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Enhancing the Fatigue Life of PCB Assemblies through Strategic Positioning and Novel Support Techniques for Ball Grid Array Packages

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Abstract: The fatigue life of solder balls in Ball Grid Array (BGA) packages of a Printed Circuit Board (PCB) assembly is a key factor that influences the reliability of electronic devices. This study explores three novel methods to enhance the fatigue life of the PCB assembly with BGA packages, focusing on stress reduction techniques in solder balls under random vibration. The numerical analysis of the PCB assembly examined stress distributions and identified optimal design strategies to improve resistance to fatigue under random vibration. The findings demonstrate that strategic positioning of BGA packages, the use of additional supports, and modifications to PCB assembly can significantly reduce stress on solder balls, thus extending their fatigue life 8 to 10 times that of the existing design.

Keywords: Fatigue Life, Ball Grid Array (BGA) packages, PCB, Reliability, Optimal design, Random Vibration

Povečanje življenjske dobe PCB sklopov s strateškim pozicioniranjem in novimi tehnikami podpore za ohišja Ball Grid Array

Abstract: Življenjska doba kroglic spajke v BGA (Ball Grid Array) ohišjih tiskanih vezij (PCB) je ključni dejavnik, ki vpliva na zanesljivost elektronskih naprav. Ta študija raziskuje tri nove metode za povečanje življenjske dobe PCB-sestavov z BGA ohišji, s poudarkom na tehnikah zmanjševanja napetosti v kroglica spajke pod naključnimi vibracijami. Numerična analiza PCB-sestavov je preučila porazdelitev napetosti in identificirala optimalne strategije oblikovanja za izboljšanje odpornosti proti utrujenosti pod naključnimi vibracijami. Ugotovitve kažejo, da lahko strateško pozicioniranje BGA elementov, uporaba dodatnih podpor in spremembe PCB-sklopov znatno zmanjšajo napetost na spajkalnih kroglicah, s čimer se njihova utrujenost podaljša za 8- do 10-krat v primerjavi z obstoječo zasnovo.

Keywords: utrujenost, Ball Grid Array (BGA) ohišja, PCB, zanesljivost, optimalna zasnova, naključne vibracije

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1 Introduction

Ball Grid Array (BGA) packages are integral components in modern electronic devices, providing a compact and efficient means of connecting integrated circuits to printed circuit boards [1,2]. These packages are subjected to various mechanical stresses during operation, including thermal cycling and mechanical vibrations, which can significantly impact their reliability and lifespan [3]. Understanding the fatigue behavior of BGA packages under dynamic loading conditions is crucial for ensuring the longevity and performance of electronic assemblies [4]. Solder balls are integral to the BGA package, providing the electrical and mechanical connections between the package and the printed circuit board [5]. Understanding the factors that influence their fatigue life is vital for ensuring the reliability and longevity of electronic devices. Failure of these solder balls can lead to a range of issues, from intermittent connections to complete device failure, posing a significant risk to product reliability and consumer safety [6]. Moreover, the transition from potentially hazardous Pb-based solders to Pb-free solders has emphasized the need for research in fatigue life estimation of the PCB assembly with Pb-free solder BGA packages.

Various researchers have investigated PCB assembly with BGA packages to improve the fatigue life. Gharaibeh et al. [7] investigated the impact of support and fixation methods on the fatigue life and dynamic properties of electronic assemblies under vibration using a finite element analysis study. The findings of the study proved the dependability of the fatigue life on the support type and its locations. Liang et al. [8] investigated on the multi-layered PCB subjected to random vibration loads using finite element analysis. Solder joint stress was examined individually, and the combined sinusoidal-exponential equation was used to determine the normal and shear stresses, and reported the improved reliability with the reduced solder height.

Wang et al. [9] proposed an innovative approach combining Finite Element Analysis (FEA) simulations with random vibration tests to accurately predict solder joint failures. The study validated the accuracy of FEA-derived responses against experimental results, offering a time-efficient method for estimating an electronic device's fatigue life. Gao et al. [10] investigated the impact of vibrations on the BGA solder joint using finite element simulations. They identified optimized circuit configurations and stress distributions, emphasizing the influence of component positioning on the PCB. Yang et al. [11] studied the fatigue characteristics of Chip Scale Package (CSP) assemblies under vibration, providing design recommendations for improving fatigue life. The study highlighted the importance of component location and excitation intensity on fatigue behavior. Gharaibeh et al. [12] investigated the solder axial stresses and strains of the PCB assembly subjected to random vibrational loading using Taguchi's approach and reported that larger and thicker ICs, smaller and thicker PCBs may reduce solder strains and enhance fatigue performance of such assemblies.

