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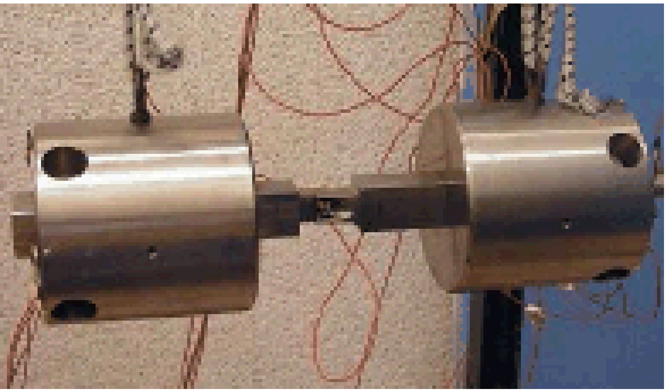

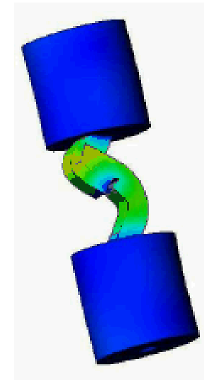

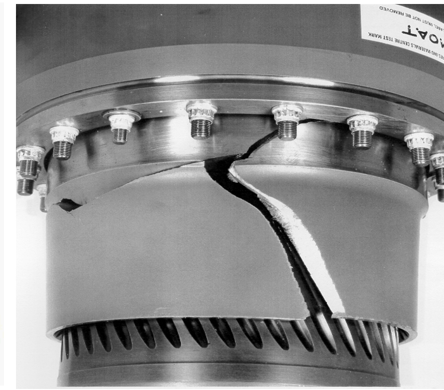

Influence of Edge Boundary Conditions and Cracks in Ferroelectrically Excited Vibrational Modes

Giuliana Davis, Jonel Ortiz, Kevin Troyer, Paul Heyliger, Ward Johnson

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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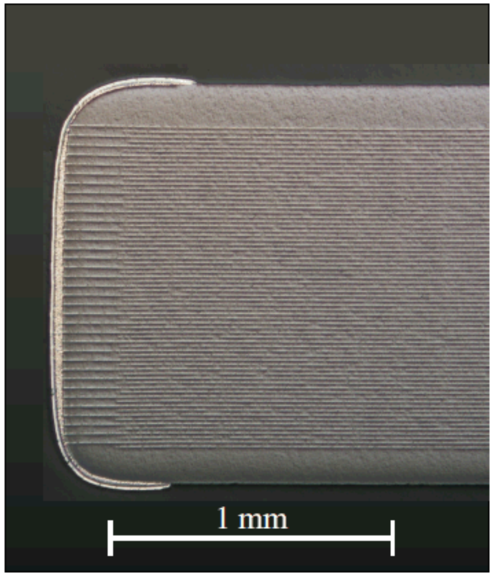
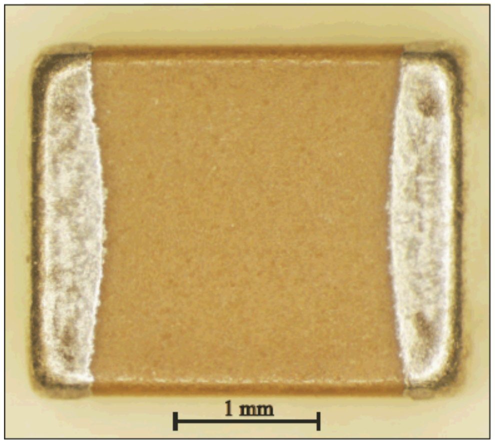
Overview

- Project motivation/continuation
- Capacitor modeling and model validation
- Computational methods/Design of experiments
- Review of boundary conditions and types of cracks
- Results/Conclusions
- Future work
- Questions

Project Motivation/Continuation

- Up to 87% of electrical failure in multi-layered ceramic capacitors (MLCC's) can be attributed to cracking within the many layers of dielectric and electrode material
- Many times cracks are not visible, and the crack is not detected until capacitor failure
- Common applications include aircrafts & automobiles





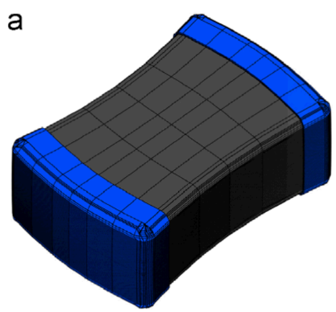
MLCC

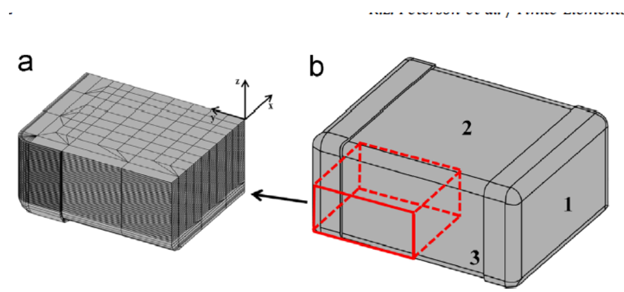
- 70 layers of alternating dielectric and electrode material
- Endcaps on either side of capacitor
- Material Properties:
    - Silver (electrode, endcap)
    - Nickel (endcap)
    - Tin (endcap)
    - Ceramic (dielectric)

Johnson, W. (2017). Resonant Acoustic Frequency Shifts Associated With Cracks in Multilayer Ceramic Capacitors: IEEE Transactions on Device and Materials Reliability, VOL. 17, NO. 2 June 2017

Project Motivation/Continuation (cont.)

- **Last year: Outcomes Validated with Experimental Data**
  - Developed MLCC model (uncracked) in free space that accurately resembles common ferro-electrically excited modes compared with experimental data
  - Reduced model by applying symmetry conditions and neglecting endcap material (determined endcaps only cause affects consistent with material addition/subtraction)



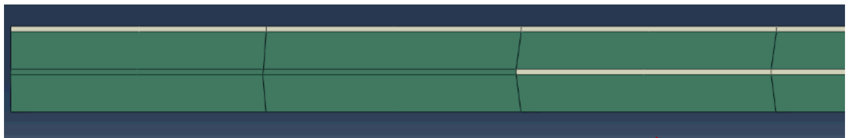


(last years model)

- **Our Problem: Outcomes validated with last years published data**
  - Accurately reproduce a tractable full un-cracked model without the use of symmetry conditions
  - Implement cracks and compare shift in natural frequencies of cracked vs. uncracked model (find non-destructive test method)
    - Cracks often result in natural frequency shift on the order of $\Delta \boldsymbol{f} = \sqrt{\Delta \boldsymbol{k} / \Delta \boldsymbol{m}}$

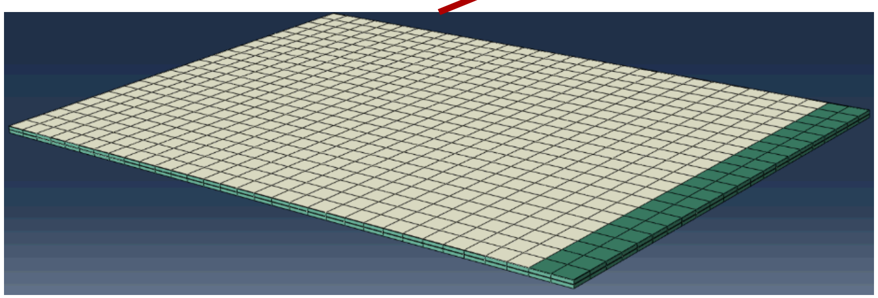
Peterson, KL. (2016). Vibrational modes of multilayered ceramic capacitors, Elsevier

Uncracked Capacitor Geometry

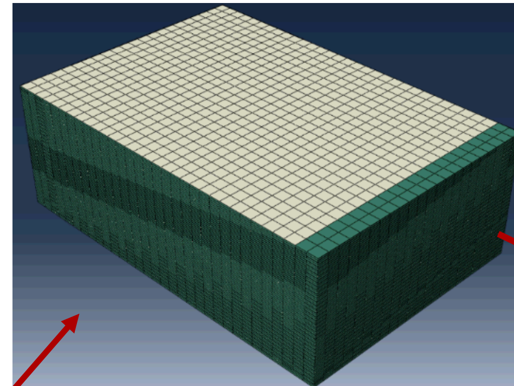


One bilayer (left edge view)

35 stacked bilayers

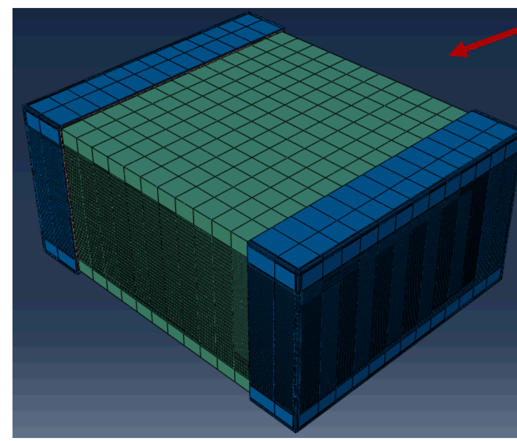


One bilayer (isometric view)



Without endcaps

Add endcaps and surrounding dielectric

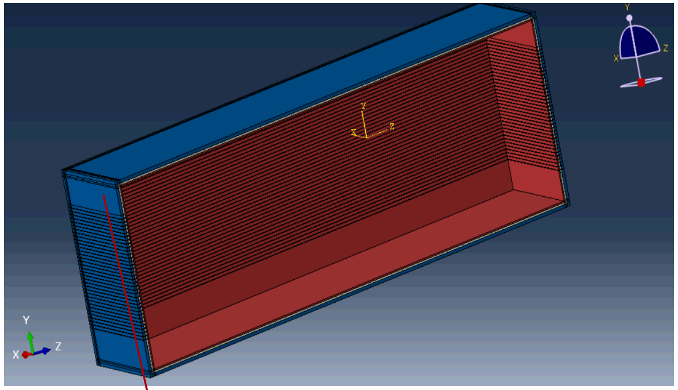


With endcaps

Dimensions:
(mm)
2.536x**3.102**x**1.476**

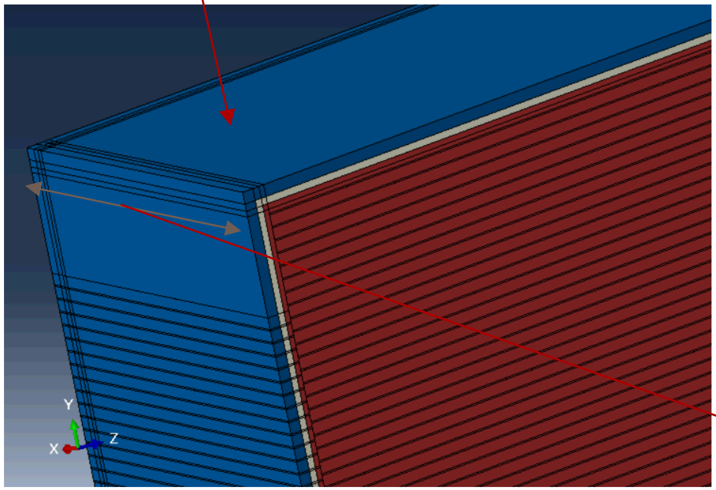
48426 elements
215564 nodes

Uncracked Capacitor Geometry (cont.)

