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# Impact of Temperature Cycling Conditions on Board Level Vibration for Automotive Applications

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***Abstract*— Board level vibration testing is a commonly used method to predict the solder joint reliability of surface-mounted components seated onto printed circuit boards (PCB). Current board level vibration test methods are mainly developed from a solely mechanical stress application standpoint. This makes such stress tests one dimensional in nature and translation from experimentally obtained test results to the field life of components experiencing combined stress environments become ambiguous. This investigation provides insights to develop a highly accelerated vibration test approach to cover simultaneous vibration and temperature loading situations in the field. In this paper, test board layouts from the board level drop test method, JESD22-B111 (rectangular PCB), and JESD22-B111A (square PCB), prescribed by the Joint Electronic Device Engineering Council (JEDEC), are used to understand the combined stress applied to the solder interconnects. The evaluation process is carried out by means of simulations, supported by targeted experiments on ball grid array (BGA) packages with dimensions sizing from 12x12mm to 15x15mm. The results on rectangular test board assembly show reduced characteristic lifetime of solder joints when stressed under combined temperature-vibration test conditions. On the other hand, the square-shaped board type exhibits a different acceleration factor with a longer solder fatigue lifetime than that of the rectangular-shaped PCB type. Finite element simulation results complement well with this finding.**

***Keywords—Board Level Reliability, Temperature Coupled Vibration Test Method, PCB dynamic response, Ball grid Array package, Highly Accelerated Lifetime Testing.***

## I. INTRODUCTION

The continuous evolution of semiconductor content in safety-critical automotive applications is changing the world of reliability at an unprecedented pace. To cope with this monumental challenge, it is required to develop reliability methodologies that are able to cover the complex and multi-physics stress loading scenarios in the automotive field. It includes coupling together key mechanical and thermo-mechanical stresses driving failures in electronic components.

Board level reliability (BLR) performance of electronic components is one of the key criteria for electronic package selection. Its ubiquitous influence is enhanced by the introduction of miniaturized packages in the automotive industry. Some of these advanced packages raise reliability concerns at the solder joint interconnect level when it is subjected to dynamic loading events in automotive applications. BLR test methods are often used to assess such reliability risks at board level.

In general, BLR testing involves mechanical and thermo-mechanical reliability stresses. These risks are usually covered independently by either employing purely mechanical test methods or thermo-mechanical test procedures. Board level mechanical tests include drop tests, bend tests, vibration tests, etc. On the other hand, thermo-mechanical tests on the board level usually involve temperature cycling stress conditions. This makes such stress tests one-dimensional in nature and correlation of experimentally obtained test results to the actual automotive field life of components experiencing combined temperature and vibration stress environments becomes ambiguous.

A board level vibration test setup is integrated with the temperature chamber to apply thermal stresses during vibration loadings (as shown in Fig. 1). It represents test conditions that are more analogous to the automotive applications than any other one dimensional BLR tests. It is also known as Highly Accelerated Lifetime Testing (HALT).

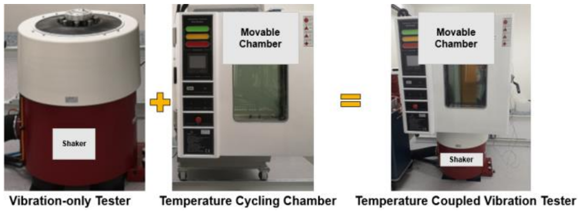

Fig. 1: Temperature Coupled Vibration Tester

The current board level reliability test methods in the industry are not capable of assessing the multi-dimension stress loadings undergone by electronic components. Similarly, the vibration test specification from JEDEC, JESD22-B103 [1] does not directly cover the reliability risks at board level. Several papers [2-4] reporting the impact of combined temperature and vibration can be found in the literature. Solder joint reliability and PCB dynamic response alterations with varying temperatures are often the focus of these studies. These investigations do not emphasize on the stability of a temperature coupled vibration test setup itself.

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In this paper, the test setup of a temperature combined vibration test method strategy is characterized. In addition, some of the pitfalls linked to this experimental methodology are revealed. Then, it is used to gauge the influence of temperature-coupled vibration loading test conditions on the PCB vibration response. This PCB dynamic response is known to govern the solder joint interconnect failure lifetime, failure mechanisms, and failure locations. The investigation procedure is carried out by means of multi-loading reliability stress experiments, supported by finite element analysis-based simulations.

PCB vibration measurements using accelerometers and laser doppler vibrometer are performed to establish a baseline. PCB assemblies are then exposed to the simultaneous application of vibrations at varying temperature conditions to understand the influence of temperature on the PCB vibration response. Then, modal analysis is performed using a finite element method (FEM) developed to mimic the combined vibration and thermal stress conditions used in the highly accelerated board level vibration tests. Next, temperature cycling coupled board level vibration tests are performed on 12x12mm BGA packages. The gathered test results are compared to the board level vibration-only test methodology.