These studies collectively demonstrate the complexity of solder joint fatigue under dynamic loading and underscore the importance of material selection, testing methods, and design considerations in enhancing electronic assembly reliability. The findings contribute valuable insights into optimizing BGA package design and improving solder joint fatigue in electronic devices subjected to challenging operational environments. However, very little literature has reported on the placement of the packages on the PCB and strategic positions of the support holes, and hence there is scope to the possibilities of improving the fatigue life by changing its design. The focus of this research is to explore methods to improve the fatigue life of solder balls in BGA packages. By understanding the factors that contribute to fatigue failure and implementing design and process optimizations, it is possible to extend the lifespan of BGA packages, thereby enhancing the reliability and fatigue life of electronic devices, especially BGA packages.

2 Methodology

The design of the PCB (Printed Circuit Board) forms the foundation for the electronic components and their interconnections. SOLIDWORKS 2022 software was used to create a precise model of the PCB assembly, adhering to the JESD22-B111 standard. This standard ensures consistent and accurate positioning of IC packages and support structures on the PCB. The designed PCB has a length of 132 mm, a width of 77 mm, and a thickness of 1.6 mm. It also includes support holes with a diameter of 3.2 mm positioned near the four corners, as shown in Figure 1.

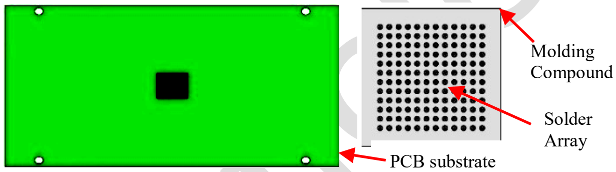

Figure 1: a) PCB assembly; b) Package with solder ball array

Solder balls in BGA are a critical component for connecting integrated circuits (ICs) to the PCB. To accurately reflect their behaviour in the model, a 144-ball (12x12 array) BGA was modelled in a square pattern, as shown in Figure 1. Each solder ball was created by revolving a half-section of a sphere with a diameter of 0.44 mm. The fatigue life of the PCB assembly is particularly influenced by the ability of solder balls to withstand high equivalent stress. Damage to the solder ball can lead to overall failure of the PCB assembly. Therefore, the material properties of the solder balls are typically superior to those of other PCB components. The materials used for different parts of the PCB assembly, such as the BT (Bismaleimide Triazine) substrate, silicon die, solder balls (specifically SAC 305), and dummy die (which are silicon), are detailed in Table 1.

Table 1: Material Properties [13]

Material	Young's Modulus (GPa)	Poisson's Ratio	Density (kg/m³)
FR 4	22	0.28	2000
Silicon Die	130	0.22	2300
SAC 305	51	0.36	7400
Molding Compound	20	0.30	1890

The numerical analysis of the PCB assembly was performed using ANSYS 2021 R1, where the model was meshed using a combination of multi-zone, refinement, face sizing, and sweep mesh (shown in Figure 2) along with the adaptive mesh method. The solder balls were meshed using a multi-zone approach to differentiate between the structured and free regions. Refinement meshing was used on the surface above the solder balls to improve the accuracy of the results. The refinement of the contact surfaces was given in order of '2' for more accurate results. Considering the irregular meshes in the PCB assembly, a 10-noded quadratic element 'SOLID 187' was used for the analysis. All the degrees of freedom (DOF) of support holes in the PCB assembly were arrested during the analysis, and the same boundary conditions were followed for the entire analysis of the four corner support configurations. Modal analysis of the PCB assembly was performed in order to understand the dynamic characteristics of the PCB assembly. The natural frequency and mode shapes that fall under the operational range of 100 Hz to 1000 Hz were extracted from the analysis [14].

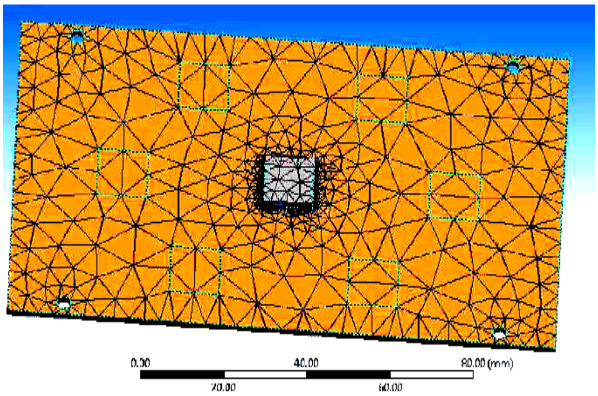

Figure 2: Meshed model of a single package PCB assembly

Random vibration analysis was performed using the mode-superposition method. Based on the results of modal analysis, random vibration was performed with input acceleration power spectral density (PSD) of 0.01 G^2/Hz over the frequency range of 100 Hz to 1000 Hz. For this condition, the maximum equivalent stress and the components where they occur were analyzed under random vibration. The fatigue life of the PCB assembly was estimated using frequency spectrum-based cumulative fatigue damage methods, viz., Miner's rule [15], Wirsching & Light Method, and Ortiz & Chen Method [16-17]. Whereas the Miner's rule finds the cumulative fatigue damage based on stress PSD from the numerical simulation and the other two methods estimates the fatigue damage under wide-band based on the damage under narrow band with a correction factor.

