with electronic packages surface mounted on the centre position only. Vulnerability of the other positions of the package on the PCB was not well explored in any of the existing literature. Hence a novel attempt has been made to look at the possibility of improved fatigue life of electronic package at other locations of the PCB. Moreover, all the existing literature works in this domain are endeavoured only to estimate the fatigue life under various environmental conditions. No work was found in literature to improve the fatigue life of the PCB assembly considering the position of the package. Also the magnitude of 1008 lead-free solder ball's stress distribution pattern on the locations other than centre package of the PCB, its correlation with respect to the position and their criticality was not detailed reported in any of the literature work. Furthermore, this location study lays a foundation for optimizing the package's (PBGA-144) location and orientation on product level.

In this work, modal and random vibration analyses were done to find the stress induced in the critical solder joint, eventually finding the corresponding fatigue life of the PCB assemblies. The results are validated with the experimentation, and the position of the packages on the board was studied with a single PBGA package in a PCB assembly located at seven different positions, namely U2A, U4A, U6A, U8A, U10A, U12A, U14A of the PCB which are the positions on the test vehicle for whom any researchers do not explore the dynamic characteristics.

2 Methodology

Modern applications require multi functionalities of an electronic system that incorporates multiple surface mount packages to do the given tasks [12]. With hundreds of bare chips that may be arranged extremely closely together on a substrate, Multi-Chip Modules (MCM) offer a very high level of system integration. As a result, systems based on MCM architectures can produce much denser circuits and much shorter interconnect distances between the chips than the systems in which the chips are packaged in single-chip modules of the PCB [13].

The dynamic behavior of such a system depends upon the equivalent mass (m), stiffness (k) of the system, and damping (c) characteristics. Whenever such a system is perturbed with an exciting force, 'F_0' at an operating frequency (ω), all the components of the system would start to vibrate with the same frequency of excitation [14].

$$m\ddot{x} + c\dot{x} + \ kx = F_t \tag{1}$$

$$F_t \ = \ F_0 cos\left(\omega t\right) \tag{2}$$

If the surface mount packages are located in positions with the maximum dynamic displacements, the critical solder joints may experience more strain [15]. The phenomenon of resonance will occur when the frequency of excitation (ω) exactly matches the fundamental frequency (ω_f) of the components mounted, and the dynamic amplitude (X) of the components will go larger [14].

$$X = \frac{F_0}{\left[\left(k - m\omega\ ^2\right) + c^2\omega\ ^2\right]^{1/2}} \tag{3}$$

In order to impede the dynamic amplitude of the electronic components on a PCB, it is essential to avoid encountering both frequenciesthe same to extend the fatigue life of electronic components [15].

For a printed circuit board of length 'a' and breadth 'b', setting the strain energy of the board equal to the kinetic energy (when there is no dissipated energy) will result in the natural frequency if the board of uniform cross section is fixed on four corners. The resulting natural frequency is [16],

$$f_n = \frac{\pi}{2}\sqrt{\frac{D}{\rho}}\left(\frac{1}{a^2} + \frac{1}{b^2}\right) \tag{4}$$

where 'D' is a plate stiffness factor, and 'ρ' is the density of the PCB substrate.To investigate the dynamic characteristics of the PCB assembly, solder balls with SAC 305 (96.5% Sn – 3.0% Ag – 0.5% Cu) was used in this research work considering the health concerns over the toxicity of lead (Pb) based solders [17–20].

2.1 Design of PCB Assembly

The dimension of the PCB used in the study was 132 mm x 77 mm x 0.8 mm, designed as per JEDEC-JESD22-B111 standard [21] and made of FR-4 epoxy material. The CAD model of the PCB with PBGA packages was created using SOLIDWORKS 2018 modeling software, where each PBGA package has 144 solder balls located at U2A, U4A, U6A, U8A, U10A, U12A, and U14A positions and they are modeled with a solder material SAC 305 [22]. This PCB assembly was used for the modal analysis to predict the natural frequency and mode shapes that are determined by the properties like stiffness, mass, and damping properties. The numerical analysis was performed with the help of ANSYS 2021 R1.

2.2 Modal Analysis

The modal analysis of the PCB assembly was performed in ANSYS 2021 R1. The material properties of various elements used for the modal analysis are listed in Table 1. The PCB assembly was meshed with solid elements, and adaptive sizing was used for meshing. The mesh quality metrics, skewness, and average orthogonal quality values were found to be 0.4042 and 0.5937, which fall in the good spectrum as per the ANSYS mesh quality recommendations. The meshed model of PCB assembly is shown in Fig. 1. The PCB was constrained in all degrees of freedom by providing fixed support to the four corner holes used to mount the PCB. As the dynamic characteristics of the PCB only in

Table 1 Material Properties used for the analysis [10]

Material	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m^3)
FR-4	18.9	0.3	1900
SAC 305	51	0.36	7400
Silicon Die	130	0.22	2300
Molding Component	22.54	0.21	1880
Substrate	22.0	0.28	2000

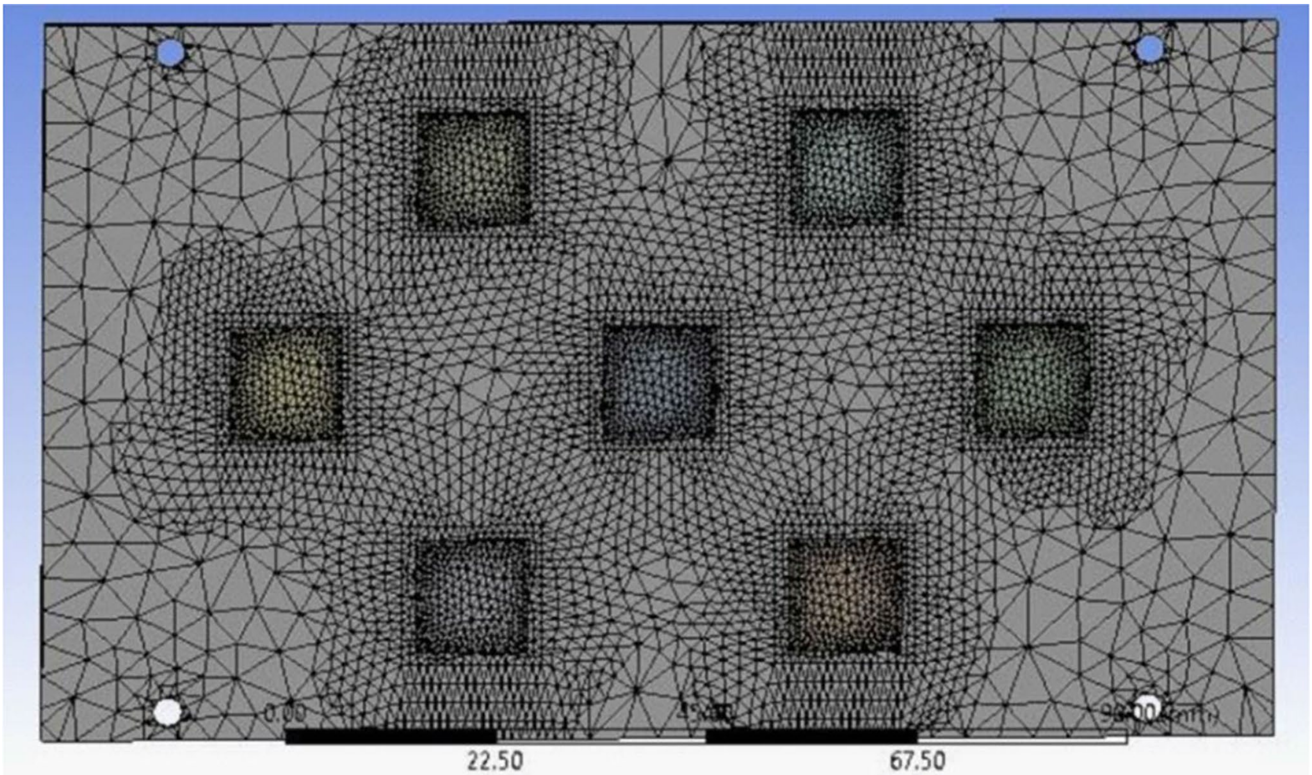

Fig. 1 Meshed model of the PCB Assembly

transverse vibrations are desired, even though the PCB is made up of FR-4 composite material, the whole assembly is assumed to be of a linear system.