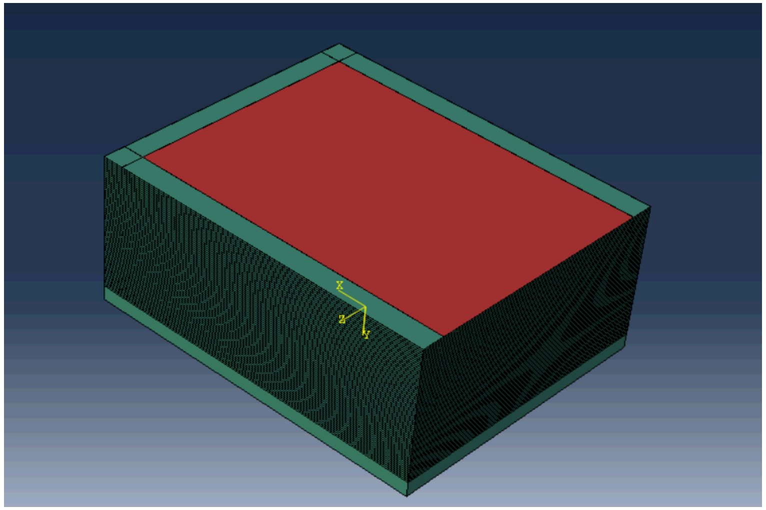


Color	Material	E (MPa)	v	p (kg/m^3)
Red	Silver	82405.6	0.3643	1050.1
White	Nickel	220608	0.302288	8909
Blue	Tin	47883	0.252	7297
Green	Ceramic	149800	0.324	6050

Zoomed in on endcap to see layers



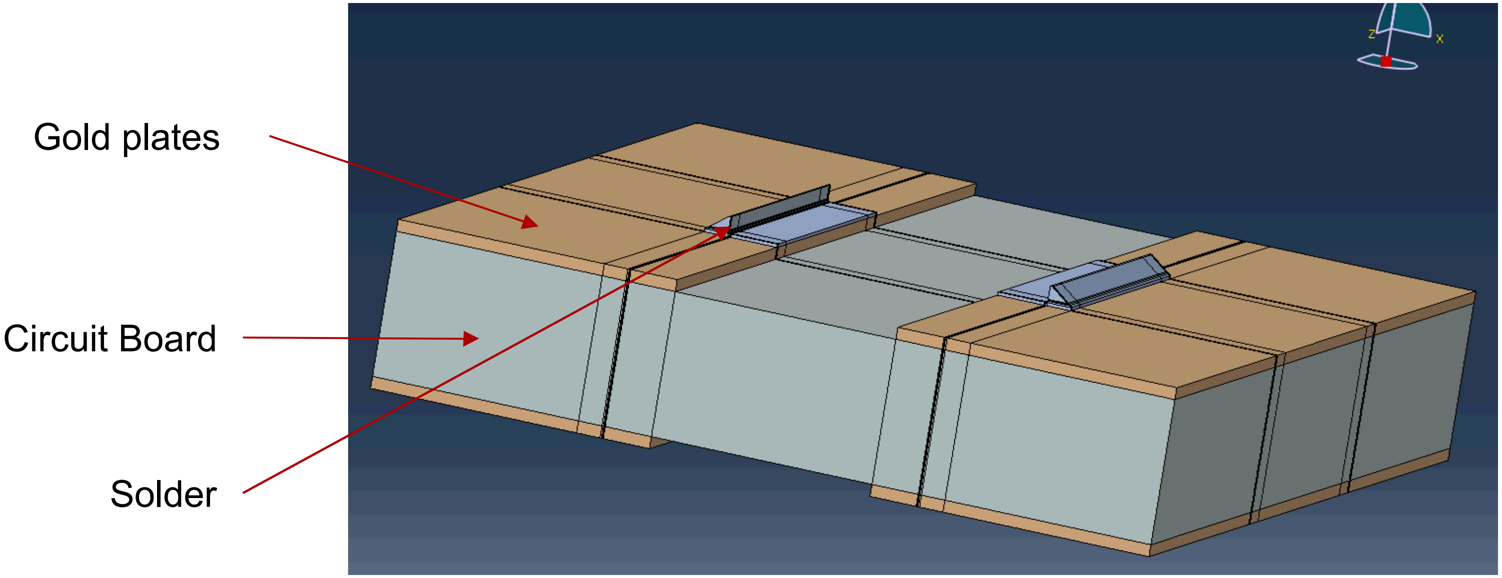
Termination Length



70 Capacitor Layers without endcaps

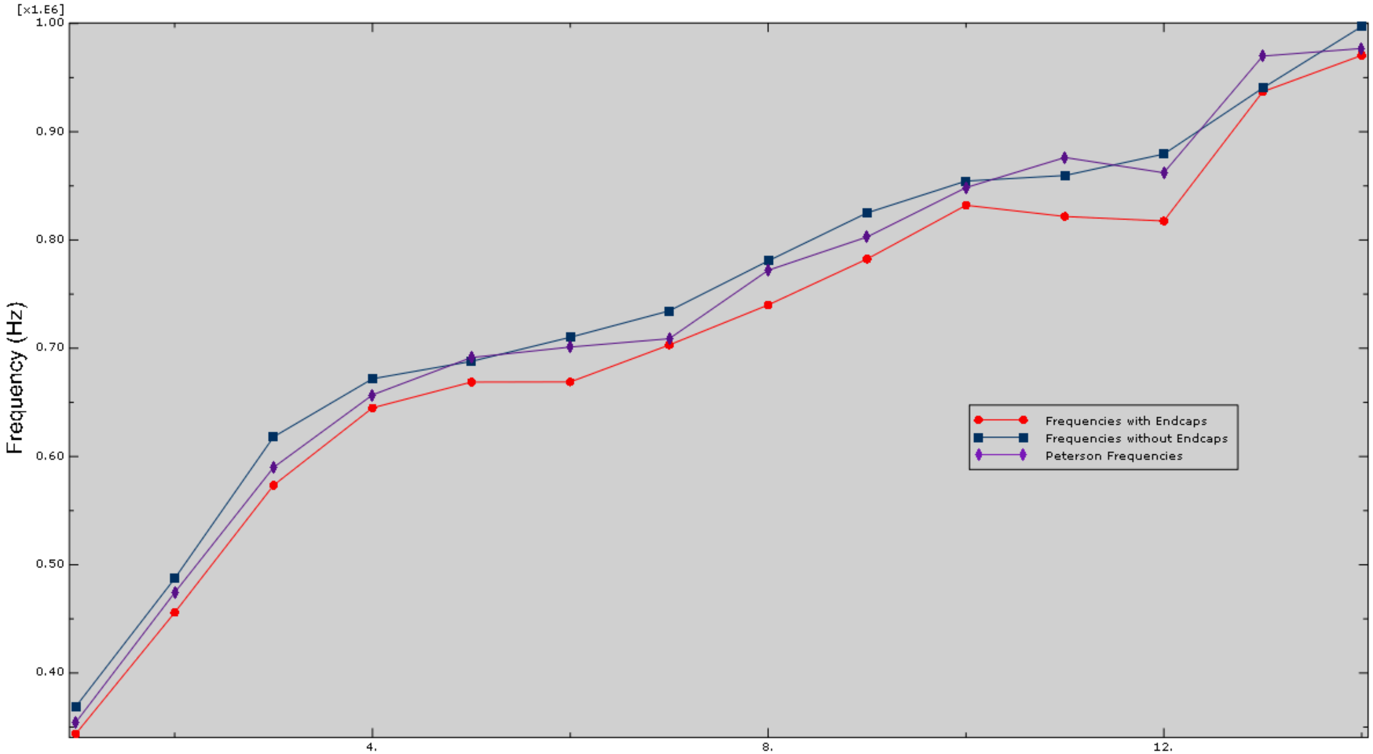
- Red = Electrode
- Green= Dielectric

Circuit Board Geometry



Color	Material	E (MPa)	v	p (kg/m^3)
Purple	Solder (63-Pb37)	43225	0.38	8520
Tan	Gold	77200	0.42	19320
Grey	Arlon 85	22063.22338	0.15	1840

Model Validation/Comparison

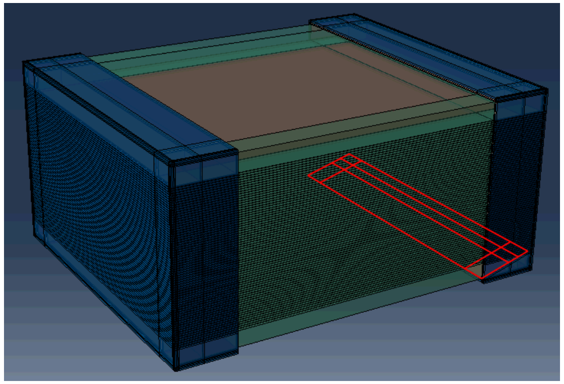


- Model currently has good agreement with published literature and has expected slight drop in natural frequencies when endcap material is added
- Small differences can be attributed to difference in endcap termination length and use of fillets on capacitor edges
- Average percent difference between published model and our model (with endcaps) is 2.7%

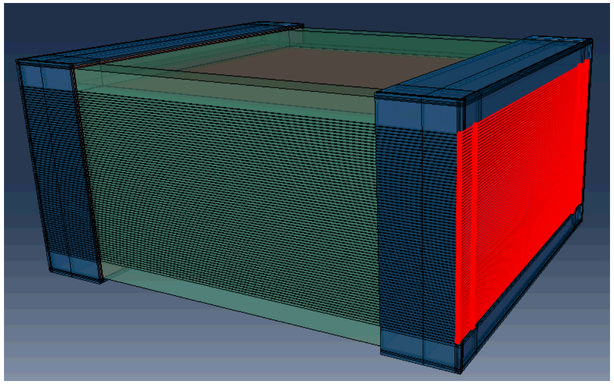
Computational Methods/Design of Experiments