2.1 Design based on positioning of the package

The location of a Ball Grid Array (BGA) package on a Printed Circuit Board (PCB) significantly impacts its fatigue life. The fatigue life of BGA assembly is affected by the stresses experienced due to various factors that cause random vibrations during operation, shipping, and uncertain external mechanical loads. These stresses can cause cracks to initiate and propagate over time, ultimately leading to package failure. The location of the BGA assembly on the PCB directly influences the stress distribution on its solder joints. Areas with high-stress concentration accelerate fatigue and reduce the lifespan of electronic packages. To improve fatigue life, one can optimize the location of the Packages on the PCB through the FEA method. By simulating different package placements, the locations that would experience minimal stress can be identified and optimized to improve fatigue life. For simulation, the JEDEC (JESD22-B111) standard gives the basic outline of the test vehicle, which has 15 different locations as shown in Figure 3.

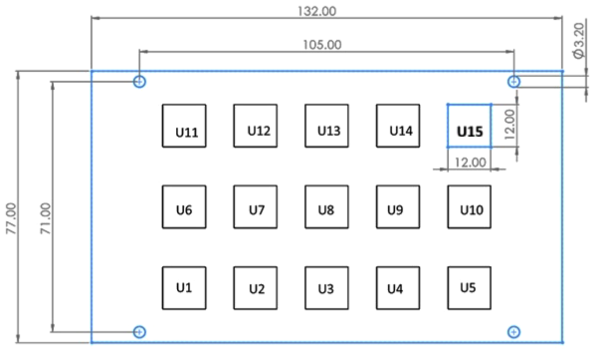

Figure 3: Test specimens overview based on JEDEC standard [18]

To optimize the PCB assembly under random vibration, the positions U1, U2, U3, U6, U7, and U8 were analyzed, encompassing all locations as shown in Figure 4. The stress patterns experienced by U1 are the same for U5, U11, and U15 because they are positioned at the same distance from the supports and centre. Similarly, the stress pattern in U2 is the same for U4, U12, and U14 due to their positioning relative to the supports and centre. The stress in U3 is equivalent to that in U13 because of their identical distance from the supports and centre. Similarly, the stress in U6 is comparable to that in U10 for the same reasons, and the stress in U7 is the same in U9 due to their similar positioning relative to the supports and centre.

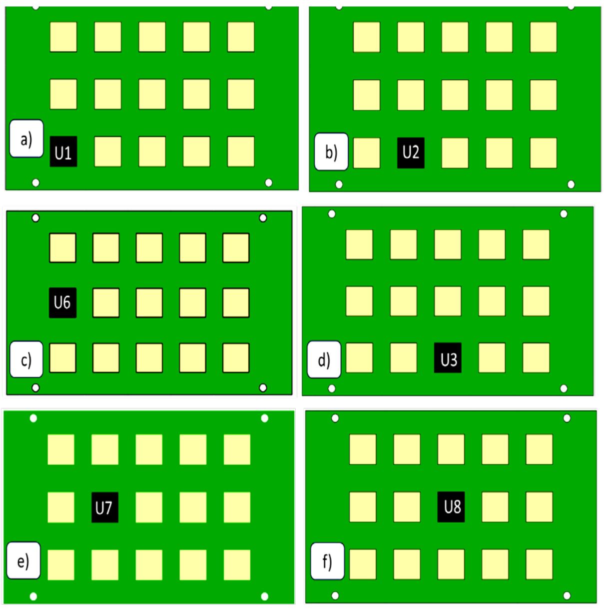

Figure 4: PCB assemblies with package at a)U1 b)U2 c)U6 d)U3 e)U7 and f)U8 positions.

2.2 Design based on modified support locations

Improving the fatigue life of a Printed Circuit Board (PCB) can be achieved by strategically modifying the supporting methods, particularly focusing on the support points as shown in Figure 5. One method involves configuring the support holes in a diamond shape pattern instead of a traditional square or rectangular layout. Another approach is to add extra support points along the length of the PCB. Similarly, added an extra support point along the width of the PCB. Another approach is to add extra support points along both the length and width of the PCB.