2.3 Random Vibration Analysis

By virtue of the probabilistic nature of random vibrations, the future behavior of such a vibrating system cannot be predicted precisely [23]. The randomness is not a characteristic of the mode shape or natural frequency, but is a characteristic of the input or excitation. Power Spectral Density (PSD) is a probability statistic method where the power spectrum can be displacement, acceleration, velocity, force spectral density, or other forms.

Random vibration analysis was performed to analyze the fatigue life of the PCB assembly with SAC 305 solder junctions, which are susceptible to high cycle fatigue due to random vibrations. The analysis was performed to determine the PCB assembly's structural response and dynamic characteristics under vibration loading conditions. ANSYS software was used to perform the finite elemental analysis to determine the response of the PCB system. For determining the PCB assembly's response PSD, the modal analysis results were given as input for the random vibration analysis.

The input PSD provided for the random vibration analysis was a white noise of 0.01 G^2/Hz with root mean square acceleration of $3G_{rms}$ over a frequency range of 100 Hz to 1000 Hz [24]. The same boundary conditions used for the modal analysis were also used for the random vibration analysis. The four corner holes on the PCB used for mounting were established as fixed supports during the analysis. Figure 2 represents the input PSD G-Acceleration (in G^2/Hz) over the frequency range of 100 Hz to 1000 Hz.

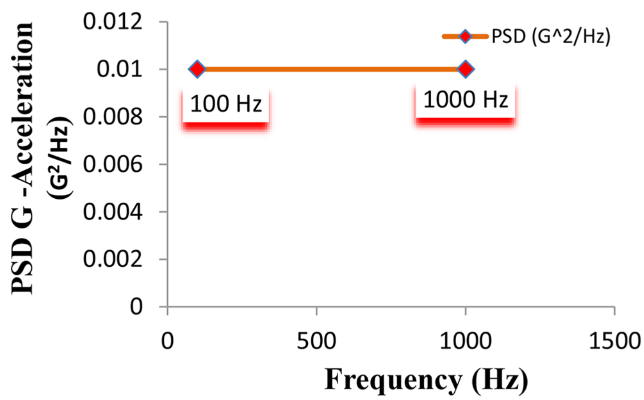

Fig. 2 Input PSD G-Acceleration Vs. Frequency graph

2.4 Experimentation

Experimental validation is generally done to check how numerical analysis results agree with the experimental

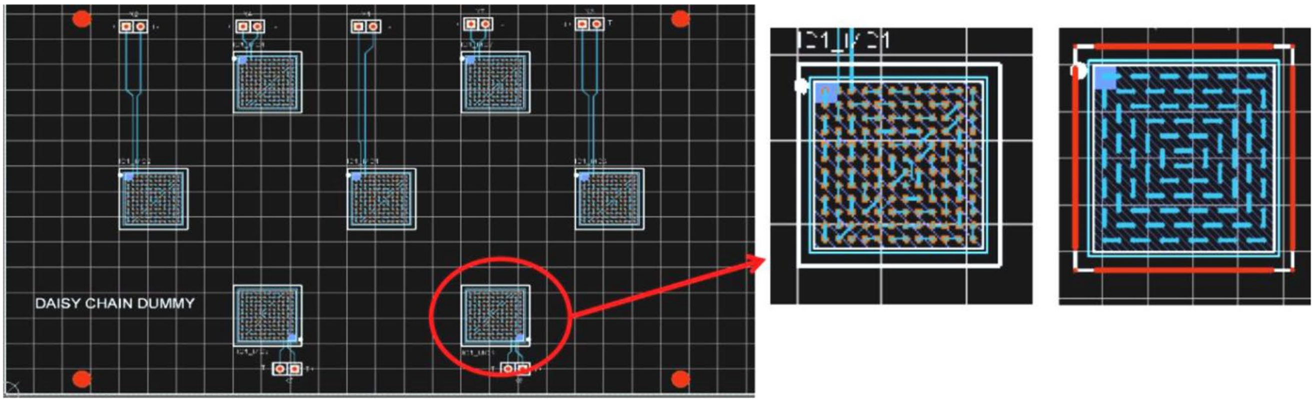

Fig. 3 Schematic circuit diagram of the PCB (top side) and Package (bottom side)

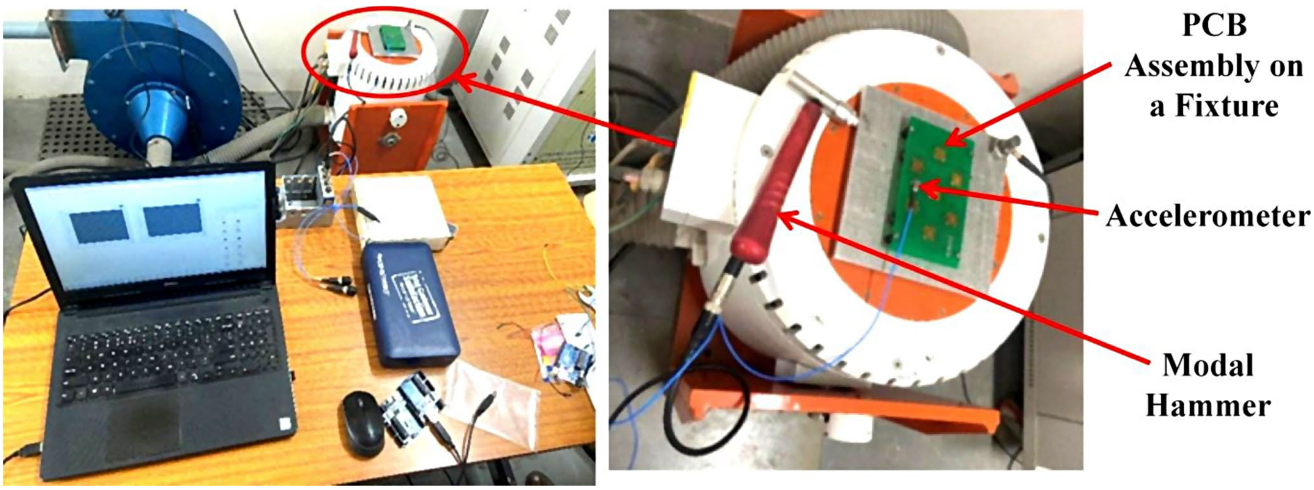

Fig. 4 Modal analysis setup

results. Here, results of the numerical analysis performed using ANSYS 2021 R1 were validated against the experimental results of the PCB with 7 PBGA package assembly to compare the efficacy of the developed model. For manufacturing the PCB, a schematic circuit diagram of the PCB system was designed using the software Altium Designer V19.1. The PCB with dimensions of 132 mm x 77 mm x 0.8 mm was designed beholding the footprint of 7 PBGA packages with the specification of 144 pins and 0.8 mm pitch. The PBGA packages of 12 mm x 12 mm x 2 mm were also designed and placed on the PCB as specified in the CAD model. Figure 3 shows the Gerber file image of the PCB and the package.

Figure 4 represents the modal analysis setup used for the experimentation. The natural frequency was observed using the LabVIEW V19 software. A block diagram was created using the software for performing experimental modal analysis to find the natural frequency of the PCB assembly [25]. In order to monitor the response of the PCB assembly, which was supported by a fixture for free vibration, a tri-axial accelerometer was mounted on it. Furthermore, a DAQ card was connected to the system, and the channel to which the DAQ card connected was given as input in the LabVIEW V19 software. To perform the modal analysis, a modal hammer was used to create free vibration, and the response plot of the vibration was obtained between the time domain and frequency domain.

The LabVIEW program used for the modal analysis is shown in Fig. 5. The DAQ card collects the data during the vibration, and the waveform was plotted to visualize natural frequency. The results from the experimentation are compared with the numerical analysis results [26].