## II. NUMERICAL ANALYSIS DETAILS

### A. *PCB vibration response analysis*

PCB dynamic response comprises of resonance frequency ($f_0$) and peak-peak displacement (d) of the PCB under test. The resonance frequency is one of the material characteristic of the PCB excited under board level vibration test. It can be described by the following empirical relation from Steinberg [4]:

$$f_0 = \lambda \left(\frac{1}{a^2} + \frac{1}{b^2}\right)\sqrt{\frac{Eh^3}{12\rho(1-\upsilon^3)}} \tag{1}$$

where, λ is clamping constant, a and b represent length and width of the PCB respectively, E is the Young's modulus, h is the board thickness, ρ and, υ refer to the metal density and Poisson's ratio respectively. On one hand, the dependence of resonance frequency on Young's modulus makes it an indirect measurement of specimen's material properties during temperature loadings. On the other hand, factors such as clamping constant, PCB dimensions and, pre-stress can also be temperature dependent. Consequently, it cannot be discarded from the overall temperature dependence equation.

On the other hand, peak-peak displacement ($d$) is expressed as two times the peak displacement of the PCB at its resonance frequency. It can be described using the following empirical formulae [5-7]:

$$\mathrm{d} = \frac{a}{2\pi^2 {f_0}^2} \tag{2}$$

where, $a$ is the peak acceleration measured during PCB resonance, and, $f_0$ is the resonance frequency of the PCB. In this equation, PCB motion is assumed to be sinusoidal in time. It is only applicable at the center of the PCB during its first resonance frequency.

### B. *Simulation model*

The Marc/Mentat software is used to derive PCB vibration spectrum results numerically. It is capable of estimating PCB level strains with respect to the measured PCB peak-peak displacements from the PCB dynamic response measurement experiments. The test board are meshed into 8-node brick and 6-node penta elements comprising of PCB material properties. It is shown in the following image.

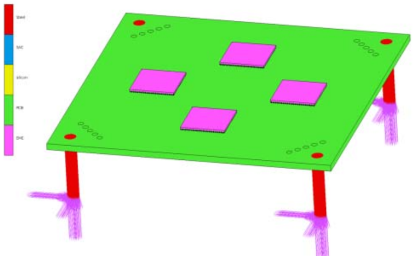

Fig. 2: PCB model with mounting pillars

## III. EXPERIMENTAL TEST SETUP CHARACTERIZATION

Test board layouts examined in this study are designed according to the JEDEC board level drop test method for handheld electronics [8-9] (images shown in Fig. 3). Such board assemblies allow an easier understanding of the stress experienced by the solder joints and comparison to the various other board level vibration test-only and drop test investigations [5-7][10]. These test PCBs are built to represent a typical automotive stack-up. It is 1.6mm thick and comprises 8 copper layers. Ball Grid Array (BGA) type packages with 0.65mm pitch and body sizing 12mm are mounted onto these test boards. These components weigh about 0.5grams. The material properties of these boards are summarized in TABLE I.

TABLE I. TEST PCB DESCRIPTION

| **PCB characteristics** | **PCB Type** | |
|---|---|---|
| | **Rectangular** | **Square** |
| PCB dimensions [mm x mm] | 132 x 77 | 77 x 77 |
| PCB thickness [mm] | 1.6 | 1.6 |
| PCB Material | FR-4 | FR-4 |
| Storage Modulus [GPa] | 22 | 22 |
| Number of Copper layers | 8 | 8 |

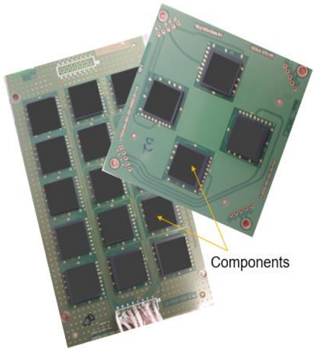

Fig. 3: Test Boards: Rectangular and Square PCBs

The PCB vibration modes are excited using swept sine vibration motions that involve constant acceleration of 5g within a frequency range of 200-500Hz. A control accelerometer (shown in Fig. 4) is used to control the accelerations at the shaker plate. Four standoffs (also seen in Fig. 4) are used to mount test board assemblies onto the shaker plate.

The shaker plate is designed in a way to keep the thermal loading to minimal during temperature coupled vibration tests. The shaker is combined with a temperature chamber that is capable of varying the temperatures ranging between -40˚C to 125˚C.

The desired temperature swing in this study is limited to -40˚C to 125˚C which is following the board level temperature cycling conditions described in the [11-12] specifications. A thermal barrier sheet (shown in Fig. 4) is needed to minimize the temperature leakages to the outside of the temperature chamber and acts as a thermal shield for the shaker armature system.