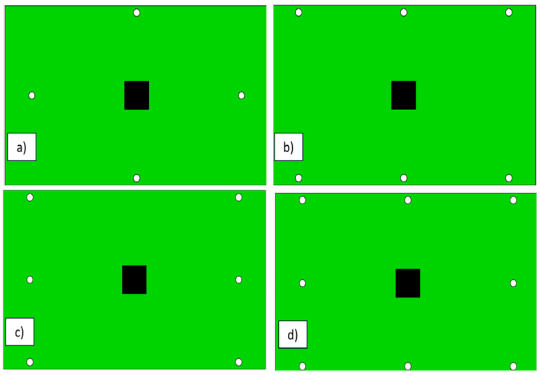

Figure 5: PCB assembly with a) diamond support b) additional support along length c) additional support along width d) additional supports along both length and width.

2.3 Design based on additional supports

To improve fatigue life by adding additional support around the package, a model was created with support structures located at varying distances from the centre of the package, as shown in Figure 6. Specifically, supports were implemented at distances of 40 mm, 35 mm, 30 mm, and 25 mm from the centre of the package. These kinds of additional support points are used in processor applications.

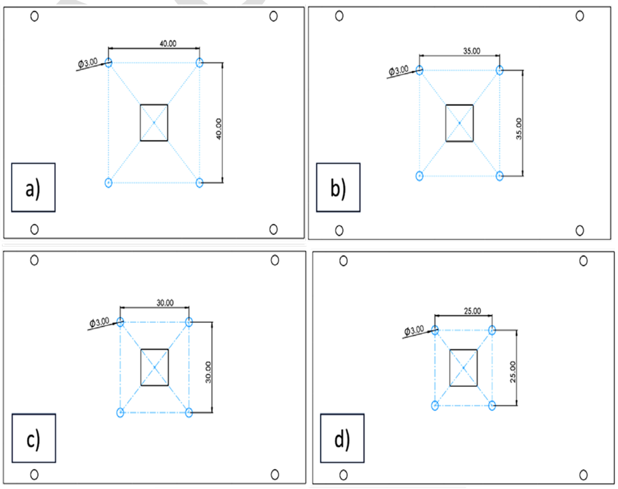

Figure 6: Support Configuration around the Package for Fatigue Life Improvement.

3 Results and Discussions

3.1 Results of preliminary analysis

Modal analysis of the PCB assembly was performed using the solution module in ANSYS 2022 R1. The results from the modal analysis give natural frequencies of a system, which are the frequencies at which it will vibrate freely, where the first natural frequency was observed as 343.24 Hz. Knowing the natural frequencies of a system is important for avoiding resonance, which can cause the failure of the solder balls in PCB assembly.

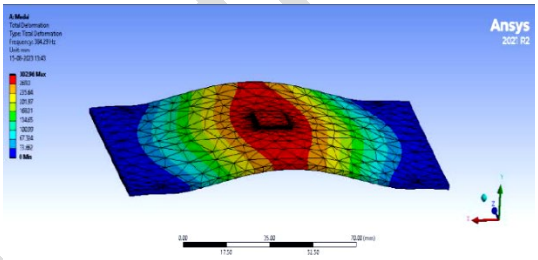

Figure 7: Modal Analysis of the PCB assembly.

Table 2: Result of modal analysis of the PCB assembly.

Mode	Natural Frequency (Hz)
1	343.24
2	625.02
3	714.83

The mode shapes of the first three modes show that the PCB is most likely to vibrate in a bending mode at low frequencies. The bending mode is the most common mode of vibration for PCBs, as shown in Figure 7. The combination of bending and twisting is observed in higher modes with a good effective mass and a higher participation factor in the y-direction. To check the consistency of the numerical results, the mesh independency study was performed for various mesh sizes of the PCB assembly (in X axis) against the natural frequency (in Y axis), where the results (shown in Figure 8) have converged after 74000 elements, and the same mesh size (0.4 mm) along with the adaptive mesh was used throughout the numerical study.

