Structural and Random Vibration Analysis of LEDs Conductive Polymer Interconnections

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Abstract. Many devices consist of electronic parts and can be operated in a certain vibration environment for some instant without undergoing failure. Interconnection or joint plays a very important role in electronic devices to connect various electrical and mechanical parts altogether. The main objective of this study is to investigate the effect of interconnection performance under vibration loading in terms of natural frequency, mode shapes and transfer function. Four different models of LEDs are built for pull strength and vibration tests. The structural analysis of these models are carried out by using universal testing machine. The dynamic responses of four build matrices under certain random frequency are observed by random vibration analysis. In structural analysis, the samples are subjected to vertical displacement loading while in random vibration analysis, the models run in a frequency range of 3 Hz to 500 Hz. It is observed that the structure of the adhesive joints affect the strength of interconnection between circuit pad and LED joints. Furthermore, FEA analysis is also carried out to determine the stresses at solder joint under vibration condition. The models are excited from natural frequency and good comparison of the experimental results and FEA analysis are observed.

1. Introduction
The electronic system such as control module, has been used by many companies, especially automation companies. These electronic components are mostly operated in severe vibration environment for certain time period without undergoing failure. An electronic system can be subjected to many different forms of vibration. The most popular form of vibration is random vibration. Random vibration is the most related vibration condition subjected to destabilization created by rotational and tumbling masses. The degree of freedom of vibration in a system with certain natural frequency is known as vibration mode. The range of frequency varies according to its application such as [1] proposed that 2.5 Ton truck has 15 G and 19 G acceleration level with 15 Hz – 40 Hz frequency range at a speed of 10 mph – 15 mph. The vibration frequency range in automobiles increases with the system, i.e., vibration while driving, suspension and steering systems. The frequency range in this case ranges from 3 Hz to 1000 Hz [2]. A range of frequency is excited at the same time which means that the frequency loading corresponds to all masses are represented at the same time and therefore, large displacement amplitudes are obtained to produce failure impact in analysis system. Power Spectral Density (PSD) input is assigned in the simulation to quantify the random frequency. PSD is the input curve of acceleration units per Hz² versus range of frequencies. PSD input is referred from JEDEC Standard 22b103B vibration, variable frequency. JEDEC standard is used to test the reliability of electronic devices under different vibration applications to which component can be exposed [3]. In this paper, PSD input is based on level where a
component can be exposed to the most severe vibration condition. PSD excitation is applied on the fixed supports of models in y – axis direction. Furthermore, harmonic response analysis is then used to determine the response of model structure under a steady state sinusoidal (harmonic) loading at a given frequency. In harmonic analysis, the peak response corresponds with the natural frequencies of the structure to be analysed [4]. Usually, harmonic response analysis is done to obtain the values of stress equivalent, displacement and relative sensitivity of the frequency response [5].

Several electronic components are connected together by means of interconnection materials. These interconnection materials are known as solders. The most common solders are lead – based solder, lead – free solder and conductive adhesives. Solder joint failure occurs in electronic devices due to vibration loading, therefore, the structure and reliability of solder joint play a very important role. Now a days, tin – lead solder (Sn – Pb) that is lead – based solder does not longer used by electronic industries due to restriction in law and new requirements for non – toxic materials. The lead – free solders and conductive adhesives are being used to meet new environmental and green requirements [6], [7]. Lead – free solder is a tin – based alloy such as Sn – Ag, Sn – Cu, Sn – Zn, Sn – Ag – Cu, etc. Conductive adhesives are the combination of adhesive epoxy and a conductive metal such as silver, copper, gold, tin oxide, or indium. Silver is used as an epoxy filler because it is a good conductor of electricity, easily available and cheap in cost. Conductive adhesive is applied in the form of paste to an electronic circuit before placement of electronic components. It does not require particular pressure for curing and its curing temperature ranges from 130°C – 180°C which is suitable for thermal sensitive electronic components [8].