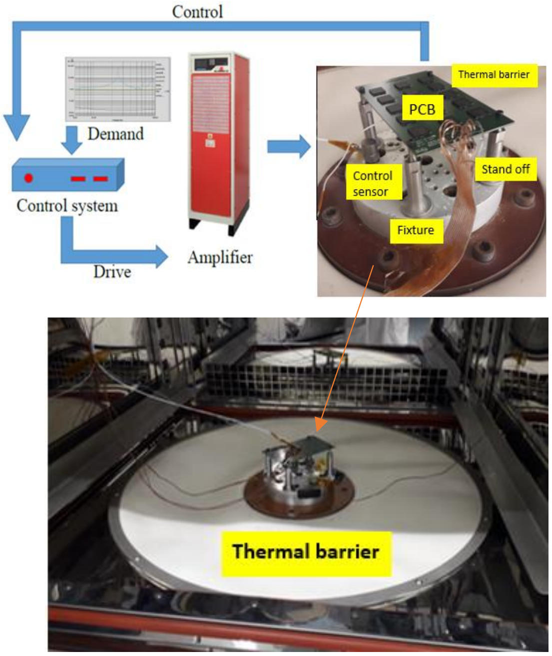

Fig. 4: Board Level Vibration Test Setup with thermal barrier at the bottom of the chamber

### A. *PCB Temperature Characterization Results*

Temperature measurements on a rectangular test board are carried out in a standalone chamber (without attached shaker system) and attached shaker-chamber system to testify that the impact of thermal mass introduced by the shaker fixture is minimal. The results are shown in Fig. 5.

It is found that the temperature measured during the temperature coupled shaker system is slightly lower (3˚C) than in the temperature chamber-only system. It could be ascribed to the additional thermal load introduced by the vibration fixture plate and slight air leakages in the shaker-coupled temperature chamber system. In addition, the oven temperature is not always the same as the PCB temperature. The test PCB temperature lags behind the oven temperature. It can be attributed to the thermal mass of the test board itself. These temperature differences can be counterbalanced by enhancing the desired chamber temperature.

Furthermore, board level temperature measurements are also used to assess the temperature homogeneity at the PCB level. The goal is to have stable temperatures across the test board. Firstly, temperature measurements are performed on the top side and bottom side of the rectangular PCB when it is stressed with and without the thermal barrier layer. It is found that the temperature is not homogeneously distributed along with the PCB when the temperatures in the chamber are raised in a setup that does not contain a thermal barrier sheet as illustrated in Fig. 5.

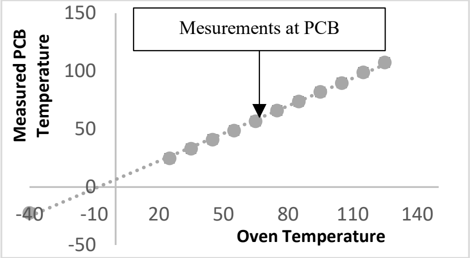

Fig. 5: PCB Temperature Characterization Results with and without Shaker

Temperature gradients of approximately 25˚C are seen for the thermal barrier exclusive setup. Whereas, the temperature differences between the top of the PCB and the bottom side of the PCB are within 1˚C for a thermal barrier inclusive system. So, the thermal barrier layer is vital to the temperature-coupled vibration tests at the board level.

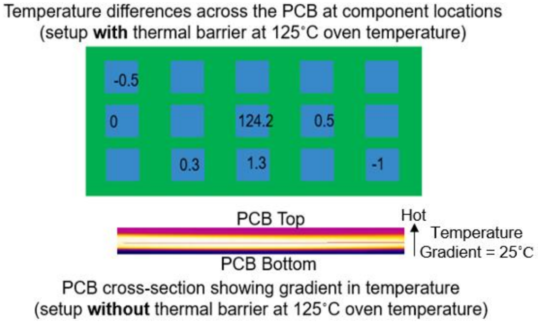

Fig. 6: PCB Temperature Gradient Measurements

Secondly, the temperature at all component locations on the PCB is measured to ensure that all components receive homogenous stresses during reliability tests. Temperatures are measured at board level when chamber temperatures are varied from -40˚C to 125˚C. It is observed that the temperature at PCB is within 1˚C at maximum and minimum temperatures (illustrated in Fig. 6). This concludes the investigation linked to the temperature characterization.

### B. *Vibration Measurement Sensor Mounting Method Assessment Results*

The dynamic response of the vibration fixture and PCB are measured using a lightweight miniature Integrated Electronics Piezo-Electric (IEPE) type accelerometer (weighing about 0.5 grams). It is placed in the center of the board as shown in Fig. 4. In previous investigations [2][5], it is shown to have a minimal impact on the PCB dynamic response during board level vibration-only tests. It is not verified during the temperature-coupled vibration setup.

In general, accelerometers are fixed onto the test board assemblies and shaker fixture plate using adhesives, wax, or screws. However, this mounting strategy might be influenced by the thermal loading conditions. The elevated temperature might modify the holding ability of the accelerometers. As a consequence, it can modify the measured accelerations at the board level.

Therefore, vibration tests are performed at elevated temperatures (until 100˚C) to define the most suitable accelerometer mounting technique. In this experiment, accelerometers are mounted using wax, screws, and adhesives onto the shaker fixture plate. Specifically, the holding ability of wax is found to be the least reliable when compared to the screws and adhesives (illustrated in Fig. 7). This lack of reliability can be attributed to the fact that the wax used in this study involves a low melting temperature. As a consequence, it results in a poor bond between the accelerometer and test board.

