# Design Guidelines for Preventing Flex Cracking Failures in Ceramic Capacitors

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## Introduction

Surface mount multilayer ceramic capacitors (MLCCs) are one of the most common components found on modern circuit card assemblies. Introduced in 1977, they are well known for their reliability and have been rapidly accepted by the electronics industry. The reliability of a nominal MLCC is extremely high, with expected operating lifetimes in the decades, if not hundreds of years. However, to attain these levels of reliability MLCCs must have no critical defects and be used properly. Reliability problems can occur due to improper handling or because of the presence of defects, introduced during the manufacturing or assembly processes.

The failures resulting from these internal defects can cause internal shorts that can lead to explosions because of the large amounts of energy stored in capacitors. This not only destroys the MLCC, and any evidence of root-cause, but can also cause damage to surrounding components, the printed board, adjacent circuit card assemblies, and in the worst-case lead to catastrophic fires.

Improper usage of MLCCs can cause them to fail prematurely this includes handling damage, thermal shock, excessive flexing, or applied voltage exceeding manufacturer's specifications. Cracks due to thermal shock or excessive flex are the most common failure mechanisms, with the primary difference between these two root-causes being the morphology of the resulting crack. Both thermal shock cracks and flex cracks tend to propagate at 45-degree angles from the termination of the end cap. Both types of cracks can also range in size, but flex cracks tend to be larger, propagating through the ceramic until the crack reaches the end cap. A schematic of a typical flex crack is displayed in Figure 1.

Failures that occur during connector insertion, depaneling, or bolting are often due to excessive printed wiring board (PWB) flexure. Excessive PWB flexure will cause flex cracks, which often emanate from the termination of the end cap and propagating at a 45-degree angle. In order to avoid designing, manufacturing or using circuit card assemblies in manner that will induce flex cracking in MLCCs, it is important to determine the failure criterion that will cause flex cracks to initiate and what drivers will increase the susceptibility of capacitors to flex cracking.

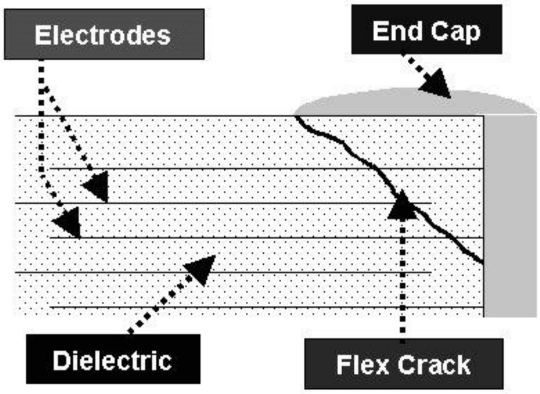

**Figure 1:** Schematic of a flex crack in a multilayer ceramic capacitor

## Bend Testing: Identification of Failure Criterion

To determine the event that could initiate flex cracking, one must determine the strain in the printed wiring board necessary to cause failure. In a paper by Prymak of Kemet [3], the failure rate of 0805 and 1206 MLCCs is detailed as a function of displacement in a three-point bend test.

Using a simple FEA model (Figure 2) of the 0805 MLCC and the materials listed in Table 1 and Table 2, the stress in the capacitor as a function of displacement can be approximated. The failure data for the 1206 capacitor will be used later to verify a model to predict capacitor failure during printed wiring board bending.

**Figure 2:** Simple FEA beam model of capacitor mounted on printed wiring board

| Material | Elastic Modulus (E: MPa) | Poisson ratio (ν) |
|---|---|---|
| Copper | 117000 | 0.355 |
| Solder | 35800 | 0.39 |
| FR4 | 14800 | 0.159 |
| X7R ceramic | 105000 | 0.34 |
| Capacitor termination | 73000 | 0.3 |

**Table 1:**Material properties, linear: elasticity [7] [9] [10]

The copper bond pad and solder are modeled as power-law hardening elastic-plastic materials with a Ramberg-Osgood type constitutive model given in Equation 1 and constants given in Table 2.

| Material | Yield Str. ($\sigma_y$ :MPa) | Strength coeff. (*K*) | Strain-hardening exp (n) |
|---|---|---|---|
| Copper | 68.95 | 319.8 | 0.540 |
| Solder | 34.2 | 49.16 | 0.057 |

**Table 2:**Material properties, nonlinear [7] [9]

$$\sigma_y = K\varepsilon_p{}^n$$

where

$\sigma_y$ : Yield stress MPa

$K$ : Strength coefficient

$n$ : Strain hardening exponent

$\varepsilon_p$ : Plastic strain

**Equation 1**

The maximum tensile stress in the capacitor is plotted verses the displacement during the three-point bend test in Figure 3.