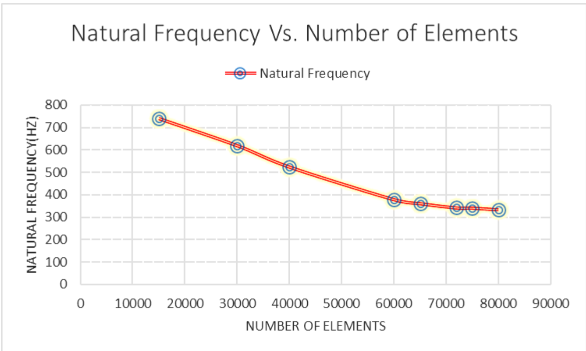

Figure 8: Mesh independency study

3.2 Experimental validation

In order to validate the results obtained from the numerical analysis, Experimental Modal Analysis (EMA) was done. A test vehicle of the PCB assembly was fabricated and mounted on a fixture. An accelerometer with a sensitivity of 10 mV/g was used to observe the free vibration. The 'roving hammer technique' was used in the EMA, where the accelerometer's position was fixed between the U7 and U8 positions of the package on the PCB, and 15 points (3 rows × 5 columns) were excited on it. A DAQ system (NI Compact DAQ-9174) connected with LabVIEW 2021 software was used to acquire the acceleration signal during the free vibration. The experimental setup used for the testing is shown in Figure 9.

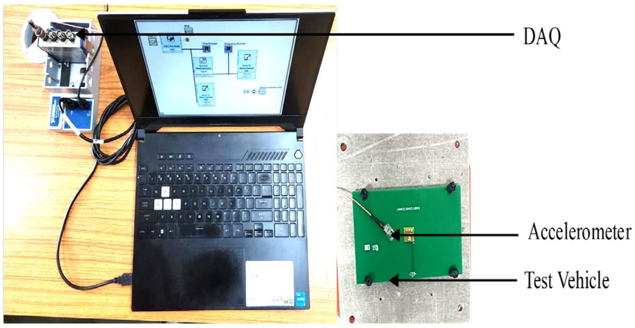

Figure 9: Experimental Modal Analysis of the PCB assembly with Package at U8 position

Using the FFT module in LabVIEW 2021, the time domain signal was converted into the frequency domain, and the amplitude of vibration observed during the vibration against the frequency is shown in Figure 10.

Table 3: Result of Experimental modal analysis of the PCB assembly.

Mode	Natural Frequency (Hz)
1	352
2	621
3	719

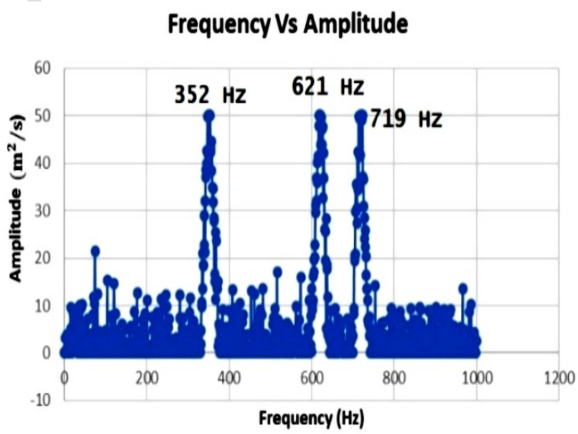

Figure 10: Amplitude Vs Frequency

The comparison between the predicted natural frequencies from the computational model and the results from the experimental modal analysis reveals a generally consistent pattern with some minor deviations. The results support the validity of the computational model and ensure good agreement with the experimental data.

3.3 Results of positioning of the package on PCB

The packages positioned near the edges or closer to support structures enhance the overall stiffness of the assembly. This increased stiffness leads to higher first natural frequencies and it is compared with that of the other positions as listed in Table 4.

Table 4: First Natural Frequency for PCB Assembly with different package locations.

S. No.	Package Location	Natural Frequency (Hz)
a)	U1, U5, U11 and U15	411.71
b)	U2, U4, U12 and U14	404.96
c)	U3 and U13	390.46
d)	U6, U10	408.39
e)	U7, U9	400.47
f)	U8	343.24

It is observed that the packages placed away from these supports tend to reduce overall stiffness, leading to lower first natural frequencies. Their corresponding mode shapes are shown in Figure 11.