- Modeling three types of cracks:
  1. Corner crack
  2. Endcap interface crack
  3. Interior multi-layer crack
- Along with three types of boundary conditions:
  1. Free
  2. Fixed on bottom
  3. Soldered to circuit board with fixed conditions
- All crack frequencies and modes are then compared to their uncracked counterparts for the same boundary condition

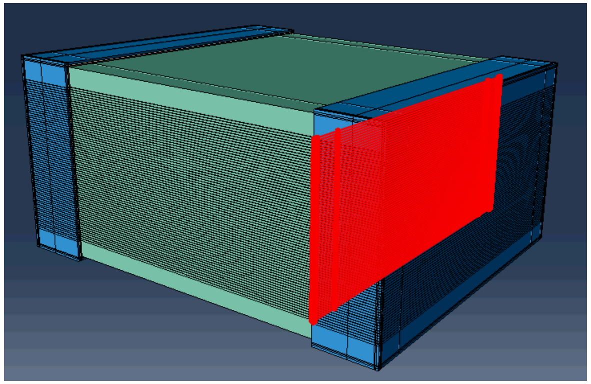
Types of Cracks



Corner crack



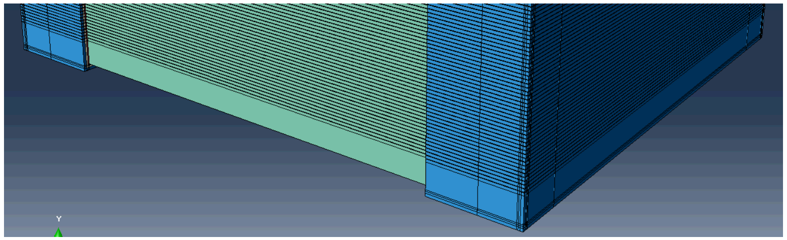
Endcap crack



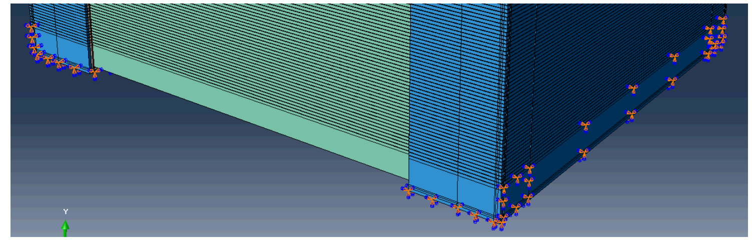
Interior crack

- Three types of cracks are modeled under three different boundary conditions
- Cracks were modeled as being very large in order to begin distinguishing important trends in natural frequencies and ensure modes would match for any smaller version of that crack
- Endcap cracks and interior cracks of this magnitude would most certainly be detected by failure of the capacitor, corner cracks are of particular interest since they are only through the dielectric and would be harder to detect through a change in capacitance

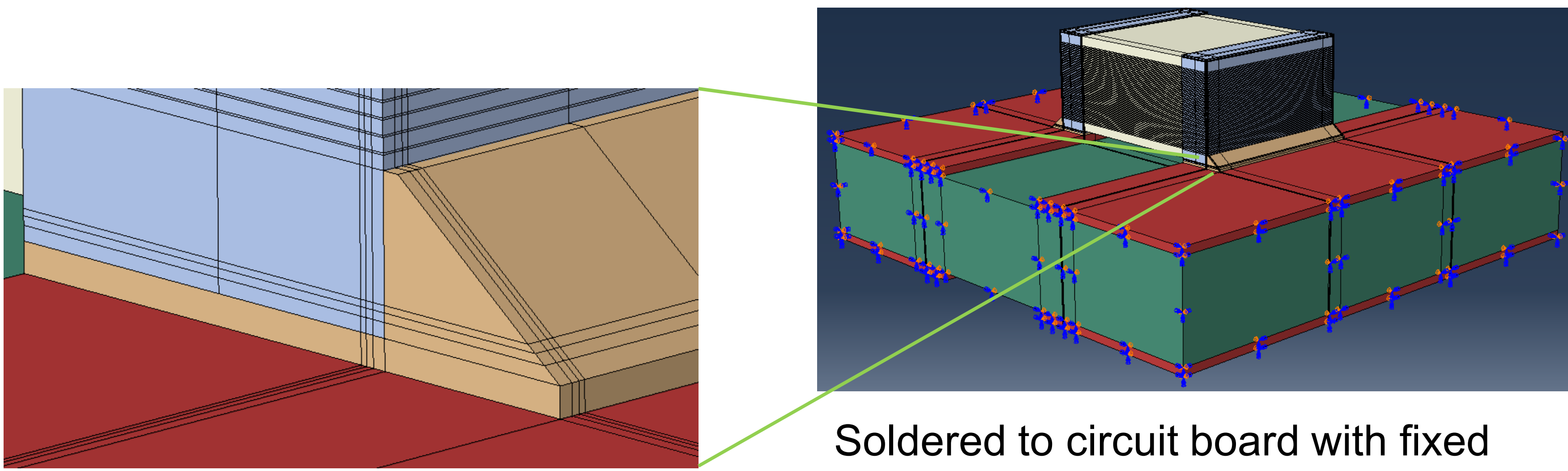
Boundary Conditions



Free



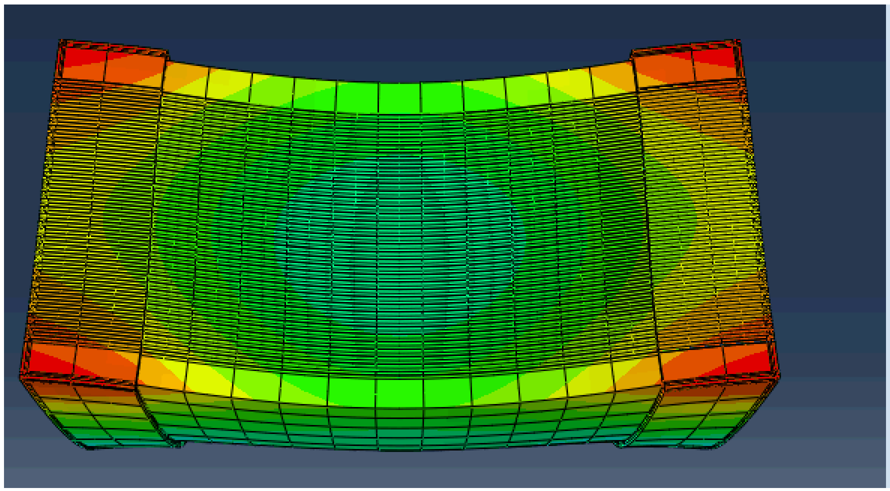
Fixed on bottom (dielectric is not constrained)



Soldered to circuit board with fixed boundary conditions

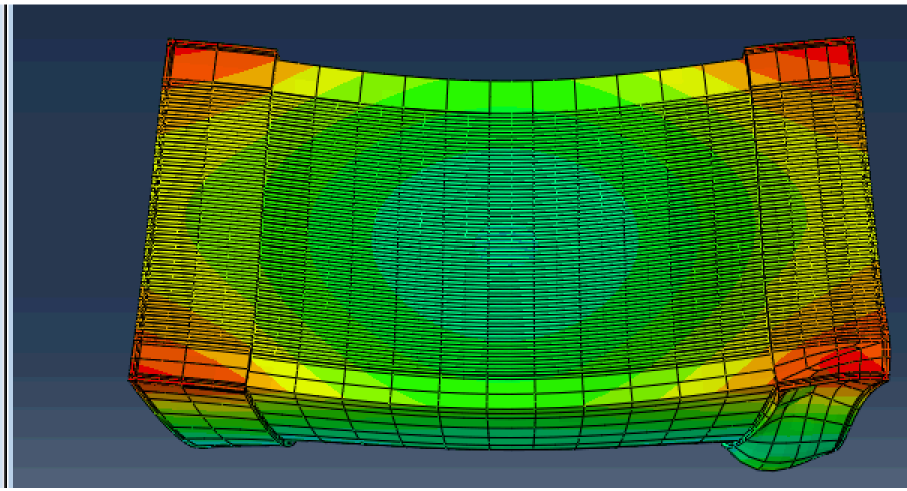
Free Boundary Condition with Corner Crack

Uncracked



12th mode, natural frequency of 668.873 kHz

Corner crack

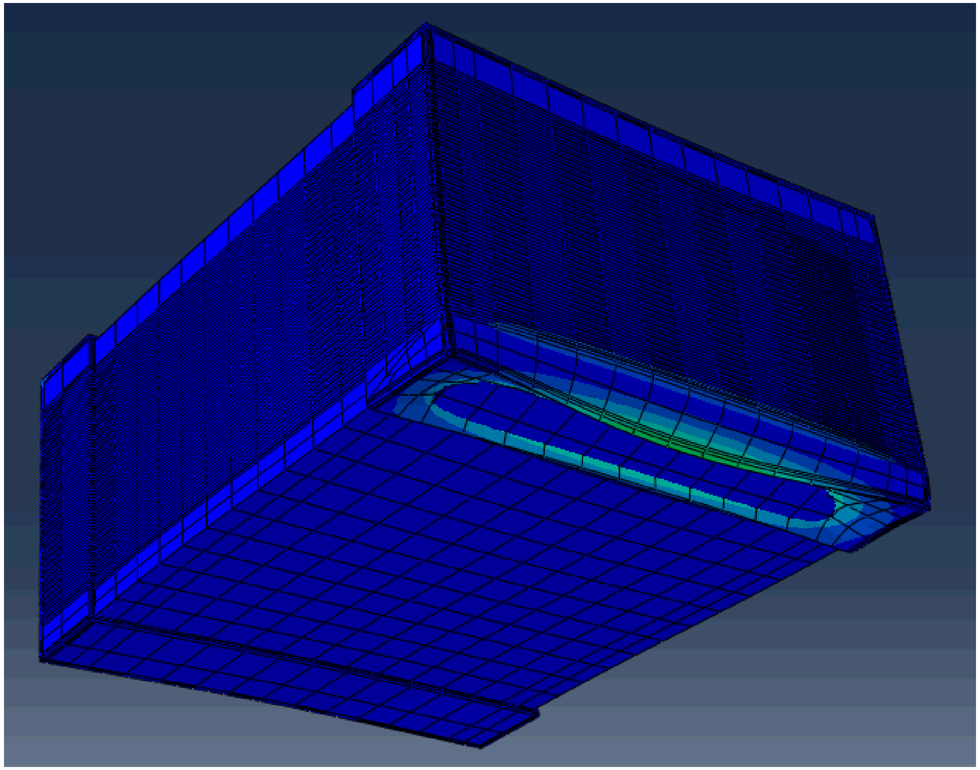


12th mode, natural frequency of 667.535 kHz

- Fundamental frequencies and mode shapes once again have good agreement, less than 500 Hz difference in their natural frequencies
- Overall much more difficult to detect shift in frequencies for the corner crack in the free boundary condition scenario

Free Boundary Condition with Corner Crack (cont.)