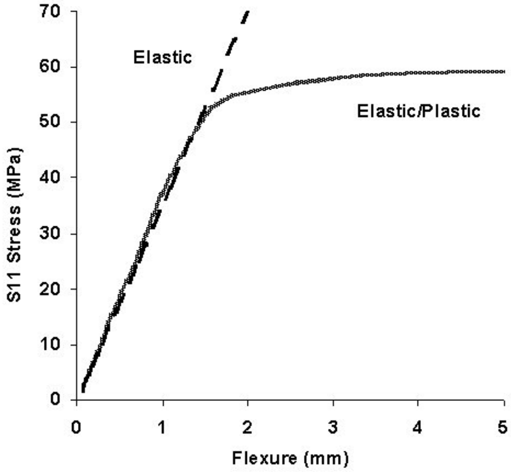

**Figure 3:** Flexure Stress relationship for 0805 Capacitor mounted on a 1.6 mm PWB including solder plasticity

Since plasticity of the solder is included, the maximum tensile stress that can be generated is limited. The critical stress in the capacitor is shown to be between 55 and 60 MPa and agrees with values found in literature [8]. This verifies that beam type equations can adequately represent the behavior of the capacitor as flexing occurs and that there isn't a large variation in the stresses required to fail the capacitors because of the solder plasticity. Neglecting plasticity and rerunning the model results in the tensile stress verse displacement plot shown in Figure 3. These results coupled with various types of finite element models will be used to extend the available experimental data to larger size capacitors.

Using the basic theory for a simply supported beam and taking into account that the capacitors were placed directly above the loading point the failure rate can be expressed as a function of the radius of curvature and the board strain near the capacitor can then be calculated as

$$\varepsilon_{xx} = \frac{t}{2\rho}$$

**Equation 2**

Where *t* is the thickness of the board, *ε* is the board strain at the outer fibers and *ρ* is the radius of curvature.

The results of the 0805 capacitor Kemet tests and the equivalent radius of curvatures and strains are displayed in Table 3 and Figure 4.

| Failure Rate | 100ppm | 0.1% | 1% | 10% |
|---|---|---|---|---|
| **Displacement (mm/in.)** | 2.29 / 0.09 | 2.67 / 0.11 | 3.14 / 0.12 | 3.55 / 0.14 |
| **Radius of Curvature (mm/in.)** | 294.8 / 11.6 | 252.8 / 9.95 | 214.9 / 8.46 | 190.1 / 7.49 |
| **Board-Level Strain** | 2.71E -03 | 3.16E -03 | 3.72E -03 | 4.21E -03 |

**Table 3:** Results of three-point bend testing of 0805 capacitors [3]. Test span was 90 mm and test board thickness was 1.6mm.

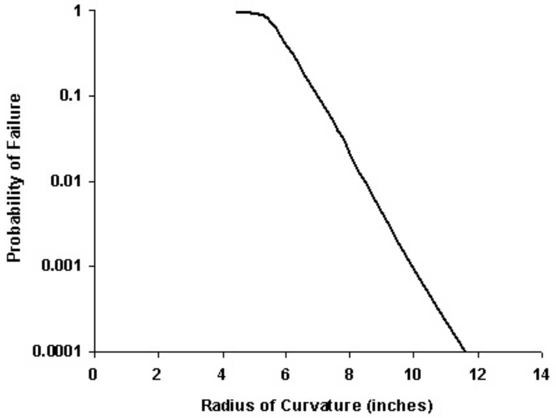

**Figure 4:** Probability of flex cracking in a 0805 capacitor as a function of the radius of curvature of the board. Plot is based upon results in ref. 3.