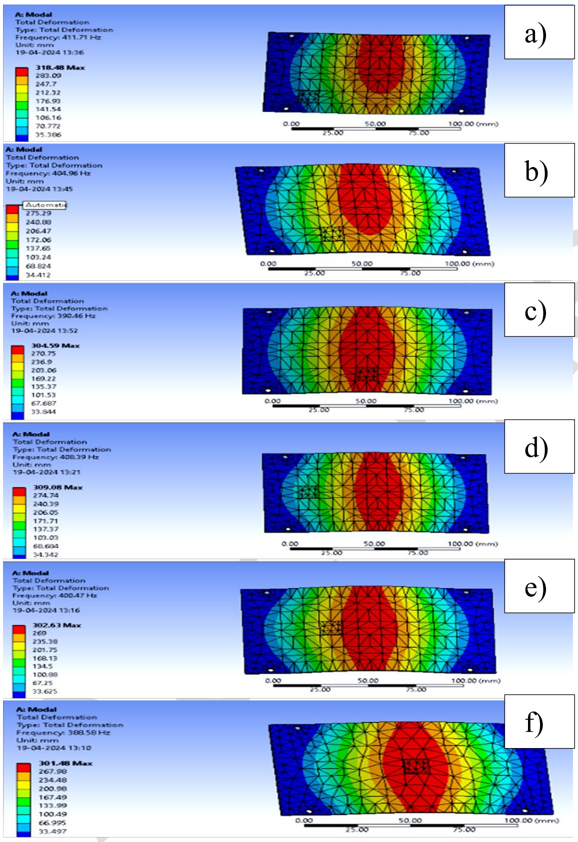

Figure 11: Modal Analysis for PCB Assembly with single package at various locations at a) U1 b) U2 c) U3 d) U6 e) U7 f) U8

Random vibration results of the single package located at various positions of the PCB are shown in Figure 12.

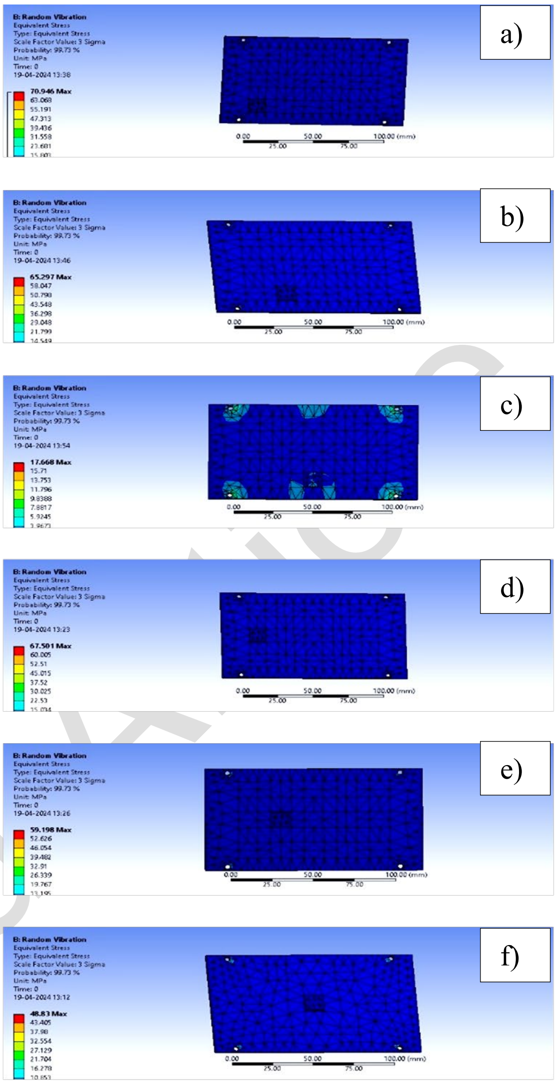

Figure 12: Equivalent Stress induced in the PCB Assembly with single package at various locations at a) U1 b) U2 c) U3 d) U6 e) U7 f) U8

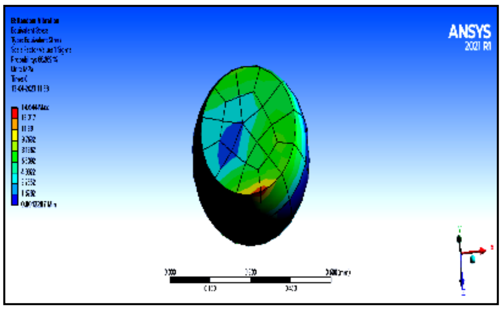

Figure 13: Stress distribution in corner solder ball (U8 position)

There are 4 corner solder balls in the solder ball array under every package. It was observed that in all the random vibration analysis, only one among of those 4 corner solder balls experiences the maximum stress. Whereas the other balls in the inner array experience a little less stress than the corner solder balls.

Table 5: Fatigue Life and Location of Stress Occurrence for Various Positions of the Package on PCB.