Finite element analysis (FEA) is then used to investigate the solder joint stresses and fatigue estimation. Many researchers have used two models of FEA that are detailed FE models and Smeared FE models. Smeared FE models give the detailed results of design while detailed FE models are not recommended because this model requires large amount of time period to build and solve. Such model is excessive in nature when simplified models can produced accurate data quickly with less efforts [9]. During FEA, the convergence of analysed frequency results can be examined by applying variation in mesh densities in the model. Therefore, large size meshes help to relocate the frequency results. The natural frequencies test vehicle are examined by modal testing method to verify FEA model [10]. The stress, strain, displacement, maximum or minimum load applications can also calculated by FEA simulation. FE analysis of solder joint fatigue estimation is then estimated with experimental modal analysis to determine natural frequencies and mode shapes [11]. The modal analysis is first done on the global model and then compared with the experimental results. The global local approach is applied to determine the equivalent strain in critical areas of solder joints [12].

The main objective of the present research is to study the structural and reliability of conductive polymer interconnections under vibration loading. FE analysis is also carried out in order to determine the stress generated due to vibration loading. The comparison of results obtained by experiment and simulation is also done.

2. Methodology
2.1 Pull Strength Test
Four LEDs are bonded to the circuit by using conductive adhesive (Loktite Ablestik ABP 2032S) with different build matrices. The pull strength test is used to evaluate the bonding strength of LEDs with conductive polymer interconnections. The four samples of each build matrix are tested and average readings are considered as final readings. Universal testing machine (UTM – INSTRON 3367) is used to measure the strength of interconnections between LED joints and circuit. The circuit is printed on Lexan 8010 polycarbonate sheet (PC) base and padded with silver epoxy as solder joint depends on different dispensing methods. The sheet is then cut into small pieces consisted of one LED per piece. The dispensing method for four LED models are shown in figure 1.
2.2 Vibration loading Test
All the four samples are then attached on a custom design L-shaped base aluminum sheet of 5 mm thickness as illustrated in figure 2. This platform is mounted on a shaker machine for vibration test, the frequency range of the shaker is set to 3 Hz – 500 Hz. The samples run at the same time under swept random vibration for 4 hours. Modal testing is done to determine the natural frequency of structure prior to the vibration test. The bonding between LED joints and circuit are observed at every 30 minutes time interval. The electrical conductivity before and after vibration loading of every sample is evaluated by connecting a power supply in terms of current variation. The bonding is further inspected by using Hirox Digital Microscope (KH – 3000) and x-ray machine (XT V 160) to detect any failure like cracks in the conductive paste.

Figure 1. LED samples with solder joints

Figure 2. Vibration Test setup for LEDs joints.
2.3 Geometry of LED Models

Based on the assembly prototype model used in experimental analysis, four 3D CAD models are developed by using SolidWorks software and then imported to ANSYS 19.2 for further analysis. These CAD models are designed by considering actual component specifications from manufacturer. The actual dimensions of solder joints failure cannot be determined because solder joints do not come under geometry structure, therefore, the solder joints can approximately be established on the basis of actual shape as illustrated in figure 3. The model of copper pad circuit on PC sheet base is modified to cater the needs of simulation as discussed in table 1. However, the complete assembly model is shown in figure 4.

**Table 1. Dimensions of each part of LED models**

| Parts                | Dimensions (mm) |
|----------------------|-----------------|
| Base of lead         | 5.5 x 2.5 x 0.5 |
| Solder joint Model 1 | 6.5 x 3.5 x 1.2 |
| Solder joint Model 2 | 5.0 x 3.5 x 1.2 |
| Solder joint Model 3 | 6.5 x 3.5 x 0.5 |
| Solder joint Model 4 | 5.0 x 3.5 x 0.5 |

*Figure 3. 3D CAD models of LED with Solder joints*

The materials applied in ANSYS are based on the material used in experimental prototype model. The mechanical properties of material are provided from ANSYS materials library and manufacturer sources. The materials are assumed to be non-linear elastic-plastic in nature. The mechanical properties of materials used in different parts of LED model are summarized in table 2.