The results of the 1206 capacitor Kemet tests and the equivalent radius of curvatures and strains are displayed in Table 4, and Figure 5.

| Failure Rate | 100ppm | 0.1% | 1% | 10% |
|---|---|---|---|---|
| **Displacement (mm/in.)** | 1.84 / 0.07 | 2.02 / 0.08 | 2.25 / 0.09 | 2.56 / 0.10 |
| **Radius of Curvature (mm/in.)** | 367 / 14.4 | 334 / 13.4 | 300 / 11.8 | 264 / 10.4 |
| **Board-Level Strain** | 2.18E-03 | 2.39E -03 | 2.67E -03 | 3.03E -03 |

**Table 4:** Results of three-point bend testing of 1206 capacitors [3]. Test span was 90 mm and test board thickness was 1.6mm

By using the results shown in Figure 3 a stress failure relationship for the 0805 capacitor can be developed and used as a failure prediction model for other capacitors regardless of size and board parameters. This is verified using the 1206-capacitor failure data from the Kemet tests. The plot in Figure 6 shows the results in ref.3 plotted against the predictions from FEA and the failure model. The results indicate that failures can be predicted within 10% for the 1206 capacitor.

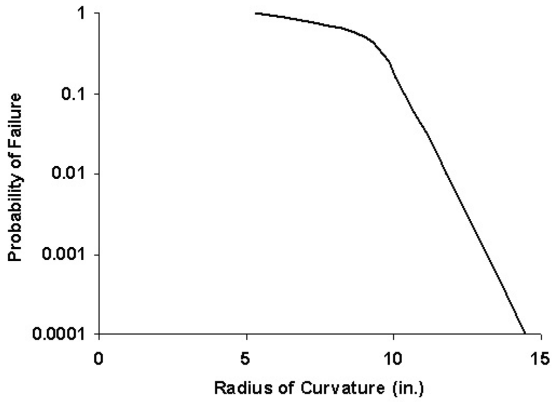

**Figure 5:** Probability of flex cracking in a 1206 capacitor as a function of the radius of curvature of the board. Plot is based upon results in ref. 3**.**

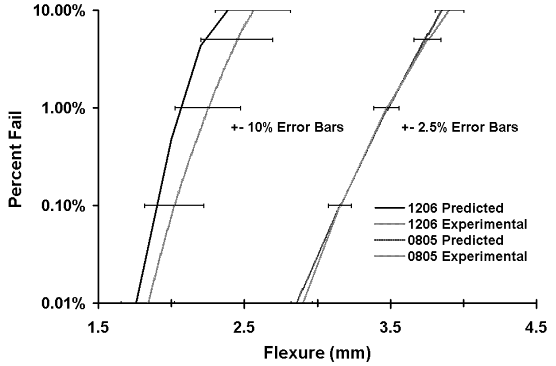

**Figure 6:** Model predictions of failure for 0805 and 1206 capacitors. Test span was 90 mm and test board thickness was 1.6mm.

Using stress as the failure criteria in simple FEA models allows for the rapid failure prediction of different size capacitors as they undergo a printed wiring board bending event.

## Stresses and Strengths that Increase the Potential for Flex Cracking

Drivers that may increase the potential for flex cracking include the occurrence of rework and the size and shape of the capacitor. Using the combination of three-point bend testing and FEA, the quantitative effect of these drivers can be determined and can be inputted into a risk assessment process.

## Effect of Rework

At the start of cool down after solder reflow, the temperature of the board and capacitor are practically equivalent. The two components are also in a stress-free state because the solder attach between them is molten and is unable to transfer the effects of differential strain. As the two components cool, the board will contract more than the capacitor because the epoxy/glass fiber composite has a higher coefficient of thermal expansion (~ 17 ppm) than the ceramic dielectric of the capacitor (~8-10 ppm). As the solder cools and becomes more rigid, this differential contraction will place the capacitor under a *compressive* stress. Based on the work by Cozzolino [1], this stress is approximately 25-40 MPa in magnitude, depending on the size and shape of the solder joint.

During rework, thermal energy is driven into the interconnects so that the liquidus temperature of the solder is quickly reached. Because of its large thermal mass, the temperature of the board will stay relatively constant during rework. However, the smaller size of the ceramic capacitor will result in an increase in the internal temperature of the capacitor. This temperature differential will result also result in capacitor contracting against a rigid printed board. This will cause a residual *tensile* stress to arise in the ceramic capacitor. Because this tensile stress will be in the 11 direction[1], it could reduce the critical displacement necessary to induce flex cracking. To determine the magnitude of this residual tensile stress, the temperature of the ceramic capacitor during rework was measured and the resulting information was entered into a two-dimensional FEM model.