Package Location	Solder Ball Number	Fatigue Life Estimation		
		Miner's Rule	Wirsching and Light method	Ortiz and Chen method
		(seconds)		
U1, U5, U11 and U15	12	78453	76991	76952
U2, U4, U12 and U14	1	23903	23631	23648
U3 and U13	12	8359	8264	8278
U6, U10	12	69910	69114	69314
U7, U9	144	17784	17582	17684
U8	144	9193	9088	9102

Under random vibration of 0.01 G^2/Hz input PSD G-acceleration, the packages located at U1, U5, U11, and U15 have fatigue life of 78453 seconds (according to Miner's Rule), which is more than 8 times longer than that of the U8 location. The corresponding stress distribution in the corner solder ball (U8 position) is shown in Figure 13. The high stress indicates a potential risk for premature fatigue and failure of the solder balls in these areas. U6 and U10 locations experience considerably lower stress compared to that of others. The packages located at U6 and U10 have the longer fatigue life of 69910 seconds according to Miner's Rule, 69914 seconds according to Wirsching and Light method, and 69314 seconds according to Ortiz & Chen method, as listed in Table 5. 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. Whereas the Wirsching & light method and Minor's rule give a more accurate prediction of the fatigue life. Also, this entire investigation is about the fatigue life's dependency on the location of the package on the PCB, and the results from all three methods proved that the fatigue life is influenced by the package's location.

The stress level suggests a relatively more favorable position in terms of fatigue life and solder joint reliability. Packages in corner positions experience unique stress patterns due to the PCB's geometry and mechanical loading. The stress distribution along the length and width of the PCB is shown in Figure 14.

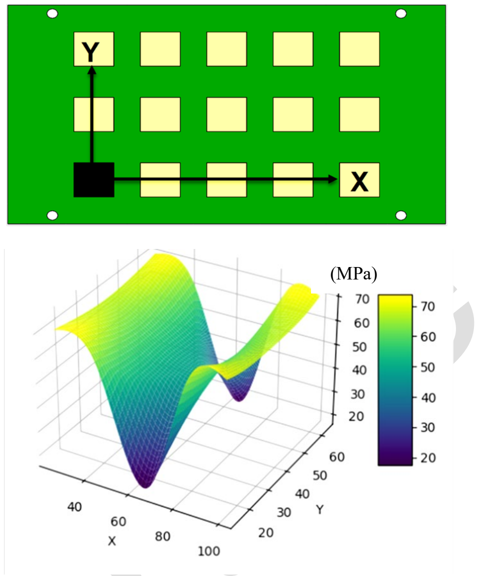

Figure 14: Stress Distribution in the PCB Assembly with a single package at different locations under random vibration

3.4 Results of modified support locations

Under Random Vibration of 0.01 G^2/Hz PSD G acceleration, adding extra support points along the length & width of the PCB is the best configuration to reduce stress during random vibration analysis, as shown in Figure 15. This is likely because the additional support along both sides helps to distribute the stress more evenly across the PCB than that of the diamond pattern method.

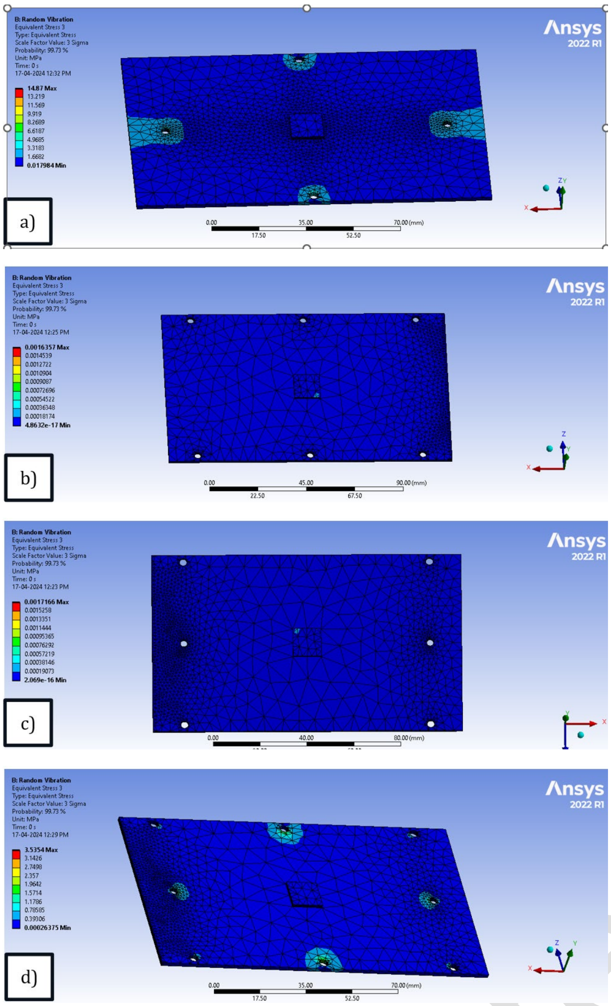

Figure 15: Maximum Stress induced for different supporting methods a) Diamond Pattern b) Additional Support along Width c) Additional Support along Length d) Additional Support along Both Sides

Table 6: Effect of Supporting Methods on fatigue life.