*Figure 4. Complete assembly model*
Table 2. Mechanical properties of materials used in different parts of LED models

| Parts                  | Materials    | Density ($kg/m^2$) | Elastic Modulus (MPa) | Poisson’s Ratio | Yield Strength (MPa) | Tangent Modulus (MPa) | UTS (MPa)  |
|------------------------|--------------|--------------------|-----------------------|----------------|----------------------|-----------------------|------------|
| Copper Pad circuit     | Copper       | 8900               | 130000                | 0.34           | 120                  | 125                   | 210        |
| Polycarbonate base     | PC           | 1200               | 2506                  | 0.38           | 63                   | .05                   | 65         |
| Interconnections       | Silver epoxy| 4500               | 4140                  | 0.32           | 24.1                 | 38.62                 | 34.5       |
| Lead                   | Copper alloy | 8300               | 110000                | 0.34           | 280                  | 1150                  | 491        |

2.4. Random Vibration Analysis
Random vibration analysis is carried out in ANSYS 19.2 to analyze the failure occurred on each model of LED under random vibration loadings. Before doing this analysis, the dynamic responses on each model are identified by performing modal analysis. Only fixed support at the end surface of PC sheet base is applied as a boundary condition. In modal analysis, six different mode shapes are identified within the frequency range of 3 Hz – 500 Hz. After that, these mode shapes are used in the random vibration test for further analysis.

Random vibration is a non–deterministic motion. The vibration pattern would be varied, to quantify the frequency excitation PSD input need to be assigned in the simulation. In this analysis, band limited white noise has been used having a constant spectral density over specified frequency range as shown in figure 5.

![Figure 5. Power Spectral Density (PSD) input curve](image)

PSD input is referred by JEDEC standard 22b 103B vibration that is used to test the reliability of structure under various vibration loadings to which components can be exposed [3]. In this paper, PSD input is based on the level where all components can be exposed to severe conditions. PSD excitation is applied in y – axis direction perpendicular to model plane at fixed support.

2.5. Harmonic Response Analysis
The solution from modal analysis is used as input in harmonic response analysis. The main purpose of this analysis is to determine the response of model structure under steady – state sinusoidal loading at a given frequency. The input parameters in harmonic analysis are Young’s modulus, Poisson’s ratio and mass density. Since modal coordinates are used, therefore, harmonic solution using the mode superposition method automatically first perform a modal analysis. The mode superposition method is much faster than other methods that’s why harmonic analysis portion gives the results very quick and efficient. The peak response corresponds to natural frequency of the structure are analyzed in harmonic analysis. The number of maximum modes is used as a first boundary condition. After that, the solution interval is set at 100 intervals so that more accurate results obtained. The free vibration analysis also performed internally with mode superposition method. It is analyzed that acceleration of frequency excitation PSD input needs to be assigned in the simulation.

3.0 Results and Discussions
3.1 Pull Strength Test

It is observed that 3rd build matrix from figure 6(c) has the highest strength value of 13.16 N than 1st, 2nd and 4th build matrices that are 10.38 N, 9.69 N and 7.04 N respectively. The strength value and area of failure depend on the amount of conductive adhesive used in connecting LEDs with circuit pad. Figure 6 describes the areas of failure of four build matrices. 1st and 3rd build matrices have the largest areas as compared to other matrices because they used larger amount of adhesive. The increment of surface contact area between the adhesive and circuit lead to increase the pull strength values.

3.2 Visual Inspection of LEDs

The vibration test analysis of all LEDs build matrices is carried out. It can be observed that no disconnection occurred at conductive adhesive or circuit interface after vibration loading in both the directions, vertical and horizontal as shown in figure 7 and figure 8 respectively. Both LED joints and adhesive are not peeled off from the circuit as well as no cracks are generated in adhesive bonding.

![Figure 6. Failed areas formation after pull test](image)

![Figure 7. Bonding at LED joints on vertical plane](image)
3.3 Structural Analysis
The interconnection strength and structure are analysed using ANSYS 19.2. The simulations of pull strength test for four models are carried out. The maximum deformation values of each model obtained from simulation are slightly different from that of pull strength test because the dimensions of solder joint are not exactly same as in experiment. These deformation values from simulation and experimental are constantly increasing with small deviations as described in table 3. Hence, FEA model is verified and the results are reliable for further analysis.