Next, a screw is used to mount the accelerometer. The accelerometer mounted with a screw caused deviations in the measurements at 100˚C. These deviations were more than 10% of the expected vibration measurement values. It is expected to be caused by a metal crack found in the screw channel. It can be introduced by thermo-mechanical loads. Whereas, accelerometers mounted with adhesive caused the least amount of vibration measurement deviations at all temperatures. Consequently, adhesive bonding is used to mount accelerometers in this study.

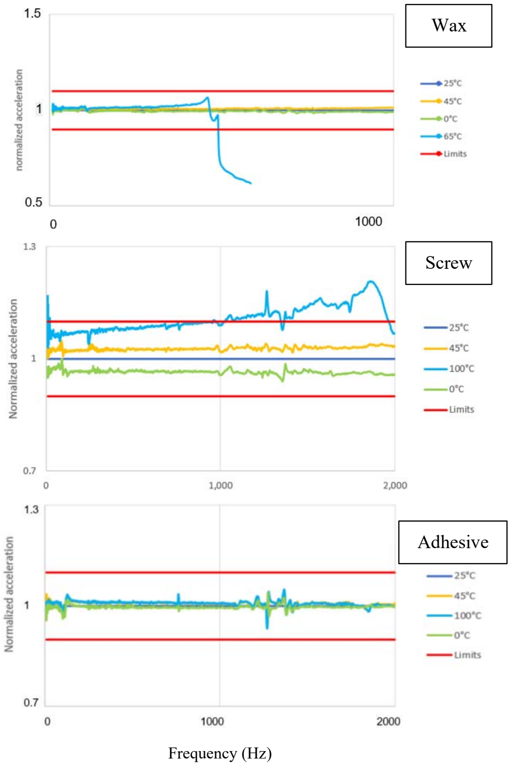

Fig. 7: Accelerometer Mounting Method Assessment Results: Wax vs. Screw vs. Adhesive

# IV. IMPACT OF TEMPRATURE LOADINGS ON BOARD VIBRATIONAL RESPONSE

A PCB vibration response entailing resonance frequency of the board is an indirect measurement for its material property, such as Young's Modulus. The material properties of the board are expected to degrade irreversibly and reversibly from mechanical and thermo-mechanical loading.

At first, the contribution from continuous mechanical loading is characterized before understanding the impact of temperature loading on the material properties of rectangular PCB. In this case, board level vibration tests are conducted at an acceleration level of 5g for 22 hours. From Fig. 8, it is clear that the resonance frequency of the PCB drops by 4Hz. Furthermore, the peak-peak displacement is increased by about 20%. This shift can be devoted to the accumulation of deterioration occurring in the PCB material during mechanical loading. The PCB damping decreases with mechanical stresses that result in increased peak-peak displacements. This trend is also in line with the previous findings from the authors [2].

With the damage contribution from continuous mechanical loading characterized, the PCB degradation is further measured under mechanically-coupled thermo-mechanical loads. The dynamic response of both rectangular and square type test boards are measured under the vibration coupled isothermal and temperature cycling test conditions.

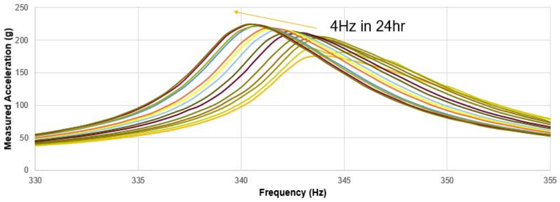

Fig. 8: Effect of Mechanical Aging on PCB Vibration Response

## *A. Isothermal temperature loadings:*

The temperatures of the bare PCB are raised sequentially to determine the impact of thermo-mechanical loads on PCB vibration response. The PCB vibration characteristics are recorded at temperatures starting from 25˚C and are stressed sequentially until 125˚C is reached with a temperature step of 15˚C. Three consecutive vibration sweeps are given at each temperature step. The results for the rectangular test board layout are shown in Fig. 9.

The resonance frequency of the rectangular test PCB declines linearly at a rate of -0.21 Hz/˚C over the whole temperature range of -40 to 120˚C (Fig. 10). It is expected to result from the changes occurring in the Young's modulus of the PCB and PCB clamping with respect to the temperatures. The Young's modulus of the PCB decreases with rising temperatures. As a result, the resonance frequency of the PCB decreases with the rise in temperatures (in accordance with equation 1).

The peak-peak displacement of the PCB is calculated using equation 2. It is found to be 0.55mm when tested at 25˚C. It is observed that the PCB damping properties increase at elevated temperatures (Fig. 11). It might indicate accumulation of stresses in the viscoelastic-based PCB material. A clear change in the damping ratio is seen at around 70-80˚C. In addition, saturation in the damping ratio can be seen at temperatures below 25˚C.