Figure 6 represents the random vibration setup used for the experiment. In the random vibration experiment, a uni-axial accelerometer was connected to the fixture of the shaker to monitor the random input response to the electro-dynamic shaker. Another tri-axial accelerometer was mounted on the PCB assembly to measure the output response of it. An Arduino board was used to measure the increase in resistance of the designed Daisy chain circuit [27]. The external circuit was created in Arduino to monitor the resistance of every package [28]. The Arduino was connected to the setup

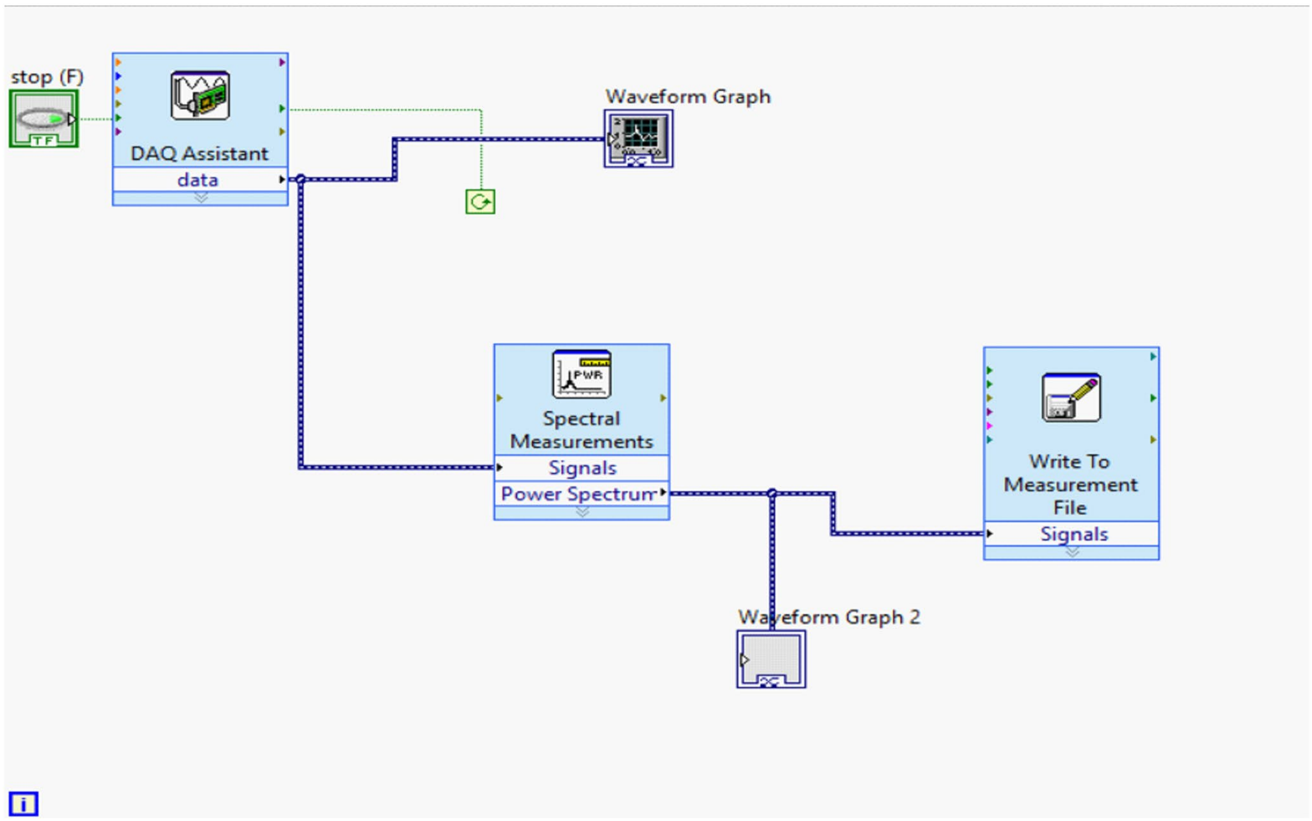

Fig. 5 LabVIEW Block Diagram

Fig. 6 Random vibration setup

with the help of single-stranded wires. Copper wires were soldered to the input and output ends for the live monitoring of the resistance.The input conditions with PSD G-Acceleration of 0.01 G^2/Hz were given in the Shaker controller software, and a pre-test was conducted to check whether the circuit was correct. Acceleration PSD was taken as an output from LabVIEW software, a plot between frequency (Hz) and amplitude (mm). The experiment was conducted until all 7 PBGA packages failed. The packages were considered to fail when the circuit's resistance exceeded 20% of the initial resistance [29].

2.5 Fatigue Life Prediction

The fatigue life of the PCB assembly subjected to random vibration loads was calculated using a narrow bandwidth approach under three different methods: Miner's rule, Wirsching & Light Method, and Ortiz & Chen Method.

2.5.1 Miner's rule

In random vibration situations, many structural components of electronic systems, such as solder joints, will be forced to operate in their nonlinear ranges. Estimating their fatigue life is challenging because they must function in differentenvironments; it is often convenient to assume that these structural components are linear to determine their approximate fatigue life. In a linear system, the stress-induced will be proportional to the dynamic displacements and the acceleration G level (in dimensionless gravity units) [23].

Based on the stress response values obtained from random vibration analysis using ANSYS 2021 R1, Miner's rule was used to find the life of the PCB assembly [].

$$S_{a,i} = \sqrt{PSD * \Delta f} * crestfactor \tag{5}$$

$$N_{f,i} = A * (S_f)^{-m} \tag{6}$$

Where $S_{a,\,i}$ is the stress amplitude (MPa), Δf is the bandwidth of the half-power points, S_f is the fatigue strength coefficient in MPa [31], m is equal to 1/b where b is the fatigue strength exponent, and crest factor = 1.414.

2.5.2 Wirsching & Light Method

A narrow-band process is harmonic and smooth. Every peak has a matching zero-up crossing, implying that E[0+] = E[P]. The wide-band method, on the other hand, is more erratic. The ratio of the zero up-crossing rate to the peak crossing rate measures this irregularity. The ratio is known as the irregularity factor, 'γ', shown in Eq. (7) [32].

$$\gamma = \frac{E\left[0^{+}\right]}{E\left[P\right]} \tag{7}$$

There are an unlimited number of peaks for every zero-up crossing when γ = 0. This is considered a random process with a wide band. A narrow-band random process with a value of $\gamma = 1$ that corresponds to one peak for every zero up crossing. Alternatively, the breadth of a process's spectrum may be used to determine if it is narrow-band or wide-band. As a result, the spectral width parameter,′ λ ′ is defined in Eq. (8) as,

$$\lambda = \sqrt{1 - \gamma^2} \tag{8}$$

If M_j is the j^{th} moment of a one-sided PSD function defined as

$$M_j = \int_0^\infty f^j W_{S_a} f\,(df) \tag{9}$$

2.5.3 Ortiz and Chen Method

Oritz and Chen also derived another similar expression for fatigue damage, D_{WB}, ORTIZ, under wide-band stresses, shown in Eq. (10) as [33, 34].

$$D_{WB}, ORTIZ = \tau_0 * D_{NB} \tag{10}$$

$$\tau_0 = \gamma * \left(\sqrt{\frac{M_2 * M_0}{M_0 * M_{k+2}}}\right)^m \tag{11}$$

and k = 2/m

2.6 Study on Packaging Location on PCB

The location and orientation of the packages on a printed circuit board play a vital role in the life of electronic systems. Stress distribution in the solder ball is influenced by many parameters such as the number of solder balls on a single package, position of the solder ball on the package, position of the package on the PCB with respect to fixed support location, length & width of the PCB board, dimensions of the package used, the material used for the package & PCB and solder connection present in the package [13].

Hence, the study of the location and orientation of the packages on a PCB is essential to estimate the fatigue life of the PCB assembly. This study modeled PCB assemblies with a single PBGA package mounted at seven different positions andthen subjected to random vibration loads. The stress distribution plot of the package at seven different positions of PCB assembly was studied to find the critical solder joint and the maximum stress on the package. The fatigue life of the PCB assembly at seven different positions of packages was calculated based on the stress PSD obtained. The package with the maximum life with minimum stress was recommended for critical applications.