Supporting Methods	Solder Ball Number	Equivalent Stress (MPa)	Fatigue Life Estimation		
			Miner's Rule	Wirsching & Light method	Ortiz & Chen method
			(seconds)		
Diamond Pattern	1	14.87	38540	38796	38446
Additional Support along Width	12	0.01716	48556	47988	47972
Additional Support along Length	12	0.001613	78822	77925	77954
Additional Support along Both Sides	144	3.5354	98543	97543	97482

It is observed that the diamond pattern method appears to have the shortest fatigue life of 38,540 seconds because the diamond pattern provides less support for the package than the other two methods. The additional support along the width method has a fatigue life of 48556 seconds, which is significantly longer than the diamond pattern method (listed in Table 6). This is likely because the additional support along the width helps to distribute the stress more evenly across all the solder balls. The additional support along the length method has a fatigue life of 78,822 seconds, which is higher than the additional support along the width method and the diamond pattern method. It is also observed from the analysis that a larger number of support points provides more stiffness to the PCB assembly, hence the fatigue life increases.

3.5 Results of additional supports

The results listed in Table 7 under random vibration of the PCB assembly with extra supports around the package show that varying the support distance from the package centre impacts the fatigue life observed in the PCB assemblies. (stress distribution in Figure 16). As the support distance decreases from 40mm to 25 mm, the fatigue life increases, indicating that closer supports around the package provide better structural stability and load distribution during the vibration.

Table 7: Effect of support distance on Fatigue Life of Solder Balls

Support Distance (mm)	Solder Ball Number	Fatigue Life Estimation		
		Miner's Rule	Wirsching & Light method	Ortiz & Chen method
		(seconds)		
40	144	89395	89302	89362
35	12	95478	96036	95038
30	12	96502	96450	96578
25	1	99759	96201	96245

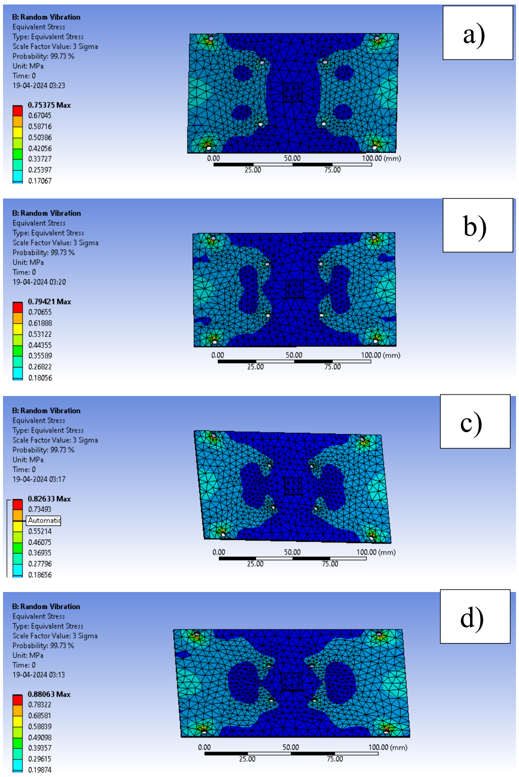

Figure 16: Stress distribution for PCB Assembly with extra support around the package at a) 40 mm b) 35 mm c) 30 mm d) 25 mm

4 Conclusions

When it comes to single-package modules, electronic manufacturers produce PCB assemblies with the BGA packages surface-mounted in the middle of the board. On the other hand, contemporary electronics with multitasking capabilities have several BGA packages surface-mounted on them. Based on the numerical analysis of the various PCB assemblies designed using strategic positioning of the package and the support locations, the following conclusions are made.

- The BGA package location near the corner of the PCB experienced less fatigue damage compared to those in the centre due to significant flexing of the PCB in the centre during random vibration.
- During Random Vibration analysis, incorporating additional support points along both sides of the PCB represents the optimal configuration for improved fatigue life up to 10 times.
- Introducing extra support structures closer to the package effectively reduces stress levels (at least 10 times) during random vibration. The closer the support distance, the lower the stress observed in the PCB assembly due to the enhanced dynamic properties of the system.

Several R&D engineers in PCB manufacturing industries were approached during this research, and observed that the accelerated fatigue life estimated using Wirsching & Light Method and Miner's rule was predominantly used by several PCB designers for product qualification and warranty period calculations. The proposed findings of the research would benefit such product qualifying agencies to come up with better solutions to the reliability of the electronic products, such as processor applications, ECU of an automobile, PCB of the aircraft & spacecrafts in the future.

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6 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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