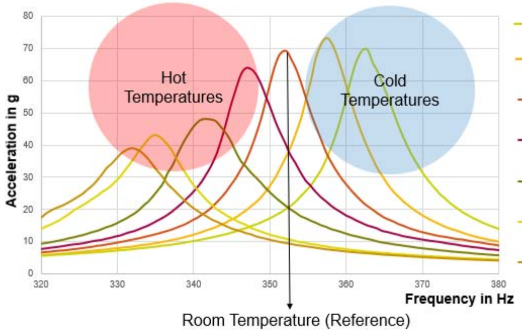

Fig. 9: Evolution of Resonance Frequency with Temperature

The peak-peak displacement of the PCB is calculated using equation 2. It is found to be 0.55mm when tested at 25˚C. It is observed that the PCB damping properties increase at elevated temperatures (Fig. 11). It might indicate accumulation of stresses in the viscoelastic-based PCB material. A clear transition in the damping ratio is seen at around 80˚C.

The transition in the damping ratio coincides well with the shift in Tan Delta measured around 80˚C during the dynamic mechanical analysis of the PCB material (Fig. 12). It might be introduced by the glass transition temperature of the solder mask. However, the temperature sensitivity of the clamping test setup with respect to the PCB can also contribute and alter the board vibration response at high temperatures.

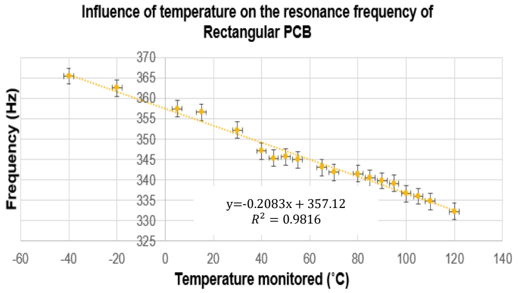

Fig. 10: Evolution of Resonance Frequency with temperature

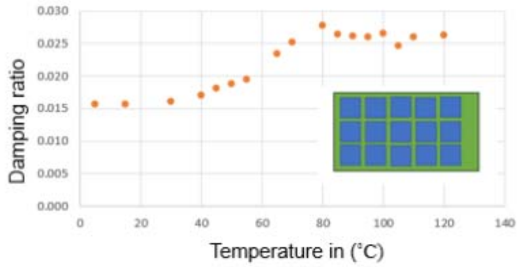

Fig. 11: Effect of Temperature on PCB Damping

## B. Temperature cyling loadings

The PCB vibration motion properties under cycling temperature conditions are studied in this sub-section. The temperature cycling profile used in this evaluation is shown in Fig. 13. The temperature cycle is about 2 hours long. It involves a ramp rate in between 4-5 ˚C/min and dwell times of 10 minutes at maximum (125˚C) and minimum (-40˚C) temperatures. The rectangular PCB is stressed for 11 temperature cycles. The PCB dynamic response is measured by giving three vibration sweeps during the dwell portion of each temperature cycle. Then, these results are compared to the PCB vibration response at the ambient temperature of 25˚C.

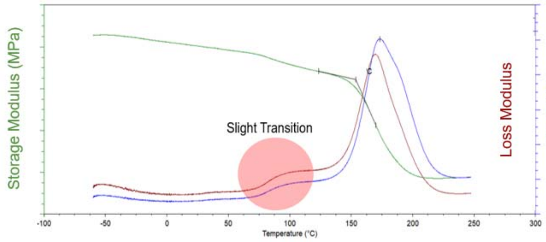

Fig. 12: Dynamic Mechanical Analysis (DMA) of Test Board

When compared to the PCB resonance at 25˚C, it is found that the PCB resonance frequency is increased at low temperatures and decreased at high temperatures (shown in Fig. 14). It is similar to the trend seen in the isothermal loads. The rate of change in resonance frequency is higher at elevated temperatures when compared to that at the lower temperatures. A range of about 100Hz (difference between the maximum and minimum value) is confirmed in the resonance frequency of the PCB.

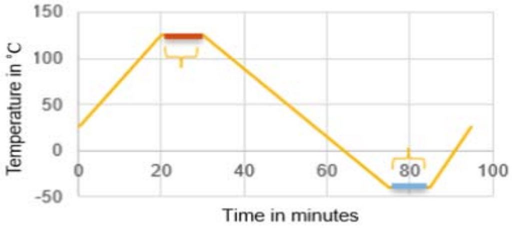

Fig. 13: Temperature Cycling (TC) Test Profile (-40˚C/125˚C)

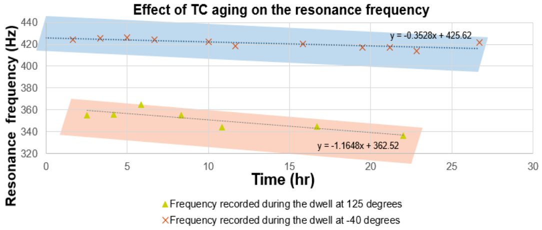

Fig. 14: Effect of TC Aging on the PCB Resonance Frequency

The PCB dynamic response is then measured after completion of every temperature cycle. At first, the resonance frequency decreases for the first four temperature cycles and then it increases for the remaining 8 temperature cycles (Fig. 15). In addition, the PCB damping increases during the course of temperature cycling stress (Fig. 16). One of the possible hypothesis might be linked to the time dependent viscoelastic nature of the PCB material properties. It might also be linked to the PCB material degradation and temperature sensitivity of the PCB clamp test setup used in this study.