2.6.1 Design of PCB Assemblies with Single PBGA Packages

The PCB assemblies with a single PBGA package were designed as per the JEDEC standard [21]. The dimension of the PCB used in the study was 132 mm x 77 mm x 0.8 mm, and it was made of FR-4 epoxy material, as shown in Fig. 7. The 7 locations of the package used were at U2A, U4A, U6A, U8A, U10A, U12A, and U14A positions. The CAD model of the 7 PCB assemblies with single PBGA packages (with the dimension of 12 mm x 12 mm x 2 mm) was created using SOLIDWORKS 2018 modeling software. The PBGA package has 144 solder balls with SAC 305 (96.5% Sn – 3.0% Ag – 0.5% Cu) as solder material. The designed PCB assembly was used for the modal analysis to predict

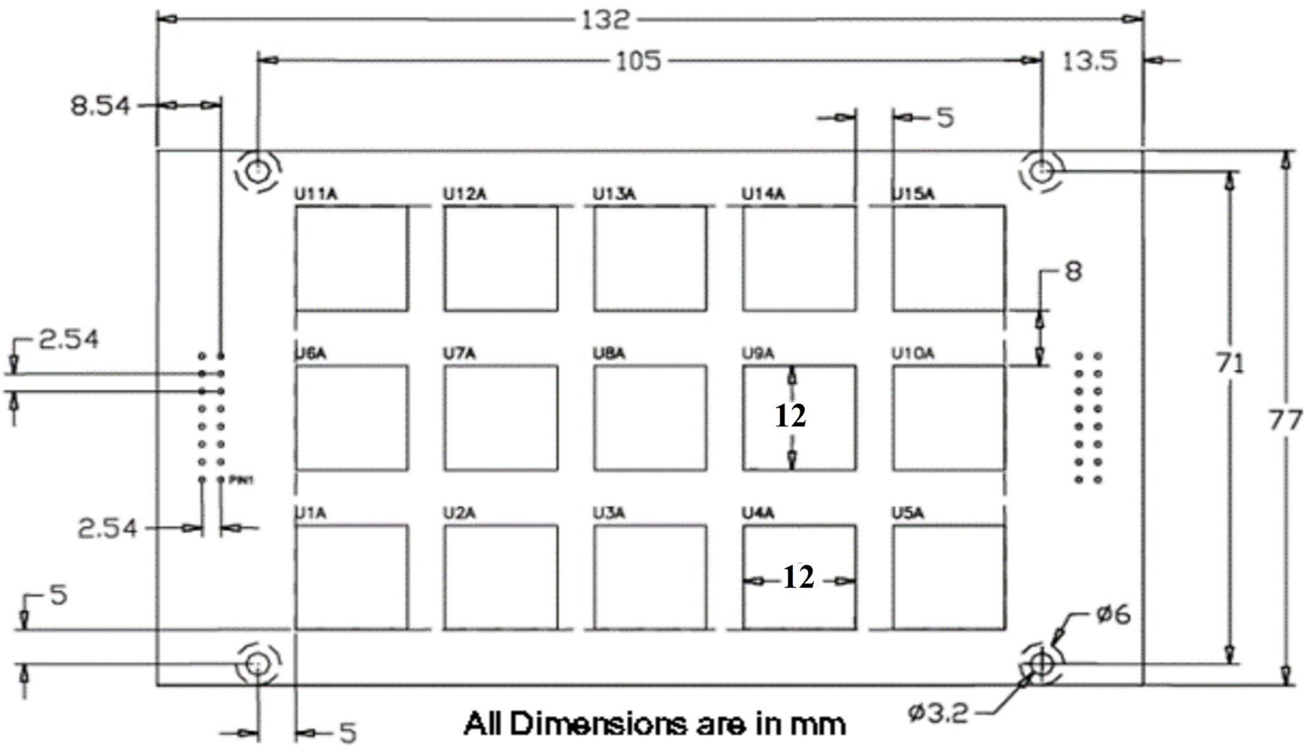

Fig. 7 Dimensions of the test board [21]

the natural frequency and the mode shapes determined by the material properties like stiffness, mass, and damping properties.

The numerical analysis was performed with the help of ANSYS 2021 R1. The four holes were given as fixed support for performing the analysis. The modal analysis results were given as input for random vibration analysis, and PSD G_{rms} of 0.01 G^2/Hz were also given as input. The equivalent stress values of 144 balls of every PBGA package were taken as output, along with the stress PSD values. The fatigue life of 7 different PCB assemblies with PBGA packages subjected to random vibration was calculated using Miner's rule, Wirsching & Light method, and Ortiz & Chen method.

3 Results and Discussions

3.1 Modal Analysis of the PCB Assembly with 7 PBGA Packages

The modal analysis was performed for the PCB assembly with SAC 305 as solder material. The analysis was performed by giving a fixed support at four corner holes of the assembly as input and natural frequency was obtained as output. The first mode obtained has maximum deformation in the U8A position of the PCB location. The PCB underwent bending in first mode, and the maximum deformation was observed at the center of the assembly. In second mode, it experienced twisting, and the highest deformation was observed at the assembly's top and bottom ends (U6A and U10A positions). In subsequent modes, the PCB experienced combined twisting & bending, and the maximum deformation was observed at different PBGA packages of the assembly [35].

The 3rd mode had its peak deformation inthe corner of the assembly at the U3A and U13A positions. The 4th mode had its highest deformation at the U6A and U10A positions. Similarly, the 5th and 6th modes had their peak deformation at the ends of the assembly in U6A and U10A positions, respectively. All the natural frequencies obtained for the PCB assembly with SAC 305 as solder material was obtained within the random white noise input range of 100 Hz to 1000 Hz. For the PCB assembly with SAC 305 as solder material, the natural frequencies and their corresponding mode shapes are shown in Fig. 8.

Table 2 shows the natural frequencies of the PCB assembly with SAC 305 as solder material obtained through FE analysis.

3.2 Experimental Validation

Free vibration test was performed experimentally to validate the dynamic characteristics of 7-chip PCB Assembly