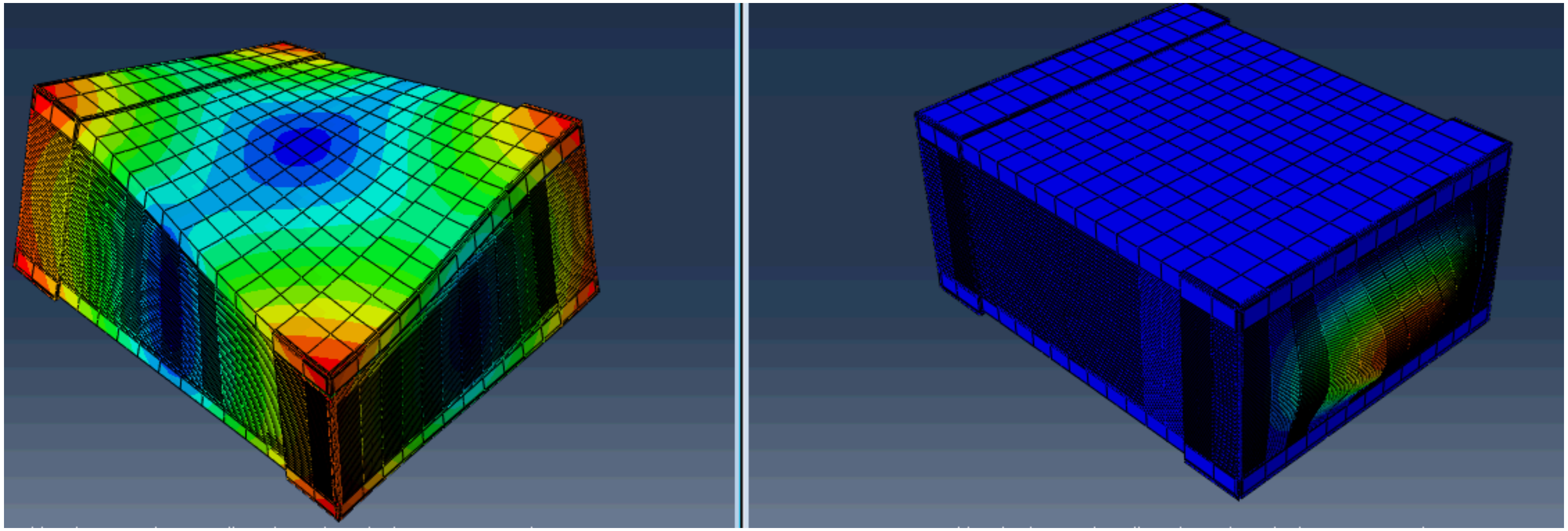
- Mode shape that is not present in the uncracked model
- Referred to as a *local mode*, in which there is a high amount of deformation and element distortion in the crack vicinity



19th mode, natural frequency of 860.736 kHz

Free Boundary Condition with Endcap Crack

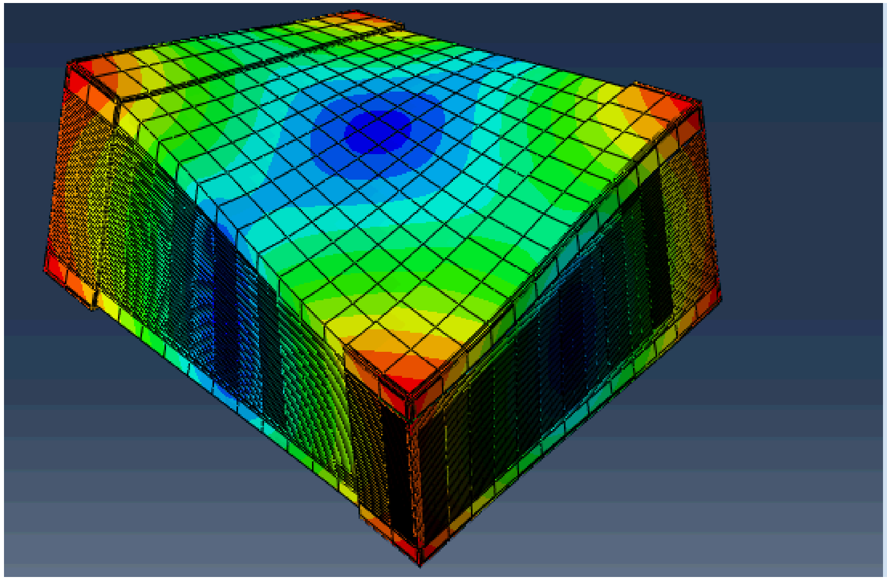
Uncracked | Endcap crack



- Fundamental frequency and mode shape do **not** agree, however all the comparable mode shapes have very good agreement with the uncracked natural frequency
- Fits with a conclusion established by previous papers that the endcap material does not have a significant contribution to the natural frequencies
- Average percent difference between comparable modes are 0.05%

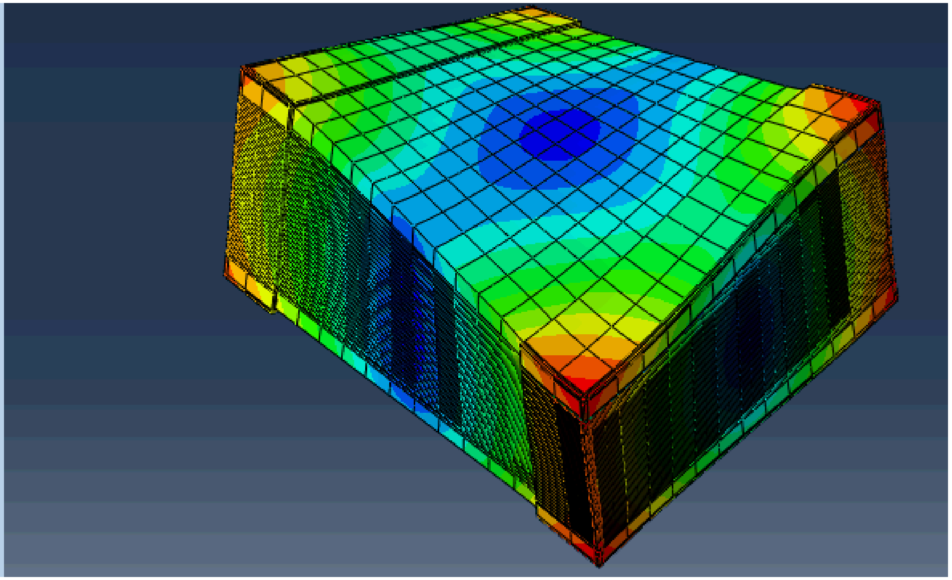
Free Boundary Condition with Interior Crack

Uncracked



Fundamental frequency: 343.71 kHz

Interior crack

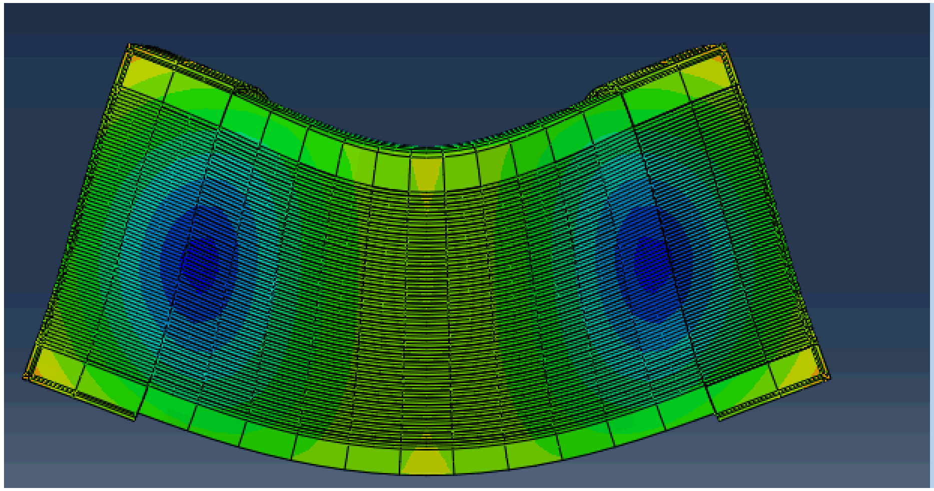


Fundamental frequency: 334.871 kHz

- Mode shapes for fundamental frequencies are quite similar, but other shapes see significant distortion with large drop in natural frequency

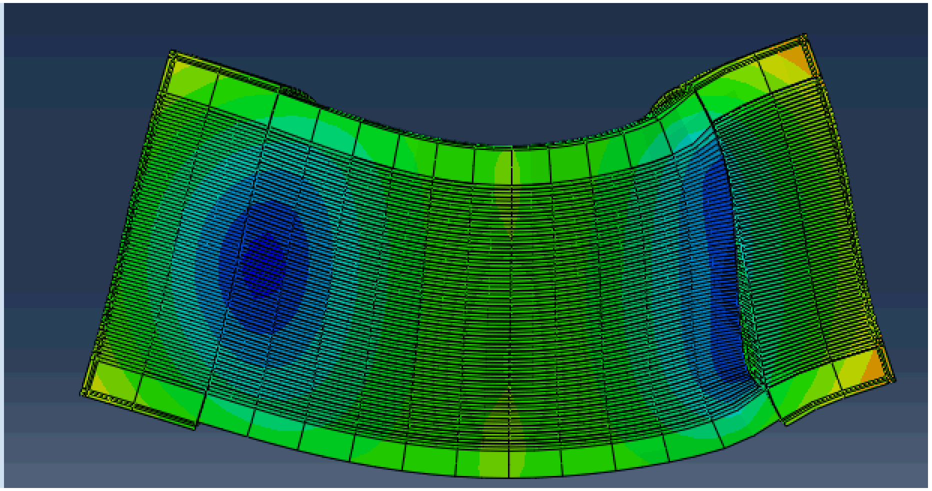
Free Boundary Condition with Interior Crack (cont.)