A thermocouple was positioned on the top of an 1825 capacitor using Kapton tape. Using standard rework techniques, the 1825 capacitor was soldered to the board. The soldering iron was in contact with the capacitor for approximately 3-5 seconds. Maximum temperature recorded was 50$^{o}$C. Temperature measurements were taken on two other 1825 capacitors. Maximum temperature was found to be 50$^{o}$C ±- 5$^{o}$C in all three cases.

In the FEA simulation the creep properties of the solder as a function of temperature were inputted into the model. After the solder joint and capacitor were heated in the simulation, they were brought back down to room temperature and the model was run an additional 3600 seconds to see if any significant stress relaxation occurred. The result of the FEM analysis is shown in Figure 7. This resulted in a residual stress in the capacitor of approximately 20 MPa. This level of stress could have a significant effect on capacitor susceptibility to flex cracking.

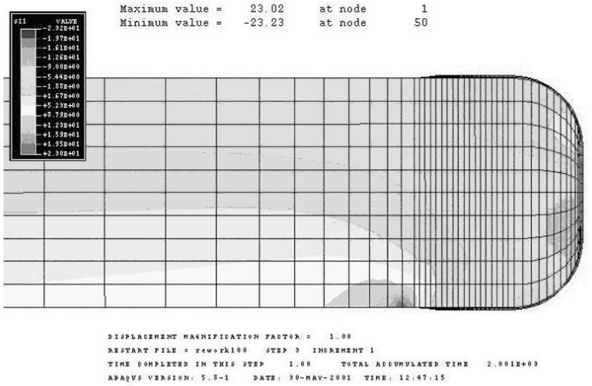

**Figure 7:** Stresses in the 11 direction (s11) in an 1825 capacitor heated to 50$^{o}$C during solder rework

Previous experiments have shown that the stress in the solder joint due to the attachment method is time-limited. Cozzolino and Ewell [1] placed micro-strain gauges on surface mount capacitors to measure stresses after solder reflow. All stresses measured were compressive in nature. The highest stresses were on the bottom surface of the capacitor and varied between 24 MPa for zero fillet height and nominal solder thickness to 43 MPa for maximum fillet height and zero solder thickness. Note that because of the size of the strain gauge, these numbers are averaged values and do not correspond to peak stresses within the body of the capacitor.

Cozzolino and Ewell also determined that there was measurable stress relaxation behavior of the solder joints, even at room temperature. At 25$^{o}$C, stresses decreased by 50% in 24 hours for zero fillet height and 6 days for maximum fillet height. At 95$^{o}$C, stresses reduced to one-half initial value in approximately 15 minutes. FEA simulation found negligible reduction in stress after one hour at room temperature. The differences between predicted behavior and experimental findings have not been reconciled.

## Size and Shape of the Ceramic Capacitor

The primary dimensions that effect flex cracking in ceramic capacitors are thickness and length. Because the termination of the end cap is the structural artifact that creates the stress concentration, the capacitor

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[1] Along the length of the capacitor

width should have little to no effect on the occurrence of flex cracking.

An initial review of the literature indicates some confusion on whether thickness has an effect on susceptibility to flex cracking. Anecdotal evidence provided by Pickering [11] implied that thicker capacitors are more resistant to cracking than thin capacitors. Viswanadham [5] states that the thicker the capacitor, the greater propensity for cracks, but does not differentiate between thermal shock cracks and flex cracks. Bergenthal [4] believes that for the available range of MLCC thicknesses, chip thickness has minimal effect on the incidence of flex cracking. The FEA model shown in Figure 8 is used to verify the effect that capacitor thickness has on the internal stresses developed.

From an elasticity-based approach, thinner capacitors are more compliant than thicker capacitors. Therefore, one would expect that for a given bend radius, the maximum $\sigma_{11}$ should be higher in thicker capacitors than thinner capacitors, thus increasing the probability of flex cracking.