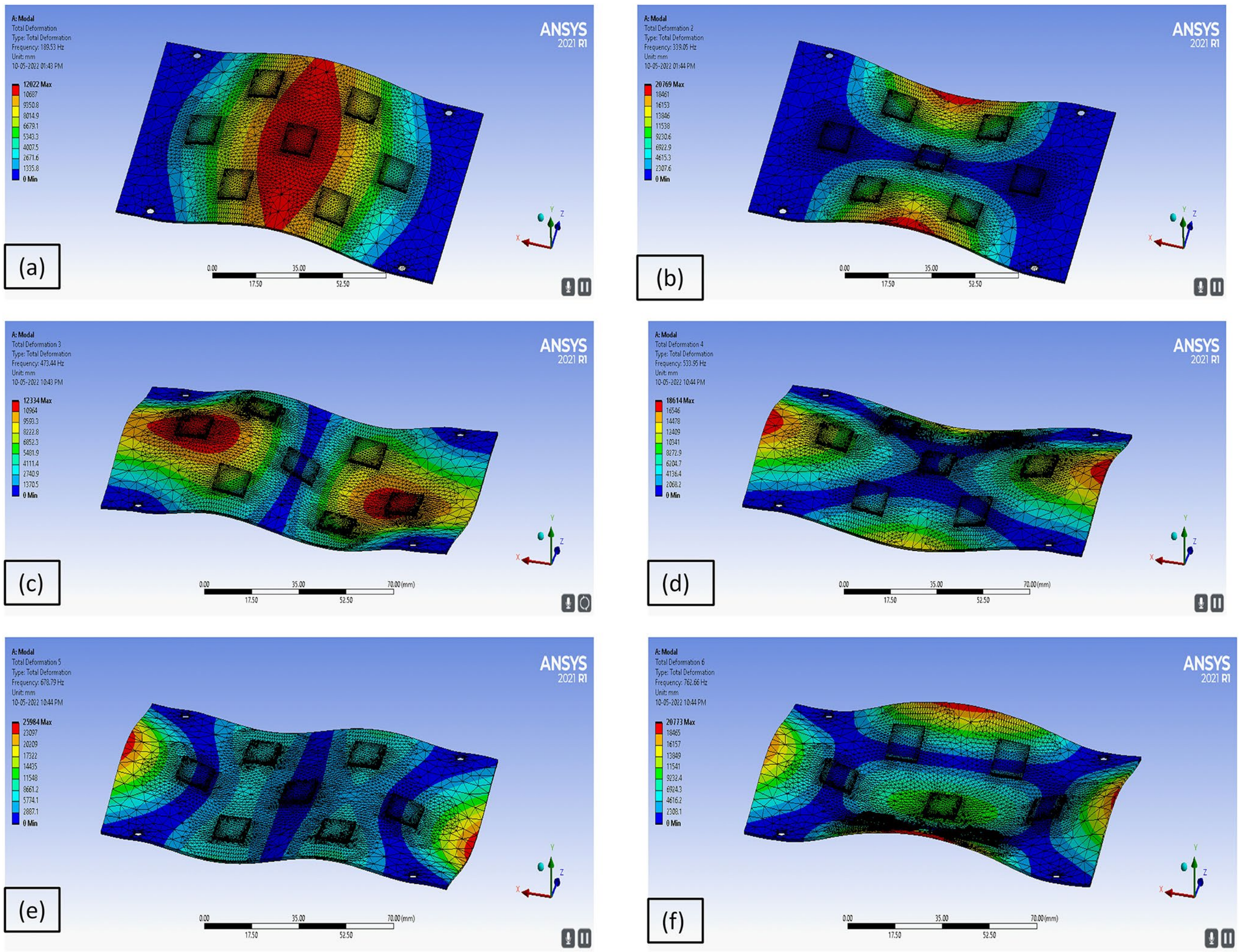

Fig. 8 Mode Shape of PCB assembly from 1st mode to 6th mode

Table 2 Natural frequencies of the PCB assembly

Mode	Natural Frequency(Hz)
1	189.53
2	339.05
3	473.44
4	533.95
5	678.79
6	762.66

with SAC 305 solder obtained from the Finite Element method. Using LabVIEW 2019 software, the amplitude of acceleration Vs.Time plot and amplitude of acceleration Vs.Frequency plot was obtained, as shown in Fig. 9. It is observed from the plot that all the natural frequencies obtained correlate well with the FE results.

In higher modes, small variations are found in the transmissibility and natural frequency of the fabricated structure with that of a numerically developed model. This is due to the differences in the manufacturing tolerances in sheet metal thickness, surface finish, interface pressures, surface flatness, material hardness, humidity conditions, and assembly sequence [16]. However, the variations found among them are within the allowable limit (less than ±10%) the numerical model developed is validated and can be used for further analysis. The damping characteristics observed from the modal testing are listed in Table 3.

3.3 Random Vibration Analysis of the PCB Assembly with 7 PBGA Packages

The results from the modal analysis were given as input for random vibration analysis along with G_{rms} of 0.01 G^2/Hz. Equivalent stress and total deformation were taken as output along with the stress response PSD. For the PCB assembly with SAC 305 solder joints, the critical area subjected to maximum stress was found in the corner solder ball of the PCB assembly (Solder ball 12) [32]. From the equivalent stress results, it is understood that the center package located at the U8A position on the PCB has the critical solder joint,

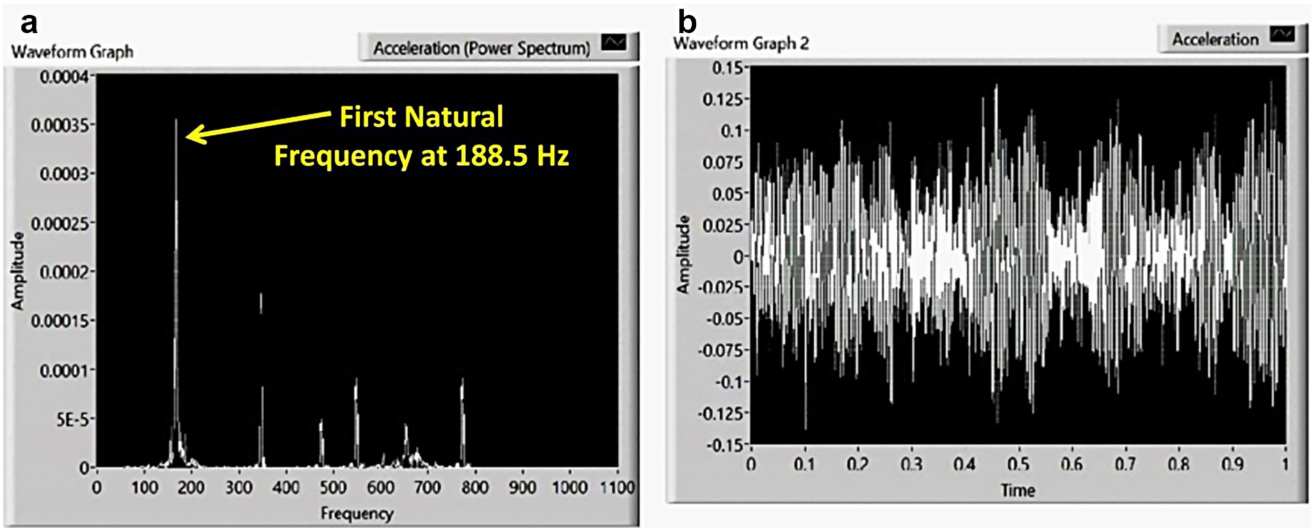

Fig. 9 (**a**) Amplitude (mm/s^2) Vs. Frequency (Hz) and (**b**) Amplitude (mm/s^2) Vs.Time (s)

Table 3 Damping characteristics of the PCB assembly

S.No.	Mode	Natural Frequency (Hz)	Damping (Hz)	Damping (%)
1.	1	188.5	2.35	1.27
2.	2	346.3	3.74	1.21
3.	3	481.0	5.13	1.05

hence the location is identified as the most vulnerable position on the PCB.

Figure 10 shows the equivalent stress induced in the PCB assembly and a critical solder joint (Solder ball 12), with a maximum stress value of 21.74 MPa. It is inferred from the results that the corner ball of the package experience maximum stress, and the corner ball tend to fail first when subjected to random vibration loads.

The stress response PSD curve is shown in Fig. 11 for the PCB assembly with SAC 305 solder. The stress response PSD values obtained due to random vibration loads correspond to the natural frequencies obtained in the modal analysis. The stress PSD value of 120.64 MPa^2/Hz was obtained in the first mode of 189.53 Hz. Similarly, the second and third peak stress PSD values of 0.3563 MPa^2/Hz and 0.1743 MPa^2/Hz occurs at fourth and sixth mode of 533.9 Hz and 762.86 Hz, respectively.

3.4 Fatigue Life Calculation

The stress response corresponding to the natural frequencies obtained from the stress response PSD of the random vibration analysis for PCB assembly with SAC 305 as solder material is shown in Fig. 11. The values of the stress PSD of the response are presented in Table 4.

3.4.1 Fatigue Life Calculation for the PCB Assembly with 7 PBGA Packages

The fatigue life of the PCB assembly with two different solder materials under Miner's rule, Wirsching & Light method, and Ortiz & Chen method are presented in Table 5.