Uncracked



8th mode, natural frequency of 455.653 kHz

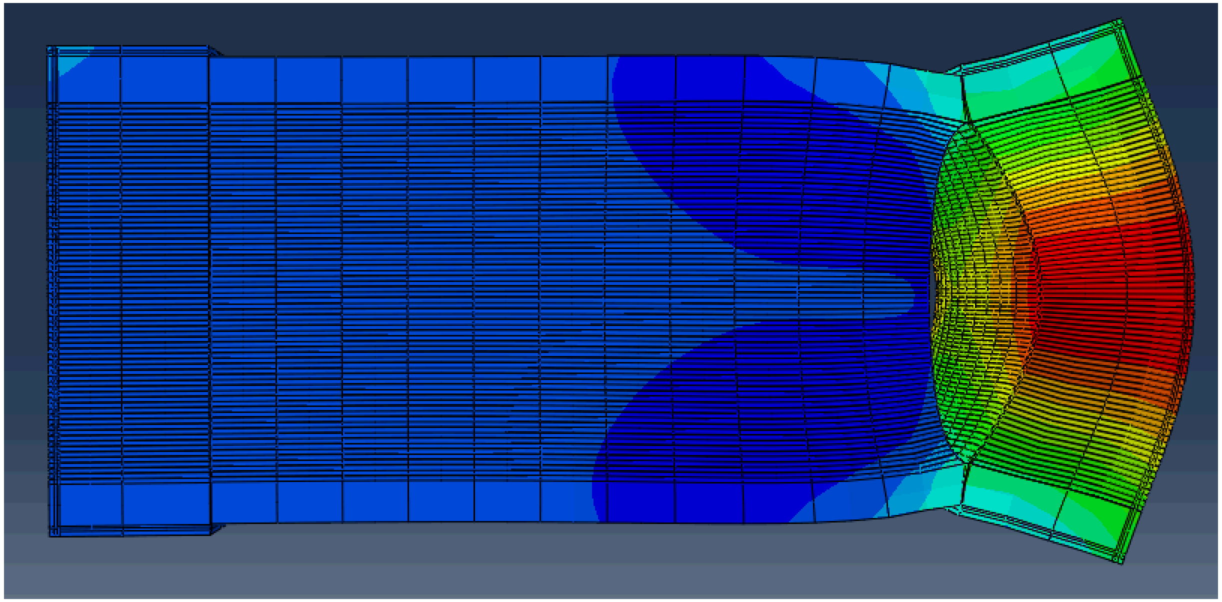
Interior crack



8th mode, natural frequency of 422.835 kHz

- Referred to as a global/local mode where local deformation is present however there is still a modal match on a global scale
- 2nd mode of both see a more significant change in mode shape and natural frequency

Free Boundary Condition with Interior Crack (cont.)

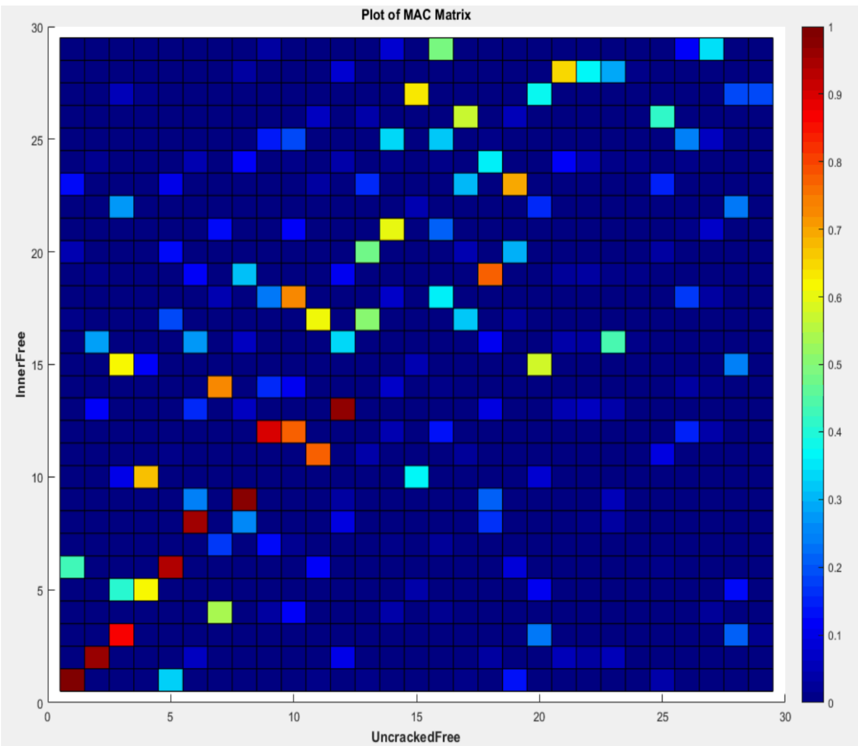


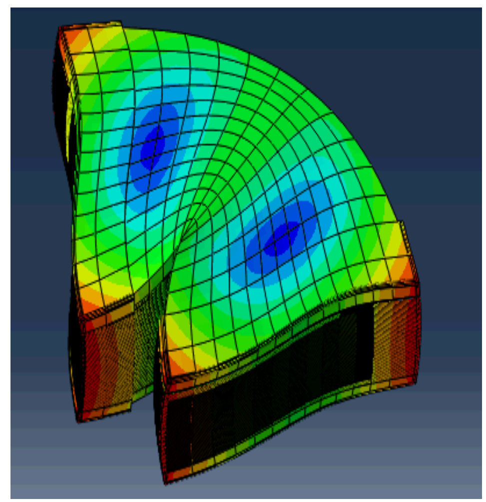
- 10th mode, natural frequency of 493.914 kHz

- Mode shape that is not present in uncracked model

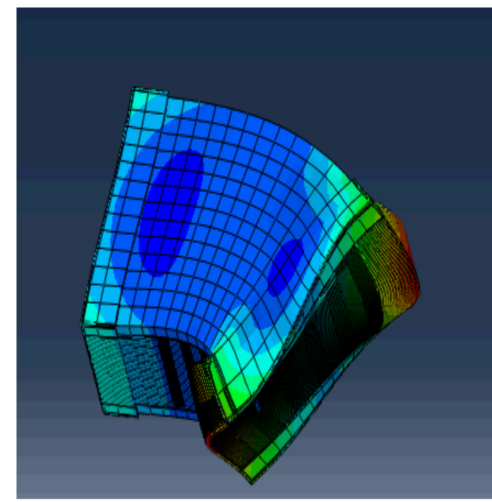
MAC Plot (Free BC)

No Crack			Inner Crack			% Difference between frequencies
Mode	True Mode	Frequency	Mode	True Mode	Frequency	
1	7	3.44E+05	1	7	3.35E+05	2.5716447
2	8	4.56E+05	2	8	4.23E+05	7.222771984
3	9	5.73E+05	3	9	4.53E+05	20.95908423
5	11	6.69E+05	6	12	6.21E+05	7.083470407



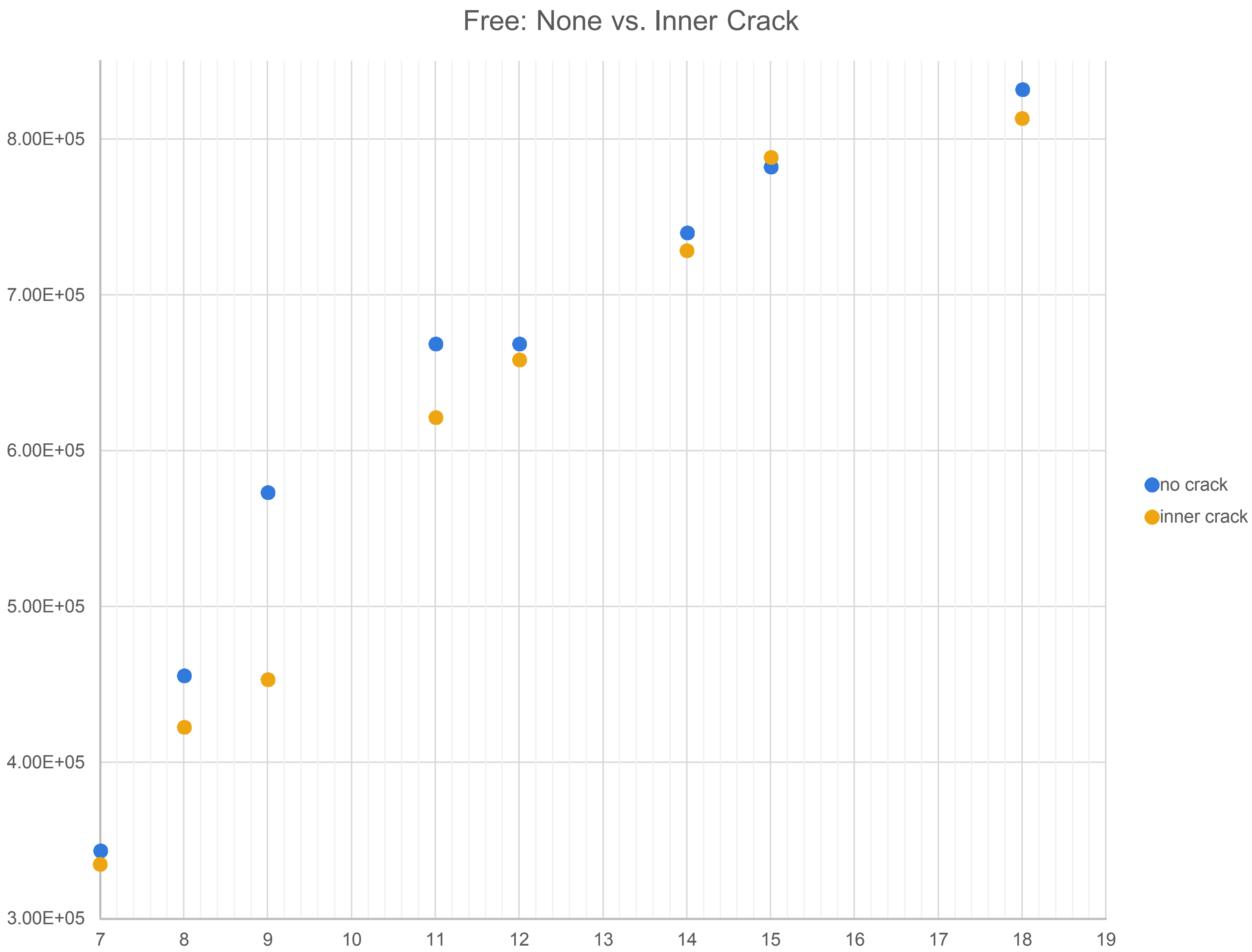


(Free no crack)