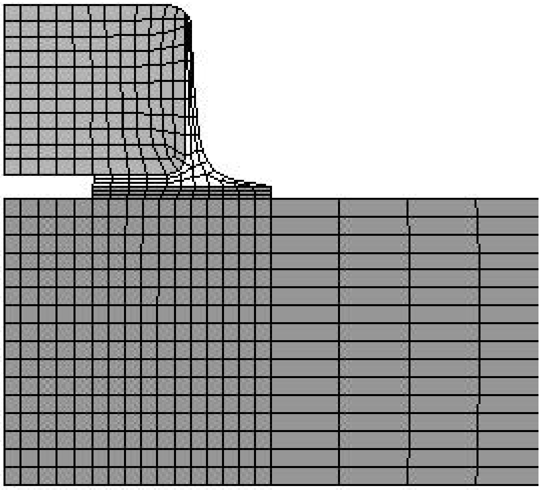

**Figure 8:** 2D FEA model used for verifying the effects of chip thickness on internal stresses, based upon an 0805 capacitor during a 3 pt bend test of a 1.6 mm pwb with a 90 mm span.

As seen in Figure 9 the bottom of the capacitor is in tension indicating that the bending moment transmitted into the capacitor is significantly smaller than the tensile forces. The effect of changing the capacitor thickness is shown in Figure 10. These results indicate that capacitor thickness has very little effect on the internal stresses and that one can expect a 3.47% increase in the internal stresses for a 25% reduction in the capacitor thickness.

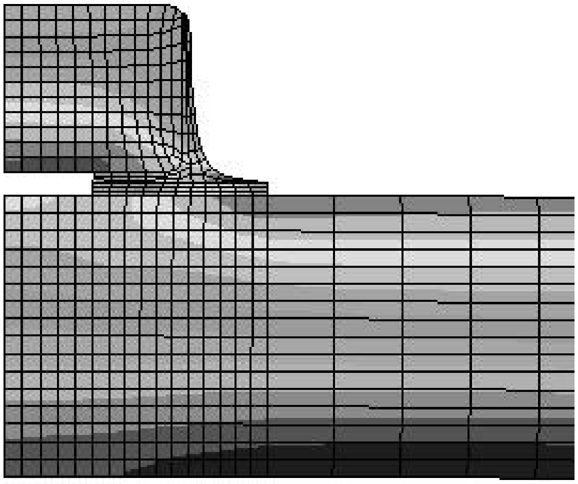

**Figure 9:** Tensile stress distribution during 3 pt bend test.

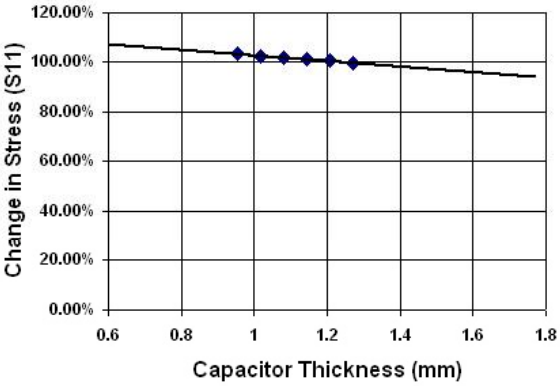

**Figure 10:** Variation in tensile stresses in the 0805 capacitor as a function of capacitor thickness.

To examine the effect of capacitor length on flex cracking, CALCE ran FEA models similar to the one shown in Figure 2 and used the previously derived stress failure criteria. The FEA results for the 0805, 1206, 1812 and 2220 capacitors undergoing a 3-point bend test are shown in Figure 11. The results show that length greatly influences the capacitors reliability with regards to flex cracking.

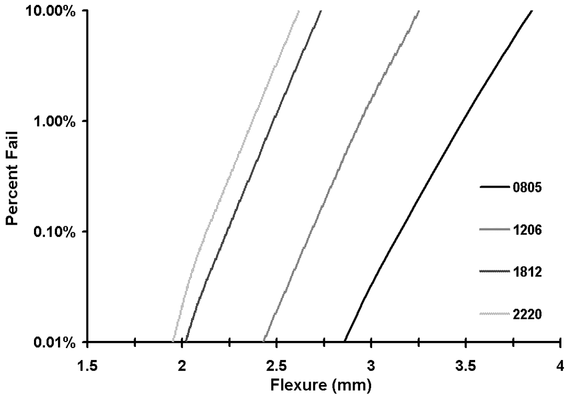

**Figure 11:** FEA and stress failure criteria based probability of flex cracking during a 3 point bend test of a 1.6 mm pwb with a 90 mm span.