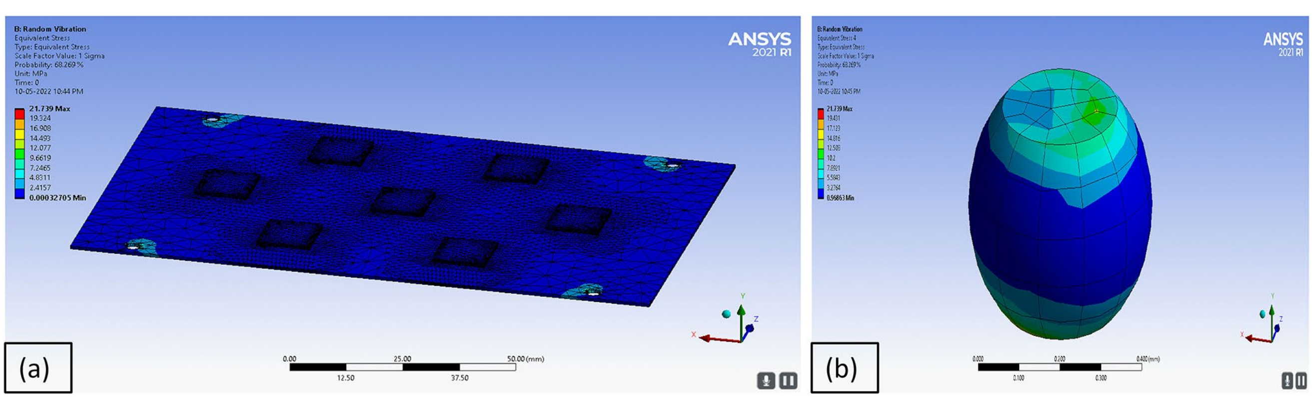

Fig. 10 Equivalent Stress induced in (**a**) the PCB Assembly and (**b**) a Critical solder joint

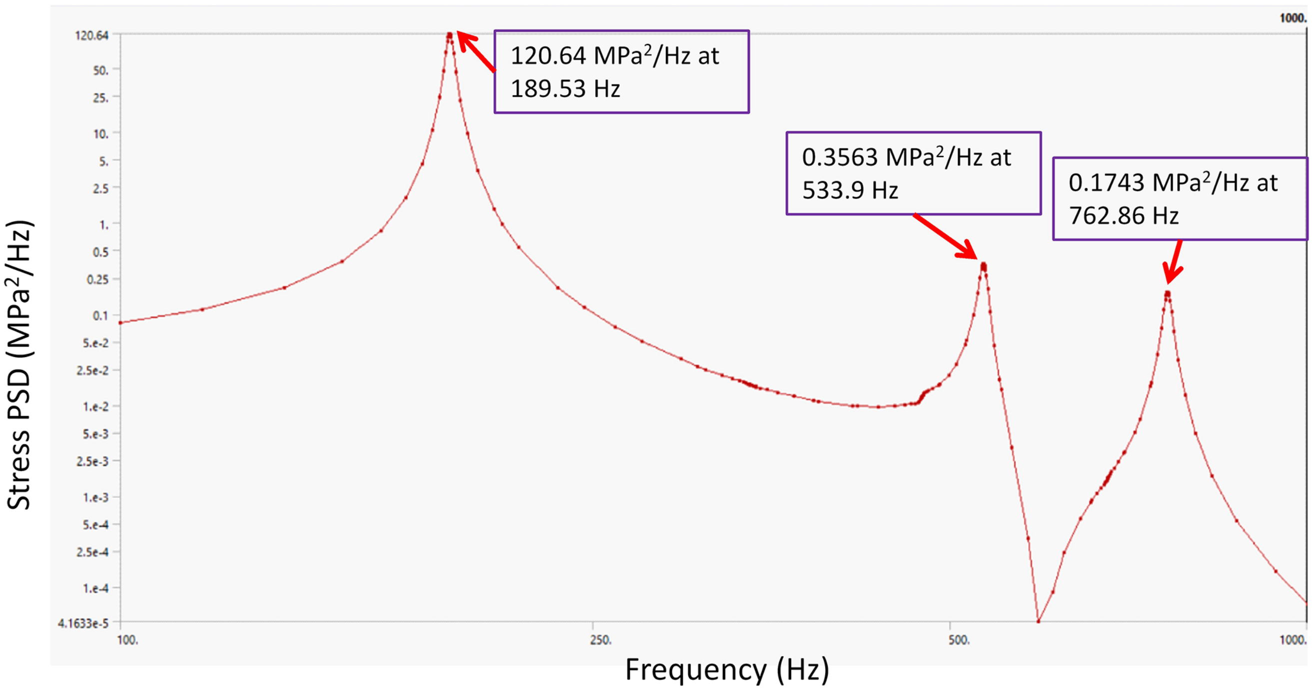

Fig. 11 Stress response PSD Curve for PCB assembly

Table 4 PSD of stress response at natural frequencies

Natural Frequency (Hz)	PSD of the Stress Response (MPa^2/Hz)
189.53	120.64
533.9	0.3563
762.86	0.17431

Table 5 The fatigue life of the PCB assembly

Methods	Solder ball material and their Fatigue Life (minutes)
Miner's rule	36.53
Wirsching & Light Method	38.77
Ortiz & Chen Method	56.5

Since the assumption of the linearity between the dynamic displacement and the induced stress was taken into account in the Miner's rule of fatigue life prediction model, it is inferred from the fatigue life study that a 6.1% of variation has been found between the Miner's rule and Wirsching & Light method. Whereas, due to the simplified assumptions in the Ortiz & Chen method, 54.7% variation has been found in the fatigue life of the PCB assembly when compared with Miner's rule.

Ortiz and Chen's method relies on simplified assumptions about the loading conditions and material behavior. It assumes that the loads are Gaussian distributed and that the material response follows linear elastic behavior. In reality, random vibration loading conditions can exhibit non-Gaussian characteristics, and material behavior may deviate from linear elastic assumptions, leading to deviated fatigue damage accumulation when compared with other fatigue life prediction methods. Furthermore, Ortiz and Chen method overlooks the frequency content of the random vibration loading by assuming the fatigue damage is solely determined by the root-mean-square (RMS) value of the load, ignoring the potential contribution of specific frequency components that may result in varied fatigue life.

3.5 Experimental Validation

An experiment was conducted to validate the fatigue life obtained from the results of the PCB assembly subjected to random vibration through numerical simulation. A swept sine test was performed before the random vibration test to validate the natural frequencies obtained from modal testing. The solder joint failure was identified by real-time monitoring of the resistance in the daisy chain circuit. The resistance of the daisy chain circuit can be calculated continuously using a simple voltage divider circuit and an Arduinocircuit [36]. In the Arduino circuit, the unknown resistance was replaced with the positive and negative terminals of the daisy chain during experimentation. The Arduino programming code was used to measure the resistance in the circuit. During the vibration test, the resistance of the daisy chain increases as solder balls fail. According to the IPC standard, the failure criterion is specified as the daisy chain resistance increased by 20% of its initial value six times in a row [29]. The initial resistance was found to