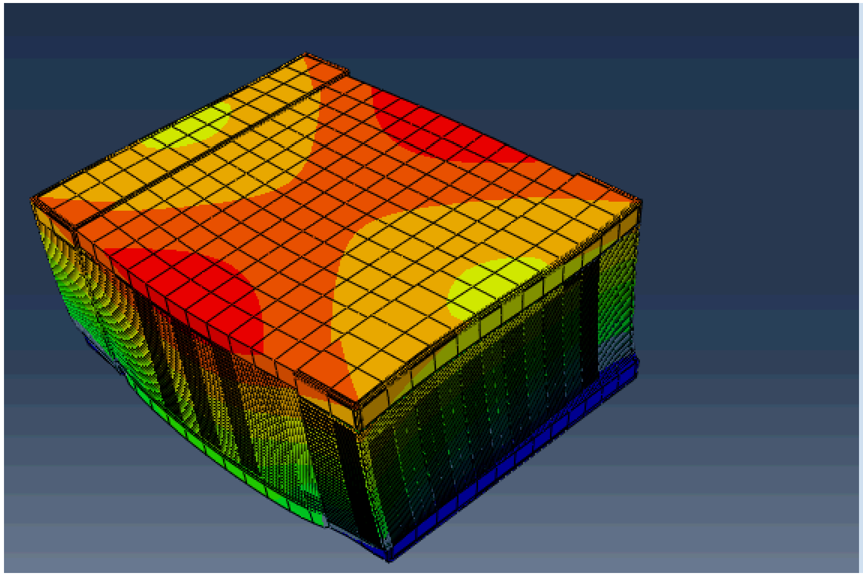
(Free inner crack)

- Comparable modes considered as 0.8 or greater


Free: None vs. Inner Crack
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
7
8
9
10
11
12
13
14
15
16
17
18
19
no crack
inner crack

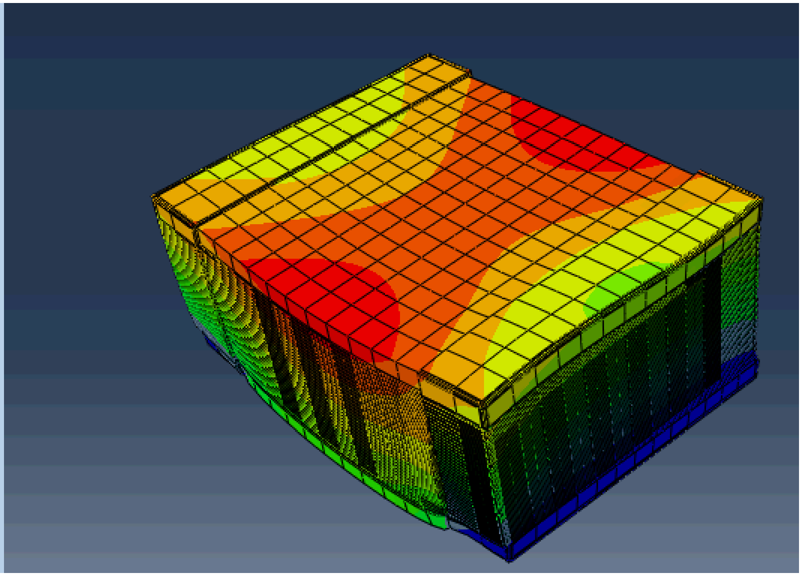
Fixed Boundary Condition with Interior Crack

Uncracked



1st mode, natural frequency of 255.373 kHz

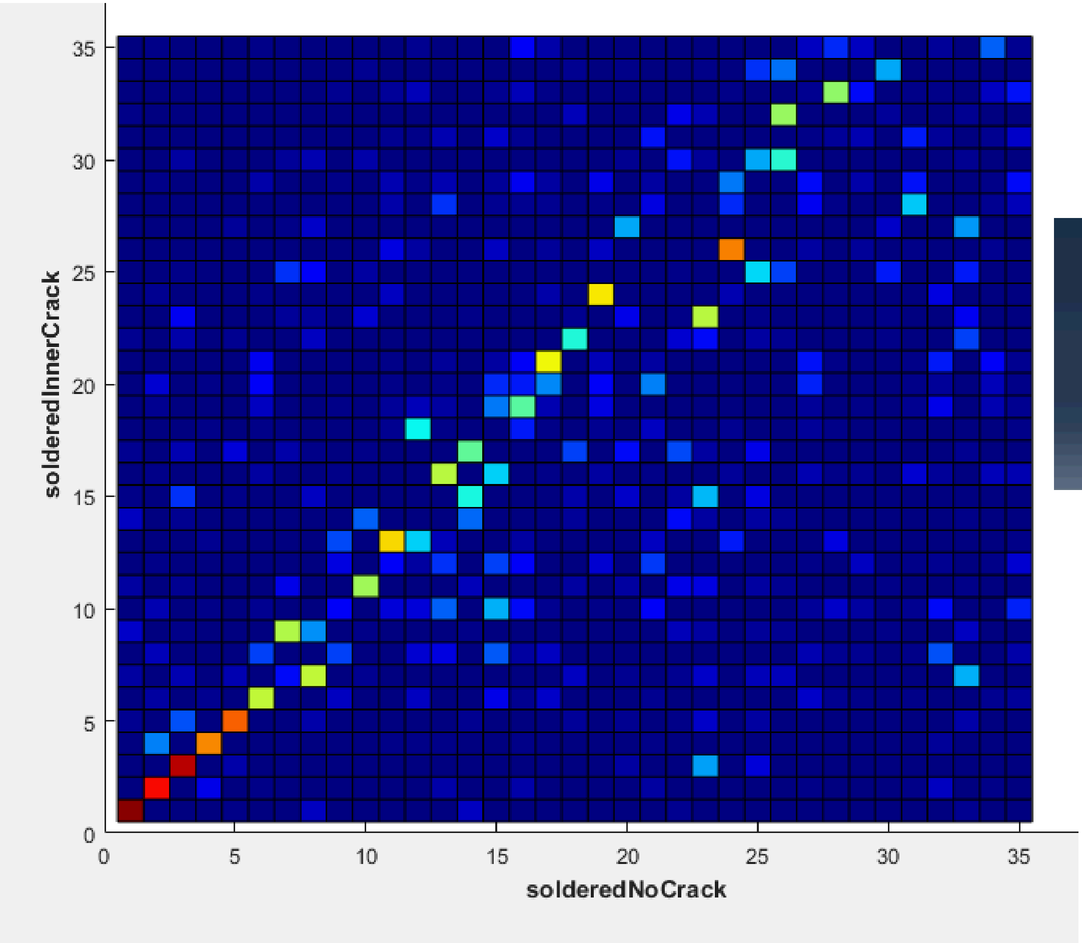
Interior Crack

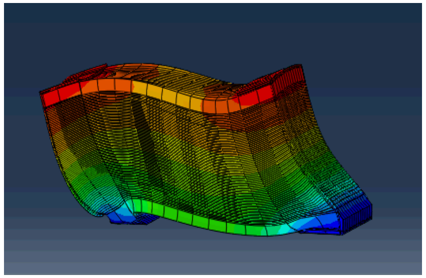


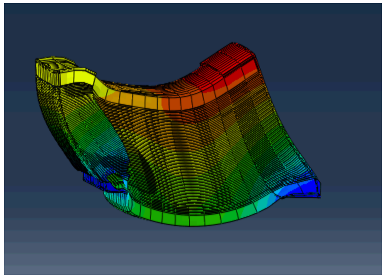
1st mode, natural frequency of 245.168 kHz

- Fundamental frequencies have roughly 10 kHz shift with a mode shape that looks very similar