**Board Constraint**

It is a common assumption that flex cracking is due to 'whole board' bending along the width of the board (parallel to the capacitor length). 'Whole board' bending describes a state in the process where the whole board curves uniformly, such as differential contraction of the board and the heat sink, or where the sides of the board remain fixed and the center of the board is allowed to flex. This situation can arise during cleaning, testing, conformal coating, or any other step in the manufacturing and assembly process where an extensive amount of handling is required. However, a critical evaluation reveals that 'whole board' bending is often an unlikely cause of flex cracks.

This is because the critical displacement necessary to induce failure drops dramatically when a smaller span is considered, such as between attachment points. In addition, when a board is constrained in some manner, the loading scenario is no longer simply supported because the ends of the beam are not free to move. Instead, the board is in a fixed supported loading condition, which is:

$$\rho_{L/2} = -\frac{L^2}{24\Delta_{\max}} \qquad \textbf{Equation 3}$$

This effectively doubles the strain on the capacitor for a given displacement. As an example, for 1825 capacitors between boltholes spaced 65 mm apart, the expected displacement necessary to induce a 1% chance of failure is given by:

$$\Delta_{\max} = \frac{-\varepsilon_{xx}L^2}{24t} = \frac{-(0.00239)(65)^2}{24(1.956)} \qquad \textbf{Equation 4}$$

which equals 215 microns.

Figure 12 and Figure 13 are displacement graphs for various chip capacitors given a 0.01% allowable failure probability for simply and fixed boundary conditions.

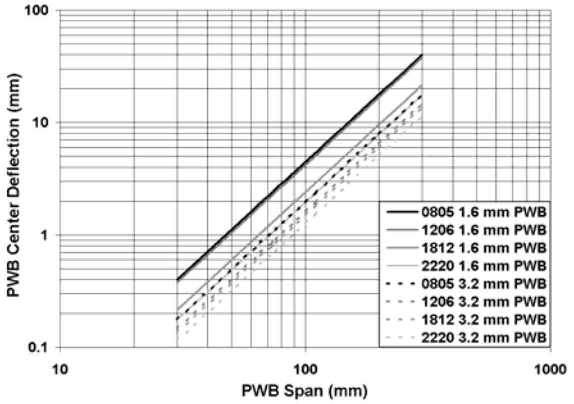

**Figure 12:** Span/displacement relationships for simply supported PWB given 0.01% allowable failure

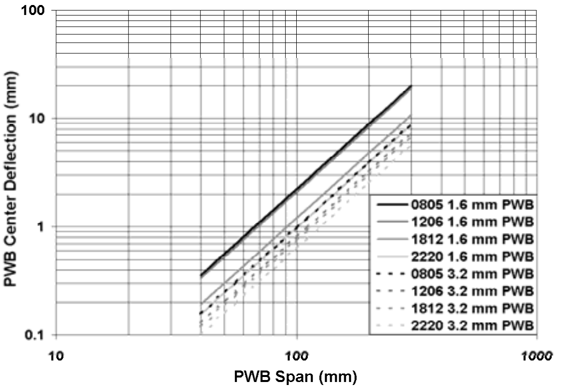

**Figure 13:** Span/displacement relationships for fixed supported PWB given 0.01% allowable failure

However, one must be aware that the actual boundary conditions will fall somewhere between the simple and fixed cases and that other components can greatly affect the allowable displacement values. The presence of a large stiff component on the printed wiring board will greatly reduce the allowable deflection.

## Corrective Actions

Once root-cause is positively identified, flex cracking, and a quantitative description of the influence of stress drivers has been presented, it is possible to make an informed decision on possible corrective actions. Eventual selection of successful corrective actions will take into consideration effectiveness, time, cost and outcome on functionality.

### Design Changes

There are three design modifications that can be made that will improve the strength of the capacitor. The first is changing the MLCC dimensions. As previously discussed the width and thickness of the capacitor have little effect on flex cracking opportunity. However, as shown in Figure 11 capacitor length can have a very significant effect on the occurrence of flex cracking. The major drawback to this design change is the reduction in capacitance for a given voltage rating. 1825 MLCC's are able to deliver 0.39 microfarads at 200 volts, while 1210 deliver only 0.10 microfarads and 0805 only deliver 0.01 microfarads[2]. Circuit design issues must be addressed before these changes can take place.