| Models | Time (sec) | Maximum Deformation (mm) | Percentage Error (%) | Min. Deformation (mm) | Max. Deformation (mm) |
|--------|------------|--------------------------|----------------------|----------------------|-----------------------|
|        |            | Simulation | Experimental |                      |                       |
| 1      | 4.5        | 0.10626    | 0.10832       | 1.94                 |                       |
|        | 7.3        | 0.17066    | 0.16689       | 2.22                 |                       |
|        | 19.3       | 0.0461025  | 0.44175       | 4.19                 |                       |
|        | 35.6       | 0.87866    | 0.83341       | 5.15                 |                       |
| 2      | 12         | 0.25287    | 0.24796       | 1.15                 | 0.25287               | 1.2328               |
|        | 22.8       | 0.46574    | 0.44646       | 4.13                 |                       |
|        | 30.9       | 0.62863    | 0.58210       | 7.40                 |                       |
|        | 43.1       | 0.87776    | 0.83560       | 4.80                 |                       |
| 3      | 5.3        | 0.15421    | 0.15293       | 0.47                 | 0.01039               | 2.0551               |
|        | 12.4       | 0.38495    | 0.33946       | 11.69                |                       |
|        | 18.8       | 0.59982    | 0.60166       | 0.31                 |                       |
|        | 26.8       | 0.87490    | 0.89646       | 2.46                 |                       |
| 4      | 6.0        | 0.13372    | 0.13350       | 0.16                 | 0.13372               | 1.2582               |
|        | 12.0       | 0.25357    | 0.23304       | 8.10                 |                       |
|        | 21.0       | 0.43438    | 0.41636       | 4.15                 |                       |
|        | 34.5       | 0.71295    | 0.72525       | 1.73                 |                       |

Model 3 has the highest maximum deformation than others because different designs of adhesive joints affect the overall equivalent stress and total deformation in a pull test simulation. Figure 9 shows FE analysis of total deformation for each model.
Similarly, the stress analysis is done for each model shown in figure 10. The maximum equivalent stresses of all models mostly concentrated at the corner of base LED. The maximum equivalent stresses of four models (Model 1 to 4) are 489.16, 363.56, 632.68 and 360.92 MPa respectively. LED model 3 shows the highest equivalent stress value than others and is most likely to fail at the corner of LED lead because equivalent stress exceeds UTS (Universal tensile stress) values. Furthermore, the stress analysis of the interconnections of four LED samples is also conducted. Figure 11 shows the maximum stress occurred at the edges of solder joints. The values of maximum equivalent stresses of adhesive joints are 51.394, 36.967, 51.183 and 38.690 MPa of four Models.

From figure 11, it is observed that models 1 and 3 have the highest values of equivalent stress than that of models 2 and 4 which means that adhesive joint structure of models 2 and 4 are stronger than that of models 1 and 3. The maximum stress values of adhesive joints materials of each sample are compared to UTS values and is concluded that all adhesive joints fail but the most suitable models are 2 and 4 that have smaller maximum stress values. According to experimental results, some LED assembly have voids at certain places and adhesive solder joints make fracture and failure.
The pull strength test simulation also emphasizes on the stress concentration of copper pad circuit. If the adhesive joint and LED has higher maximum stress equivalent then copper pads will be effected by higher stress values. The obtained values of maximum stress of copper pad circuit of models 1-4 are 105.57, 143.64, 142.51 and 146.53 MPa respectively. The simulation of copper pad is shown in Figure 12.

As a result, model 4 has the highest maximum equivalent stress value than other models. In order to identify whether the failure occurred or not, the maximum stress value of copper material is compared with its UTS value. Despite of all, the LED models are suitable to utilize the copper pad circuit. Experimentally, a model can fail at solder joint or copper pad circuit due to large difference in material properties and thickness of copper pad circuit used in simulation.
3.4 Modal Analysis
Modal analysis is carried out in order to determine the dynamic response of every model at specific frequency and range of deformation occurs on each model within the frequency range. 6 modes are generated in this analysis. The natural frequencies of these modes computed by ANSYS, are in the range of 3 Hz – 500 Hz. These modes are utilized to create the mode shape results. The deformations for each and every selected frequency are then calculated. All models have the same pattern of mode shapes and number of frequencies. 6 mode shapes with respect to frequency range 3 Hz – 500 Hz are shown in figure 13.