Fixed: Uncracked vs. Interior Crack



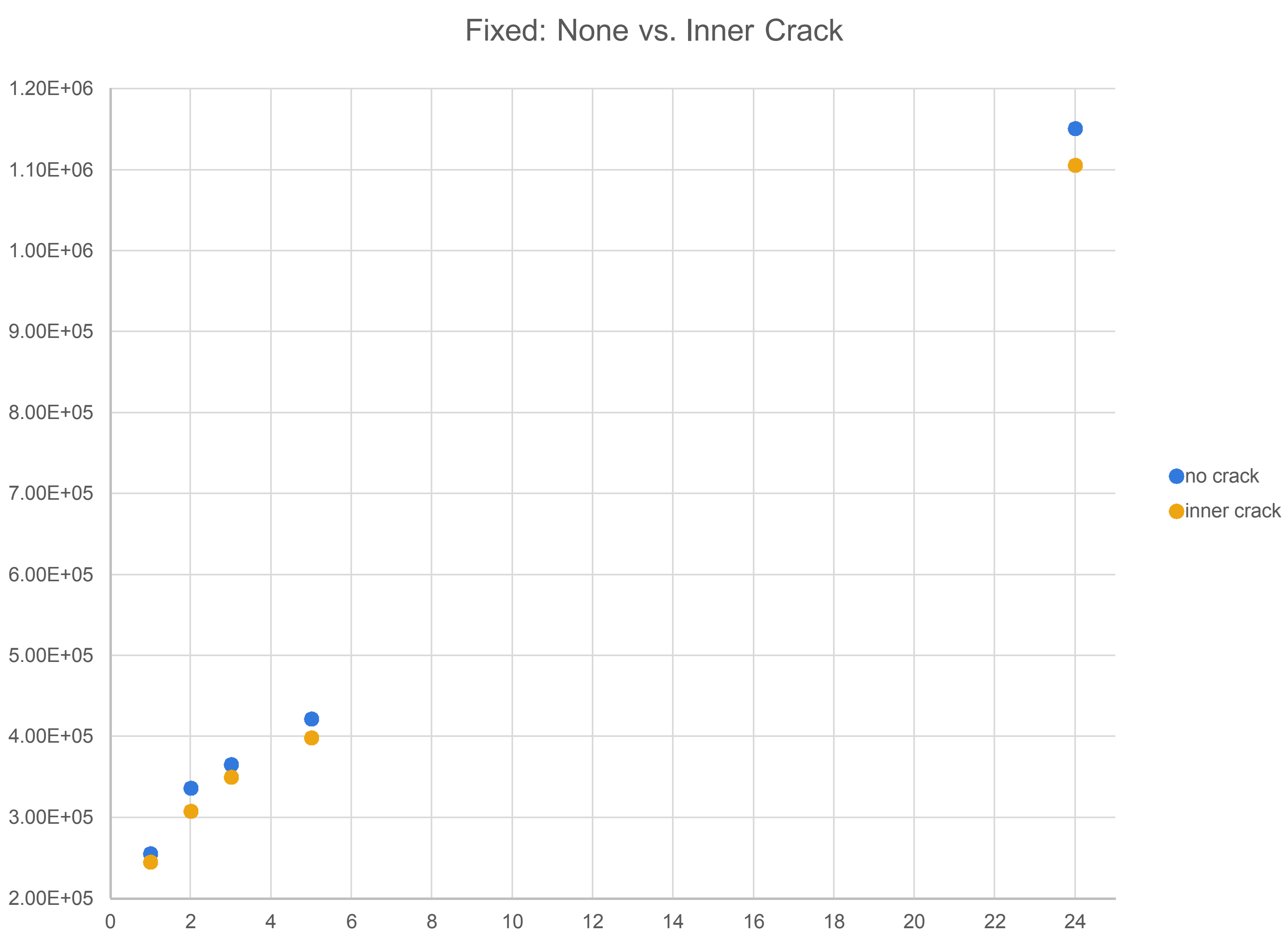




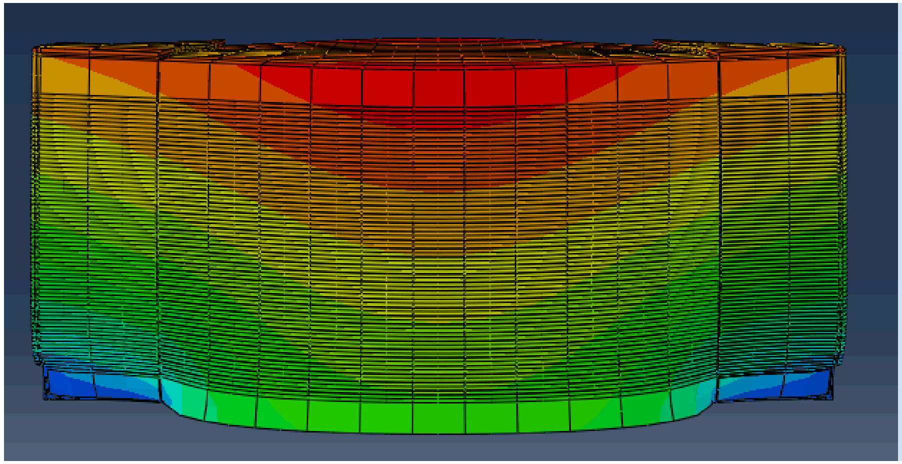
Frequency: 336.587 kHz

Frequency: 307.816 kHz

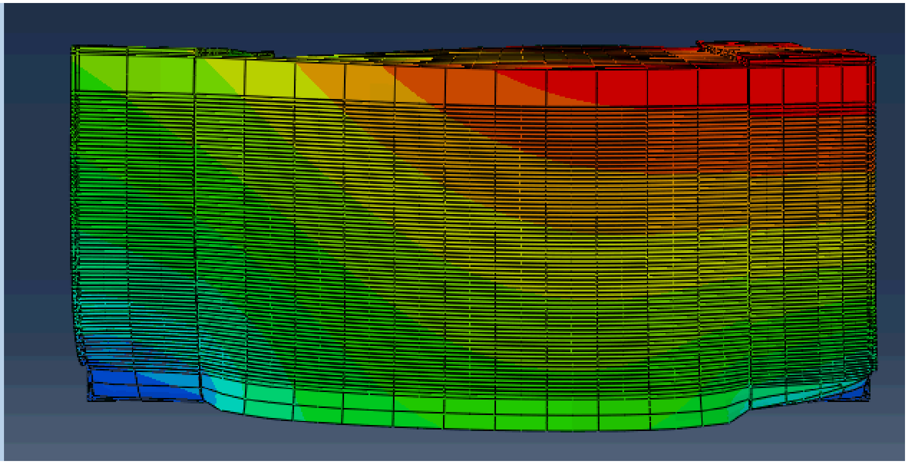
- Mode 2 has 8% difference (30 kHz)


Fixed: None vs. Inner Crack
1.20E+06
1.10E+06
1.00E+06
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
0
2
4
6
8
10
12
14
16
18
20
22
24
no crack
inner crack

Fixed Boundary Condition with Corner Crack



1st mode, natural frequency of 255.373 kHz

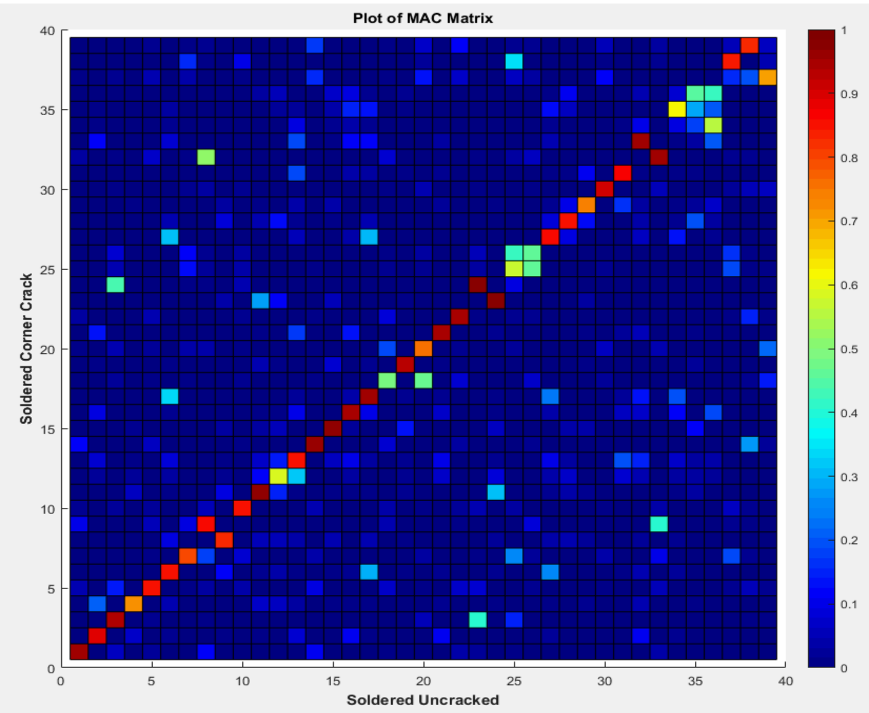


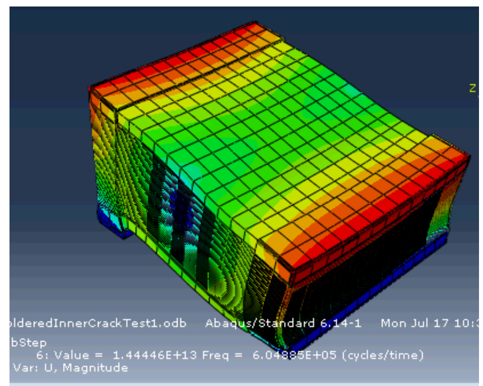
1st mode, natural frequency of 222.739 kHz

- Mode shapes corresponding to fundamental frequencies are very similar while there is a much larger difference in natural frequencies when compared to the free boundary condition for the same crack
- Generally much easier to detect corner crack effects for the soldered boundary condition case

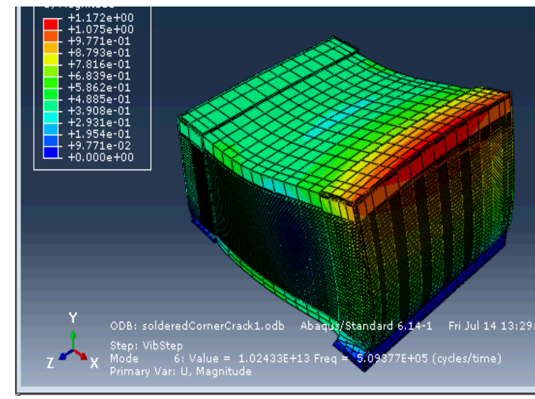
MAC Plot (Fixed BC)

No Crack			Corner Crack			% Difference between frequencies
Mode	True Mode	Frequency	Mode	True Mode	Frequency	
1	1	2.55E+05	1	1	2.23E+05	12.77973787
2	2	3.37E+05	2	2	2.95E+05	12.45086709
3	3	3.66E+05	3	3	3.34E+05	8.779814004
5	5	4.22E+05	5	5	3.85E+05	8.903613088
6	6	6.05E+05	6	6	5.09E+05	15.7896129