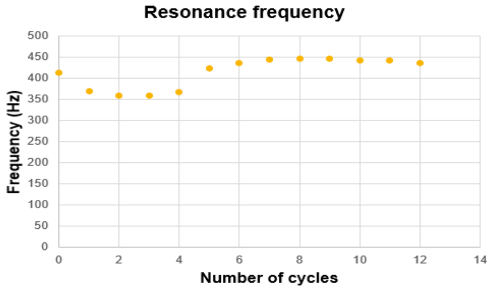

Fig. 15: Evolution of PCB resonance frequency with respect to temperature

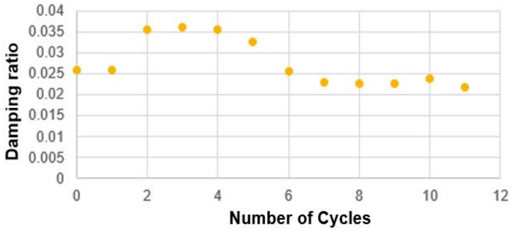

Fig. 16: Evolution of Resonance with respect to the Temperature Cycling Coupled Vibration Tests

### C. Discussions: Impact of Temperature Cycling vs. Isothermal loads on the PCB dynamic response

As per the PCB vibration spectrum analysis results, the temperature loading parameters influence the PCB resonance frequency and damping ratio. As a result, it impacts the solder joint lifetime of components.

From the vibration coupled temperature cycling test results, it is found that the resonance frequency varies at a faster rate during dwell at hot temperature as compared to the rate of change observed at soak during cold temperature. It highlights the fact that high temperatures have a greater impact on the PCB resonance frequency than cold temperatures. On the one hand, it can be linked to PCB stiffness. At high temperatures, the PCB stiffness reduces which results in large shifts in resonance frequency. On the other hand, the shifts can also be attributed to the solder mask cracks (as reported in [2]) and permanent degradation of the prepeg and core PCB materials.

In addition, a drift of approximately 60Hz is seen in the PCB resonance frequency after the first temperature cycle of 2 hours. This is increased over time to about 100Hz after 24 hours of temperature cycling tests. It is more than when compared to the isothermal temperature increment experiments. On the one hand, this observation can be attributed to the fact that the board is stressed for more amount of stress time during temperature cycling tests than in the isothermal increment tests. On the other hand, it can be linked to the variation of thermo-mechanical properties of the PCB. The variation is expected to be larger during thermo-cycling tests than compared to the isothermal incremental tests. Other hypothesis include CTE (coefficient of thermal expansion) mismatch between the metallic vibration fixture and the PCB itself. It might alter the PCB deformation during resonance.

It can also be concluded that the PCB damping ratio changes when it is subjected to temperature environments. It decreases non-linearly after completion of 11 temperature cycles. This can also give rise to the time dependent deformation in the PCB during temperature cycling tests. It is affected more in the temperature cycling tests than during the isothermal increment tests and vibration-only tests conducted in this study. It can also lead to varying peak-peak displacements at PCB level. Overall, the thermo-mechanical stress contributes more to the resonance shift and peak-peak displacement when compared to the mechanical counterpart. It is expected to accelerate the stress applied at the solder joint area.

### D. Impact of test board assemblies during isothermal temperature coupled vibration tests

The reliability test board is an essential asset of any board level reliability test. It can alter the stress at the solder joint level and hence can influence the failure mode. Therefore, it is vital to understand the impact of the test board. It is assessed by stressing the board layout from JESD-B111A [9]. The buildup of this PCB type is the same as that of the rectangular PCB layout. It is also referred to as a square-type test board in this assessment. This PCB type is known to exhibit lower peak-peak displacement and higher resonance frequency when compared to the rectangular test board [2][5].

The findings from square test board are shown in Fig. 17. The resonance frequency is reduced at high temperatures. Whereas, a rise in resonance frequency is seen at cold temperatures. Therefore, similar trends are seen for the square-type test board in comparison with the rectangular test board type (as shown in Fig. 10). In addition, an increase in damping coefficient is seen for both PCB types at around 80˚C (Fig. 18 compared to Fig. 11). It can be linked to the DMA results shown in Fig. 12.