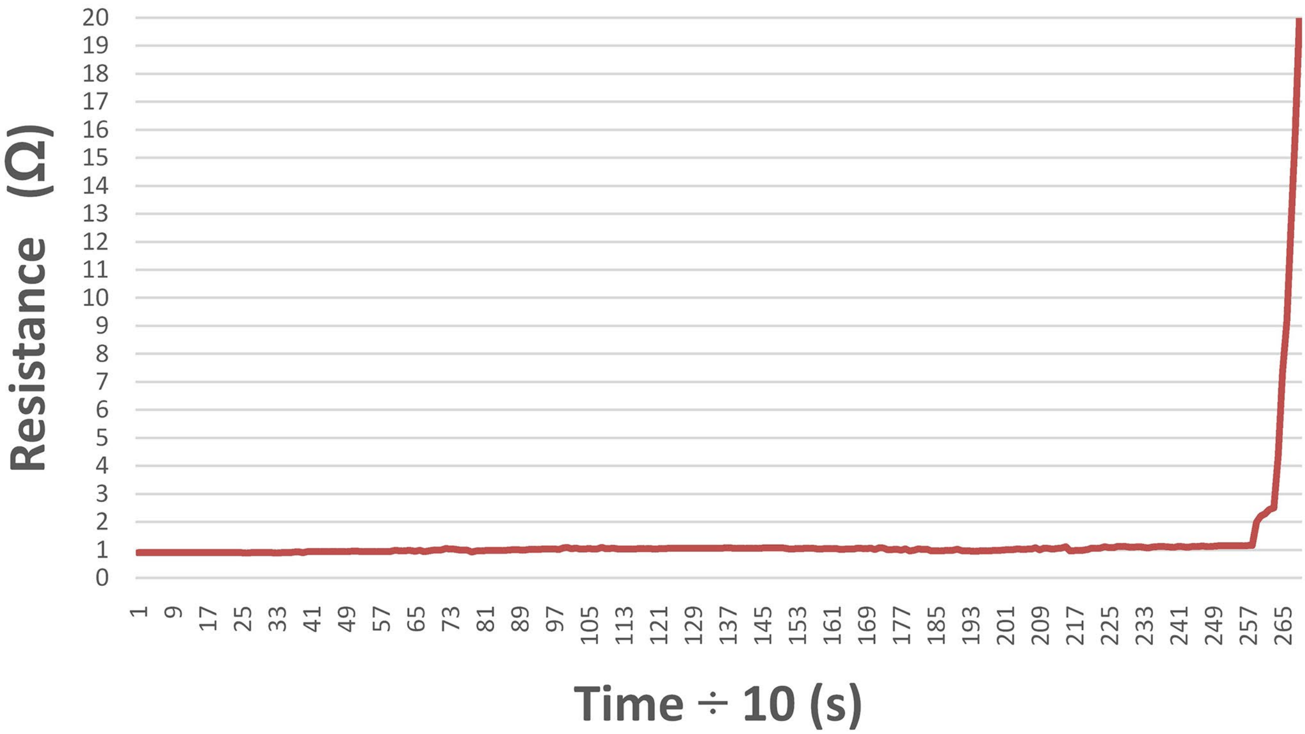

Fig. 12 Resistance (Ω) Vs.Time (s) plot

Table 6 Comparison of Experimental and Numerical Analysis results

	Fatigue Life of the PCB assembly (minutes)		Error (%)
Methods	Numerical Analysis	Experimental	
Miner's rule	36.53	42.83	14.7
Wirsching & Light Method	38.77		9.48
Ortiz & Chen Method	56.5		31.91

be 0.95 **Ω**. Figure 12 shows the resistance of the daisy chain circuit (unknown resistance) for the package mounted at the U8A position (which failed first) that was noted every 10 s with the help of the Arduino circuit.

A graph was plotted between the time interval in seconds and the resistance in **Ω**. It is inferred from the plot that the PCB assembly had failed when its resistance exceeded 1.14 **Ω** (20% increase in initial resistance). The failure of the PCB assembly is seen from the sudden steep increase in the circuit's resistance.

Table 6 compares the PCB assembly's theoretical and experimental fatigue life results of the PCB assembly with 7 PBGA packages (with SAC 305 solder).

Since the fatigue life prediction made by the Wirching & Light method agree well with the experimental results, it is considered as the most reliable and highly significant result. The deviation in the results of Ortiz and Chen's method is due to the method's assumptions and simplifications which may not adequately capture the complexities of random vibration loading, leading to potentially large errors in the estimated fatigue life.

3.6 Packaging Location Analysis

3.6.1 Stress Plot of the PCB Assembly with Single PBGA Packageat Various Locations

Considering the input conditions discussed for the multi-PBGA-PCB assembly, the random vibration analysis was performed for the PCB designed with a single PBGA package at various specified locations. Figure 13 represents the stress response plot obtained for the PCB assembly with SAC 305 solder at various locations of the PCB, namely U2A, U4A, U6A, U8A, U10A, U12A, and U14A positions, respectively.

The maximum stress obtained in the U8A position (centerpackage) was 22.72 MPa in the corner solder joint (Solder ball 133). The maximum stress obtained in the U2A position was 18.3 MPa in the corner solder joint (Solder ball 133), whereas the maximum stress induced in its symmetric position, U4A, was 18.85 MPa at solder ball 1. Similarly, the maximum stress obtained in the U6A position was 10.59 MPa at solder ball 12, and in its symmetric position, U10A was 9.74 MPa at solder ball 144. U12A and U14A positions are symmetric in nature and experience maximum stress of 19.19 MPa and 18.31 MPa, respectively, at solder ball 1 of the package.

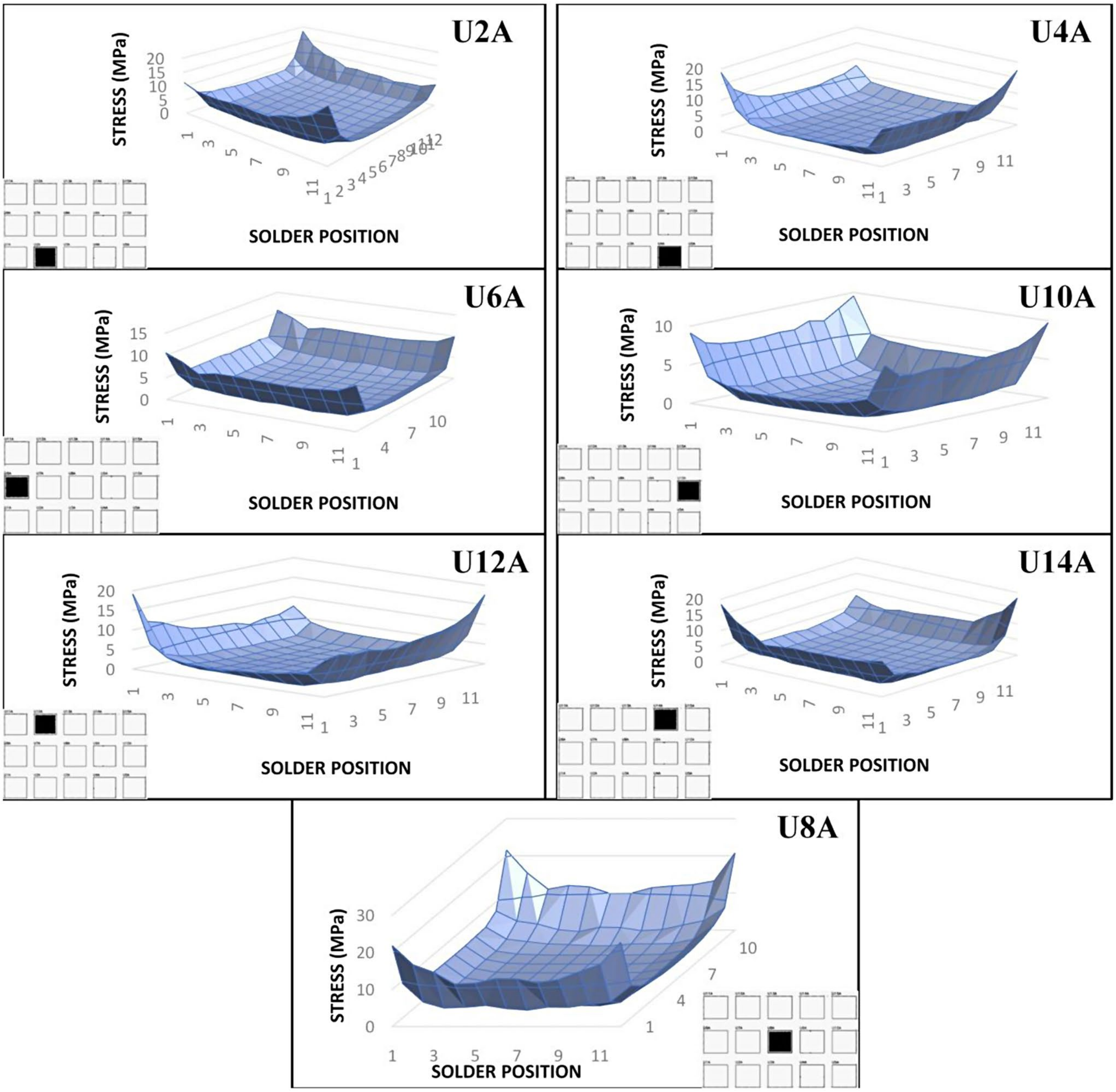

Fig. 13 Stress plot obtained for the PCB Assembly in U2A, U4A, U6A, U10A, U12A, U14A & U8A positions

The corner solder joints in every PBGA package experienced maximum stress, whereas the stressinduced toward the package's center was minimal. It is inferred from this analysis that the stress increases in the corner joint of a package along its length direction and decreases as it moves towards the package's core and once again increases towards the periphery of the package. Furthermore, the following point is inferred from the stress plot obtained for various locations. The Equivalent stress values obtained for the PCB assembly at various locations varied similarly, i.e., the stress values were maximum at the corner solder joints and minimum at the center of the row and column. The stress values followed a similar pattern in all packages, i.e., increasing stress values at the start of the solder row, then decreasing at the midway and increasing towards the end. This stress pattern was observed in all 7 locations of the PCB assembly with a single PBGA package, considering the bending was dominant under the first mode.