Figure 13. 6 Mode shapes over the range of frequency 3 Hz – 500 Hz
Random vibration is presented in the manner of Gaussian probability distribution with zero – mean and the root mean square (RMS) response is described in the form of sigma values $1\sigma$, $2\sigma$ and $3\sigma$, where these deviations lie between RMS stress values over time, with probabilities 68.3%, 95.4% and 99.73% respectively [13].

The maximum equivalent stress occurred at copper pad circuit surface. As shown in figure 14, only model 3 has the stresses at corner of LED that intersects with copper pad while remaining models have different values of stress that are not only affected to intersection with adhesive solder joint but stresses spread on overall; copper pad circuit. Table 4 gives the maximum stress values of each part of LEDs model. It is concluded that model 3 has the highest sigma value and model 1 has the lowest sigma than others.

The stress contour plot obtained in figure 15 for the solder joint shows that stresses are generated at surface below the adhesive joint in contact with the circuit pad. Figure 16 illustrates that the stresses are produced at LED lead where the maximum equivalent stress for model 1 is concentrated at the corners of LED lead and for model 2 the stresses is distributed from the corner of the LED lead to the LED lead base.

The analysis indicated that the most critical areas of all the LED models under vibration loading are at the connections of adhesive joints and circuit pad which means that there are high probabilities that interconnections are cracked or peeled off, either from the copper circuit pad or together with copper circuit pad.

| Table 4. Maximum Equivalent stresses (MPa) |
|-------------------------------------------|
| Parts | Sigma ($\sigma$) | Model 1 | Model 2 | Model 3 | Model 4 |
| copper pad circuit | $1\sigma$ | 4.0215 | 7.6233 | 8.8505 | 5.0244 |
| | $2\sigma$ | 8.0431 | 15.2470 | 17.7010 | 10.0490 |
| | $3\sigma$ | 12.0650 | 22.8700 | 26.5510 | 15.0730 |
| solder joints | $1\sigma$ | 0.6830 | 1.0485 | 1.3205 | 0.6547 |
|       | 2σ       | 2.0969   | 2.6410   | 1.3095   |
|-------|----------|----------|----------|----------|
| 3σ    | 2.0492   | 3.1454   | 3.9616   | 1.9643   |
| LED   | 1σ       | 4.7516   | 8.0057   | 8.8946   | 5.6545   |
|       | 2σ       | 9.5032   | 16.0110  | 17.7890  | 11.3090  |
|       | 3σ       | 14.255   | 24.0170  | 26.6840  | 16.9640  |

**Figure 15.** Maximum Equivalent stresses contour plot at adhesive solder joints

**Figure 16.** Maximum Equivalent stresses contour plot at LED
3.6 Harmonic Response Analysis
Harmonic response analysis is done within the frequency range of 3 Hz – 500 Hz in order to analyse the increasing and decreasing variations of stresses. The variations of stress amplitude under different exciting frequencies for all 4 models are shown in figures 17. It is observed that the stresses are not always increasing but sometimes stresses drop based on a certain frequency. According to this analysis, model 4 shows the highest value and model 2 shows the lowest value of maximum stress amplitude. Therefore, more fractures can occurred in model 4 and cracks are generated on higher maximum stress amplitude.

![Figure 17. Amplitudes for different exciting frequencies](image)

4. Conclusion
The structural reliability of the interconnections on copper pad circuit are determined by the method of dispensing adhesive. Before doing pull strength test analysis, meshing is done with higher number of elements size to achieve accurate results. The circuit pad and LED solder joints proved good structural condition and performance under mechanical loading in pull strength test analysis. As a result, model 3 shows the highest equivalent stress than the others. The solder joints in model 3 can sustained large amount of stress under mechanical and vibration loadings.

Four samples of LEDs adhesive joints can withstand under random vibration within a frequency range of 3 Hz – 500 Hz for 4 hours. After investigation, the critical areas of assembly models are at the contact surface between circuit pads and solder joints. A free vibration analysis also known as harmonic response analysis is done to get more efficient and quick results. This analysis is based on the mode superposition method. According to harmonic response analysis, model 4 shows the highest value and model 2 shows the lowest value of maximum stress amplitude. It is concluded that model 4 has more cracks generated. The stresses generated at each LED joint samples are also supported by experimental results. These results show that the interconnection method can be used in electronic devices because there is no effect on the structural integrity of solder joints under severe vibration conditions.

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