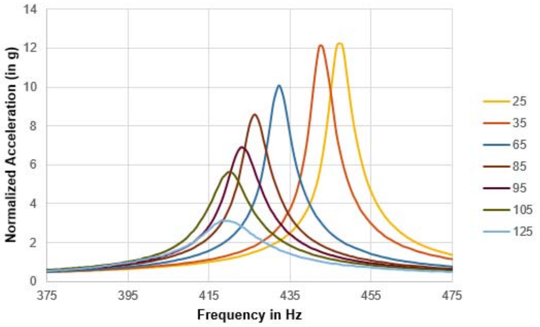

Fig. 17: Evolution of Resonance Frequency with respect to temperatures higher than 25˚C (on Square test board)

The magnitude of rate of change in the resonance frequency of the square type test board (-0.37Hz/˚C) is more than the rectangular type test PCB (-0.21 Hz/˚C as shown in Fig. 10). It recites that the PCB response of square circuit board type in a temperature coupled vibration environment is affected more than the rectangular PCB layout. It might be ascribed to the larger temperature sensitivity of the clamping test setup and/or higher bending cycles of this test board as opposed to the rectangular PCB. Table II summarizes the PCB vibration characteristics measured on the square test boards.

Then, FEA is carried out to testify the experimental measurement results. FEM results on square type board layout (illustrated in Fig. 19) complement well to the declining trend observed in the experimental findings. In addition, the slope that defines the change in resonance per unit temperature compliments well with the experimental observation. The modeling results show a slope of about -0.36Hz/˚C which is very similar to -0.37Hz/˚C determined from the experimental results.

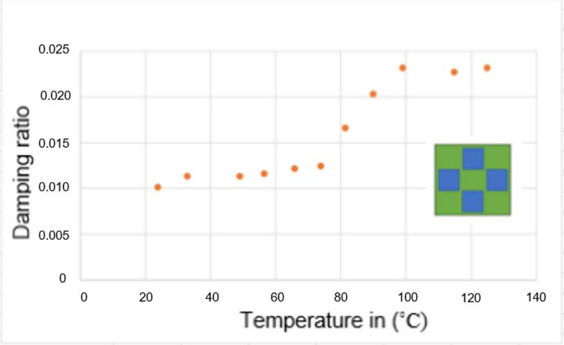

Fig. 18: Damping vs. Temperature for Square PCB

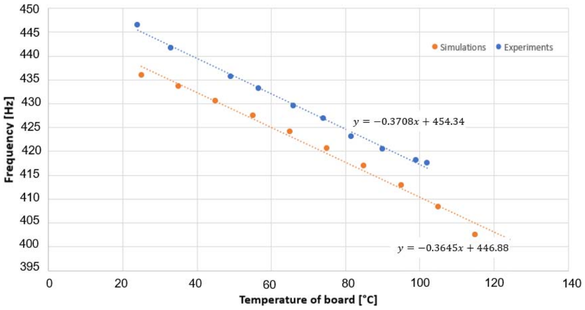

Fig. 19: Comparison of Simulation Results vs. Experimental Results

TABLE II. PCB DYNAMIC RESPONSE RESULTS

| PCB vibration characteristics | PCB Type | |
|---|---|---|
| | Rectangular | Square |
| Resonance frequency at 25˚C [Hz] | 357 | 454 |
| Peak-Peak displacement at 25 ˚C [mm] | 0.55 | 0.06 |
| Damping ratio at 25 ˚C | 0.016 | 0.010 |
| Temperature dependence in resonance [Hz/˚C] | -0.21 | -0.37 |
| Maximum shift in Resonance Frequency during isothermal loadings | 25Hz | 30Hz |
| Maximum shift in Resonance Frequency during TC loadings | 100Hz | Not tested |
| Mamimum shift in damping ratio during isothermal loadings | 0.013 | 0.014 |

## V. TEMPERATURE COUPLED BOARD LEVEL VIBRATION TEST RESULTS

Seven rectangular-type test boards are used to study the impact of temperature cycling coupled vibration tests on the solder joint reliability. It amounts to a sample size of 105 BGA package components sizing 12x12mm. Three boards are stressed under temperature coupled vibration tests and four boards are tested under vibration-only tests.

BGA packages are stressed under swept sine vibration tests. A constant acceleration amplitude of 3g is selected to minimize permanent board damage from 5g acceleration level (as reported in [2]). These devices are stressed under the temperature cycling conditions that are used in the previous section. Then, these components are excited around the varying resonance frequency region of this test board (shown in Fig. 14). A frequency range of 300Hz is varied at a speed of 2octave per minute to ensure that each vibration sweep runs through the PCB resonance frequency. The failure criteria is defined according to the board level drop test from JEDEC [8-9]. A resistance value greater than 1000Ω is regarded as a fail.

The vibration tests are conducted until the components fail. The distribution of these failing components is analyzed using the Weibull life assessment method. It is illustrated in Fig. 20. Generally, the components located in the middle of this test board (referred as Group A) receive the maximum amount of stress as compared to the remaining devices under test (referred as Group B) [2][10]. It is also established in the temperature coupled vibration test reliability assessment.

No failures are observed in Group B & C after 2051 minutes. So, Weibayes analysis (with constant shape) is used to plot the expected lower confidence interval of the test data gathered from temperature coupled vibration tests. Based on the scale factor comparison, it is found that the performance of components placed in the middle of the PCB fail (represented as Group A) is at least 50% lower than the components located in the Group B section of the test board.