The second design modification is to change the dielectric material. It is well known that the fracture toughness of the dielectric can have a strong effect on the occurrence of flex cracking and that different dielectric materials have different fracture toughnesses. The general trend is C0G > X7R > Z5U. However, C0G is not as stable a dielectric, as X7R and the reduction in electrical properties might be too critical to allow this switch to occur.

The other possible design modification is to change the type of capacitor. Examples include switching from surface mount to leaded or switching from MLCC to tantalum.

### Thicker Board

A thicker board will lead to an increase in the resistance to flex. This design change would be useful in preventing unexpected flex events through the manufacturing process, such as during handling or testing. However, a thicker board applies more load to the capacitor for a given displacement as shown when comparing the results in Figure 14 to Figure 11. This is due to the increase in board-level strain in the area of the capacitor since board level strain is a function of the bend radius and the board thickness. As shown in Figure 15 the use of a 3.2 mm thick board significantly increases the forces required to fail the capacitors during a 3 point bend test.

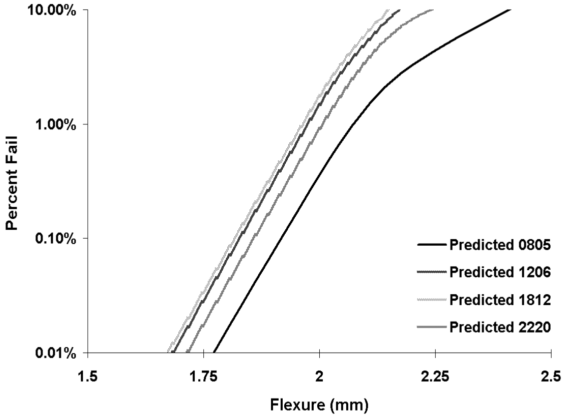

**Figure 14:** FEA and stress failure criteria based probability of flex cracking during a 3 point bend test of a 3.2 mm pwb with a 90 mm span.

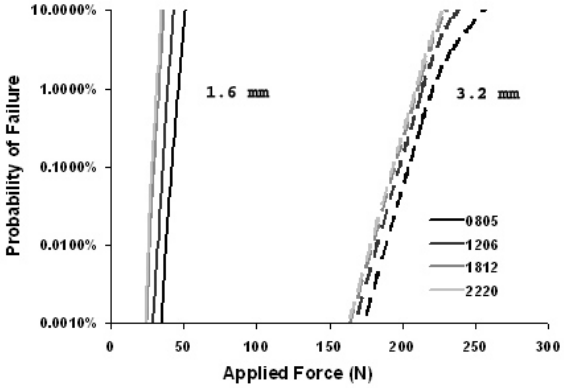

**Figure 15:** Comparison between 1.6 mm and 3.2 mm pwb applied forces during a 3 point bend test with a 90 mm span

### Manual Rework

Process optimization during rework is the only process change that can lead to an increase in the strength of the capacitor. Work by Condra et. al. [1] showed that reworked ceramic capacitors consistently showed higher failure rates in comparison to reflowed ceramic capacitors during temperature/humidity/ bias (THB) and temperature cycling accelerated testing. Condra also found that 150°C preheat followed by hot air rework produced the least failures (8%) in comparison to 100°C preheat and hot air rework, 150°C and soldering iron, and 100°C and soldering iron (12-16%).

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[2] www.kemet.com, X7R dielectric

## Conclusion

A better understanding of the role capacitor size, printed wiring board parameters and rework have on the reliability helps when trying to determine the risk associated with using multilayer ceramic chip capacitors. Graphs have been presented that quantify the effects that capacitor size, pwb thickness, and rework have on the reliability of MLC capacitors. Large capacitors are more sensitive to printed wiring board flexure. Thick printed wiring boards can be more resistant to flexure but transfer greater stresses into the capacitor negating this benefit. The OEM and the contract manufacturer should agree that rework of ceramic capacitors should be kept to a minimum. In addition, if possible, they should ensure the rework process is as benign as possible, which would include preheats and the use of hot air versus soldering iron.

## References

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