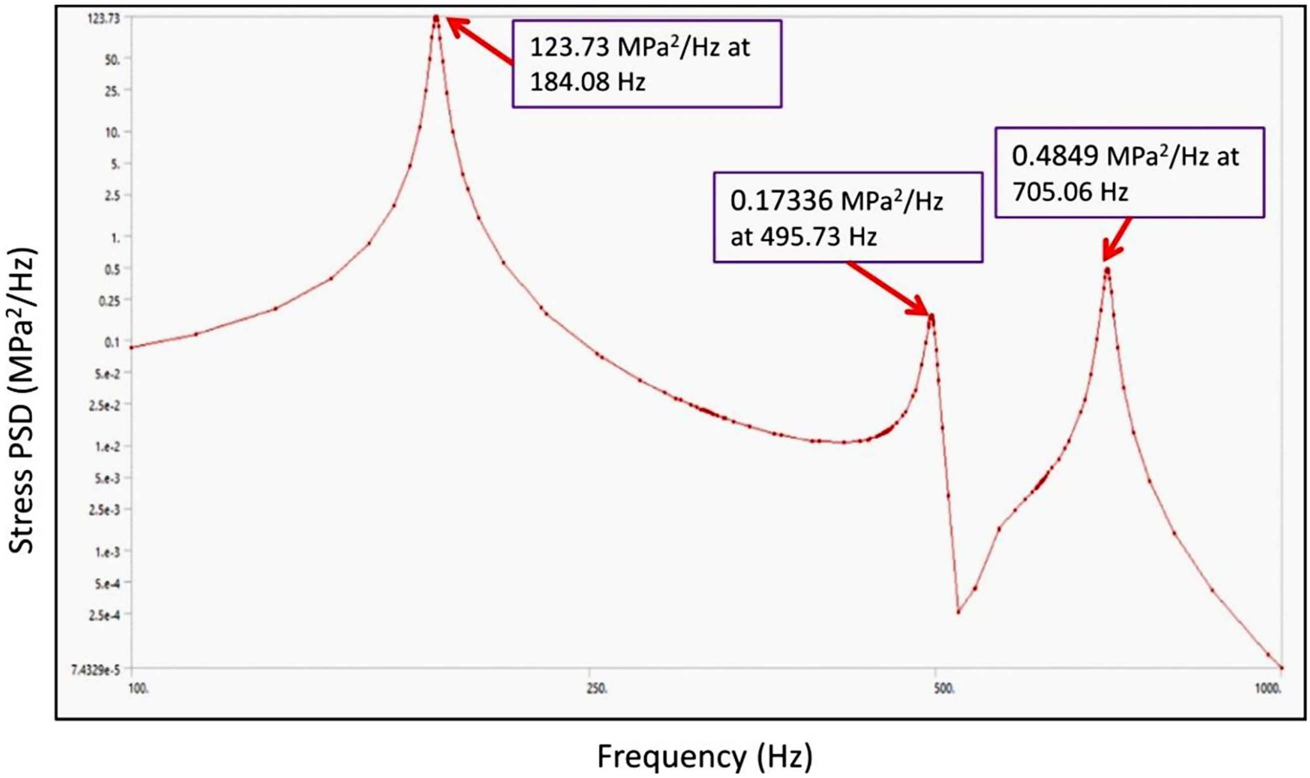

Fig. 14 Stress response PSD curve for the single PBGA package PCB assembly at U8A position

Table 7 Stress response of the PCB assembly (for U8A position)at natural frequencies

Frequency (Hz)	Stress Response (MPa^2/Hz)
184.08	123.73
495.73	0.17336
705.06	0.4849

Table 8 The fatigue life of single-package PCB assembly at various positions

	The fatigue life of PCB assembly at various positions (min)		
Package Position	Miner's Rule	Wirsching & Light Method	Ortiz & Chen's method
U2A position	57.02	60.36	96.93
U4A position	54.76	49	124.52
U6A position	124.1	125.7	165.33
U8A position	53.36	55.38	105.81
U10A position	121.02	126.13	164.62
U12A position	60.37	57.83	145.67
U14A position	68.71	72.01	128.17

3.6.2 Fatigue Life Calculation of the PCB Assembly at Various Locations

The fatigue life for the PCB assemblieswith a single PBGA package mounted at various locations was calculated using Miner's rule, Wirsching & Light method, and Ortiz & Chen method.The fatigue life of the PCB assembly subjected to random vibration loads was calculated using a narrow bandwidth approach. A sample of the stress response corresponding to the natural frequencies obtained from the stress response PSD for the PCB assembly with SAC 305 solder is shown in Fig. 14, and their values are presented in Table 7.

Table 8 lists the fatigue life of the PCB assemblies (with SAC 305 solder and the PBGA packages mounted at various locations) under random vibration loads. The fatigue life was calculated using Miner's rule, Wirsching & Light method, and Ortiz & Chen method. It can be inferred from the results that the fatigue life tends to be maximum when the chip is away from the maximum deformation zone. As the bending was dominant in the fundamental mode, the maximum deformation occurs at the center of PCB assembly; thus, the center package (U8A position) tends to experience maximum stress and has the least fatigue life of 53 min. The minimum and maximum deviation from the fatigue life of the center package with that of other positions under Miner's rule was found to be 2.62% & 132.57%, respectively.

Similarly, the minimum and maximum deviation from the center chip under Wirsching & Light method and Ortiz & Chen method were found to be 4.42% & 127.75%, and 8.68% & 56.25%, respectively. From the fatigue life values, it is inferred that U6A and U10A positions have the highest fatigue life. If a package on a PCB assembly is placed in U6A and U10A positions instead of U8A, the fatigue life of the PCB assembly increases by 132.57%. The fatigue life increases along the length direction of the assembly, and it can be seen that, as the package moves towards the support location, it is least affected under random vibration loads. This analysis concluded that if the PBGA package is placed in the PCB's U6A or U10A position, the fatigue life will be the maximum.

4 Conclusion

Electronic manufacturers produce PCB assemblies with the PBGA packages surface mounted at the center of the PCB in the case of single-chip modules. However, modern electronic devices with multi-tasking capabilities carry multiple PBGA packages surface mounted on them. When defining the positioning of the packages, the dynamic characteristics of the PCB under extreme random vibration environment conditions are not considered. To investigate the vulnerability of the packaging position on the PCB assembly, a PCB test vehicle with 7 surface mounted chips and several PCB assemblies with a single chip mounted at seven different locations were designed according to the JEDEC standard.

To predict the fatigue life of the multi-chip PCB assembly subjected to random vibration loads, firstly, modal analysis was performed numerically for the PCB assembly with SAC 305 solder material and the results of the modal analysis were validated with that of modal testing. Secondly, random vibration analysis was performed numerically to find the critical solder considering the stress response PSD from the analysis. For the PCB assembly with SAC 305 as solder, the maximum stress was identified in the solder ball no. 12 of the assembly (corner solder joint), and the value was found to be 21.74 MPa. Based on the stress response-PSD obtained from the random vibration analysis, the fatigue life was calculated using three methods, namely Miner's rule, Wirsching & Light method, and Ortiz & Chen method. The results from the numerical analysis were validated against the experiments by continuously monitoring the electrical resistance in the PCB assembly.

Fatigue life of the PCB assemblies with single PBGA packages mounted at seven different locations subjected to random vibration loads was found using the fatigue life prediction models mentioned above. It is inferred from the analysis that the U8A (center position) is the most vulnerable position according to its dynamic behavior of it, and the U6A & U10A positions of the PCB assembly had the maximum fatigue life. Hence it is suggested to those manufacturers of such PCB assemblies that if the PBGA packages were placed in those safe positions, the products would have a longer life when compared with that of the packages mounted at the center position. This research has also proven the dependability of the fatigue life of the electronic packages with respect to its position on the PCB, thereby ensuring the possibility of improved mechanical reliability of the electronic system.

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Data Availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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