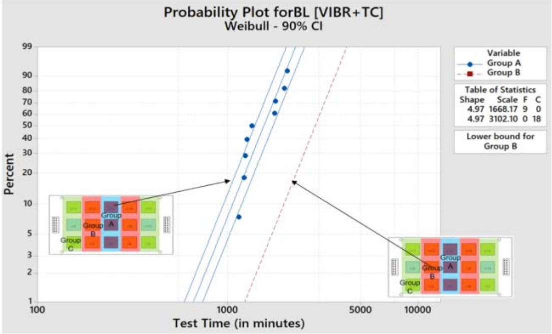

Fig. 20: Temperature Cycling Coupled Vibration Test Results: Group A vs Group B Components

The failure distributions of temperature coupled vibration tests and vibrations-only tests are compared next. A clear distinction in these two failure distributions are found (Fig. 21).

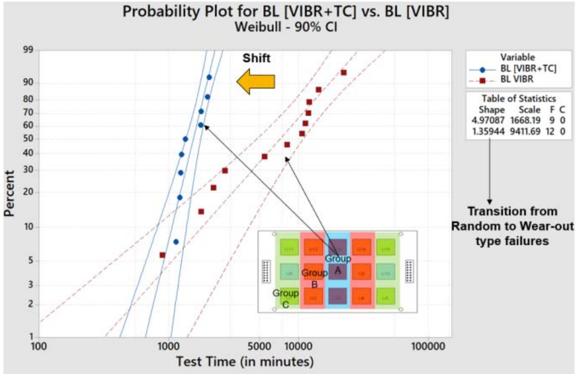

Fig. 21: Board Level Vibration Test Results: BL [VIBR+TC] Tests vs BL VIBR Tests

A reduced scale factor is found for components that are stressed under temperature coupled vibration tests. The characteristic lifetime is shortened by about five times when compared to the components stressed in vibration-only test conditions. As a result, reducing the vibration test time by 5-6 amount of time.

In contrast to the characteristic lifetime, the slope of failure distribution of components that are tested under temperature coupled vibration tests is higher when compared to the slope from vibration-only tests. It indicates that the solder crack propagation rate for these tests might differ. As a result, higher failure rate is induced by the temperature coupled vibration tests when compared to the vibration-only tests. It can be explained by the PCB vibration response characterization results presented in Section IV.

It can also be concluded from the Weibull analysis that random-type failures (shape of about 1.3) are observed for board level vibration-only tests. It is expected to involve multiple failure modes and/or random stress application to the component. Whereas, wear out-type failures (shape of about 5) are seen for the temperature cycle coupled board level vibration tests. Eventually, it can be attributed to the enhanced solder fracture rate in the temperature coupled vibration tests.

The failure analysis results after board level vibration tests shows solder joint crack towards the component side at the corner of the package (Fig. 22). It is similar to the first failure mode observed in board level vibration-only tests.

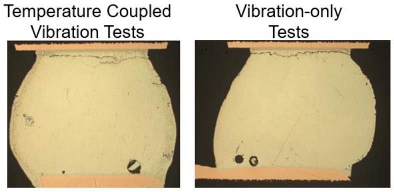

Fig. 22: Failure Analysis Results Comparing Bl [VIBR+TC] vs. BL [VIBR] tests

## VI. CONCLUSIONS

The findings from this paper revealed some of the pitfalls linked to the temperature coupled vibration test setup. For instance, the mounting strategies of accelerometers onto the PCB is assessed. It is recommended to determine the most suitable accelerometer mounting solution before testing electronic components in temperature coupled reliability stresses. This study advocates attaching accelerometers using adhesive that can withstand high temperature environments. The use of thermal barrier layer is suggested to prevent temperature leakages and maintain similar temperatures across several components. It enables homogenous application of temperature stresses on all component locations during temperature coupled vibration tests.

PCB vibration spectrum analysis results show drifts in the resonance frequency, PCB damping and peak-to-peak displacement of the stressed circuit board assemblies. This observation is linked to the stress undergone by the PCB during accelerated life test environments. When comparing the two test board assemblies, the square-shaped board type exhibits a higher acceleration factor in the resonance change with respect to the applied temperature. However, it is expected to yield a longer solder fatigue lifetime than that of the rectangular-shaped PCB type. This outcome can be explained from lower PCB deformations when comparing it to the rectangular type board layout. Then, a modal analysis was performed using a finite element model (FEM) developed to mimic the combined vibration and thermal stress conditions used in the highly accelerated board level vibration tests. FEM results show similar trends as found in the PCB vibration measurement experiments.

The reliability test results on the rectangular test board assembly show reduced characteristic lifetime of solder joints when stressed under combined temperature-vibration test conditions. In addition, a transition from random type failure observed in the vibration-only tests to wear-out type failure in the temperature coupled vibration tests. The Weibull slope (of about 5) reflects the change in failure type from random to wear-out in the combined temperature vibration test strategy. This observation might be linked to the high solder crack propagation rate in the combined vibration test conditions. The PCB vibrational characteristics such as varying resonance frequency, reduced PCB damping, and enhanced PCB deformations might accelerate the solder fracture mechanics phenomenon.

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