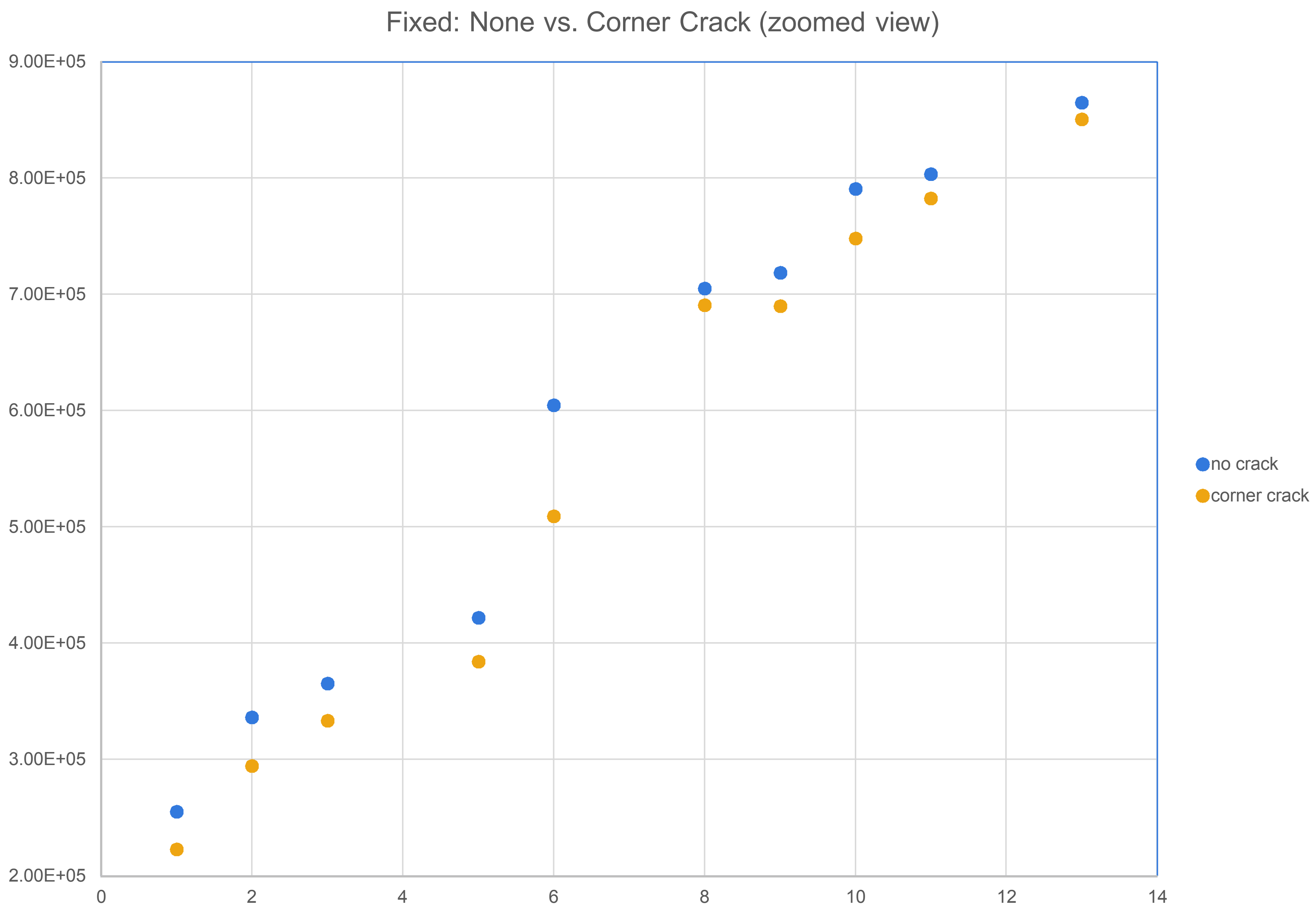


Fixed No Crack

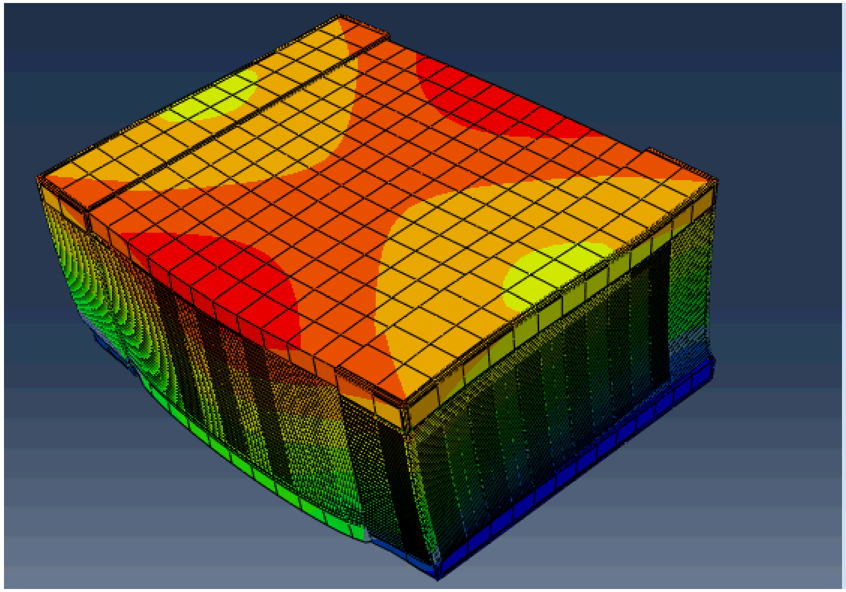


Fixed Corner Crack

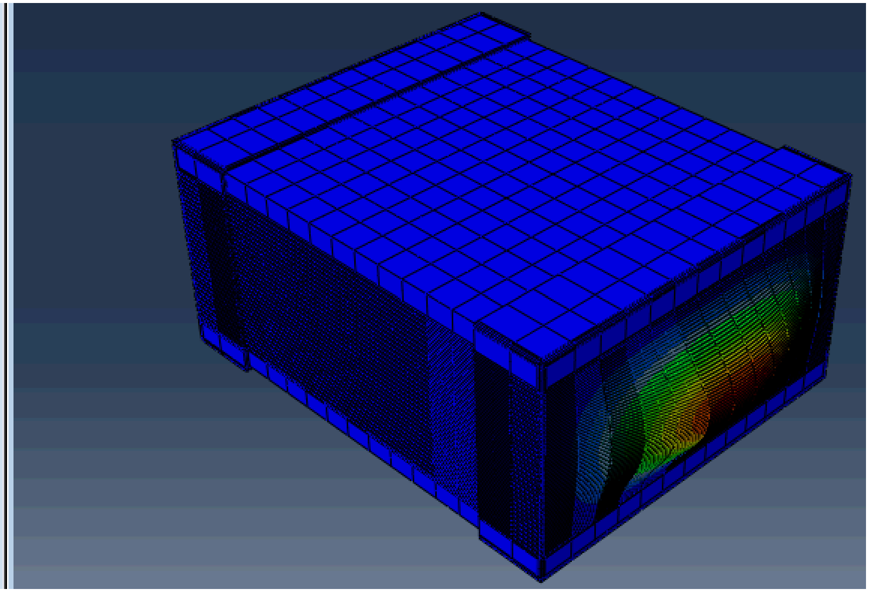
- More realistic BC's


Fixed: None vs. Corner Crack (zoomed view)
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
0
2
4
6
8
10
12
14
no crack
corner crack

Fixed Boundary Condition with Endcap Crack



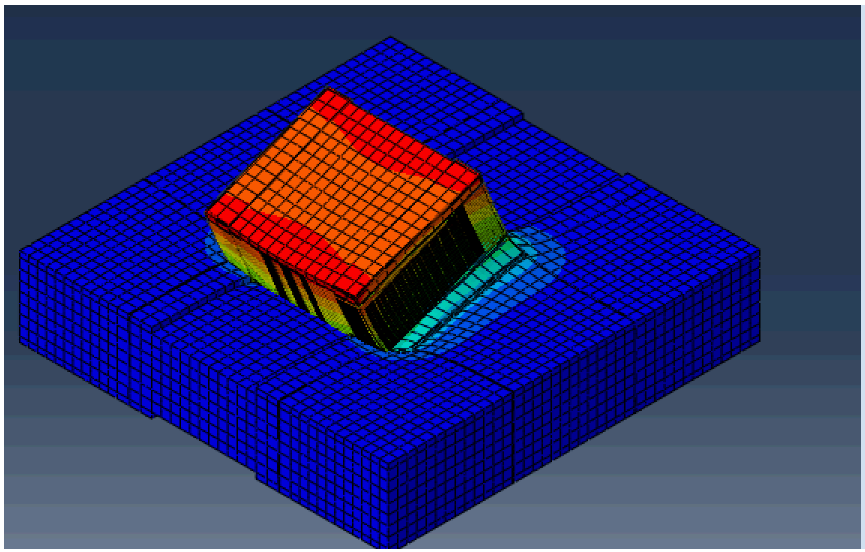
1st mode, natural frequency of 255.373 kHz



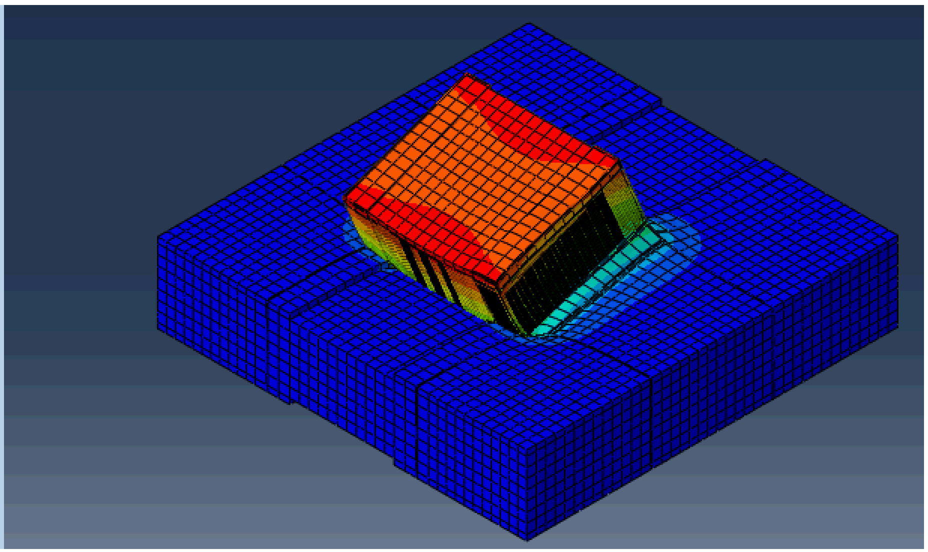
1st mode, natural frequency of 75.201 kHz

- Similar to free boundary condition, fundamental frequencies differ by a large amount for an endcap crack, however the mode shapes that do match also have a strong agreement in natural frequencies
- Average percent difference between comparable modes are 0.026%

Fixed Circuit Board with Interior Crack

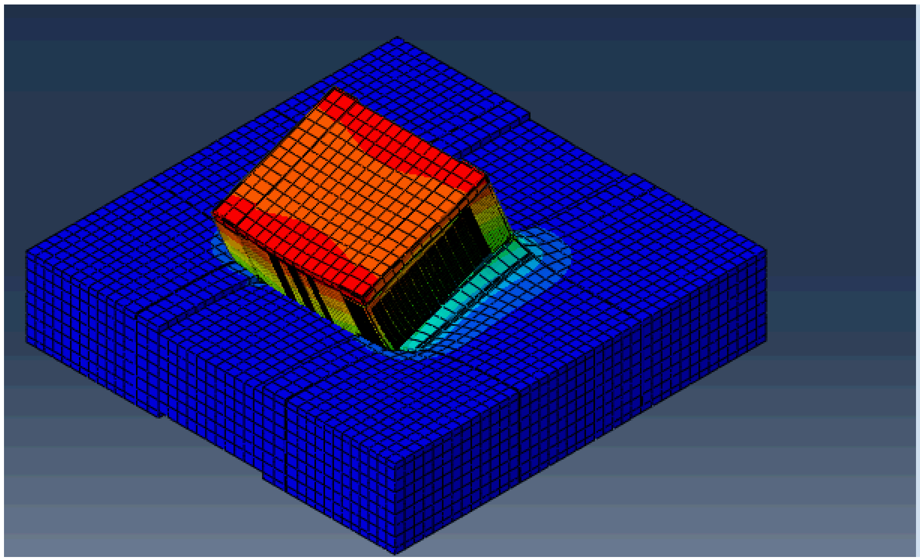


1st mode, natural frequency of 112.085 kHz

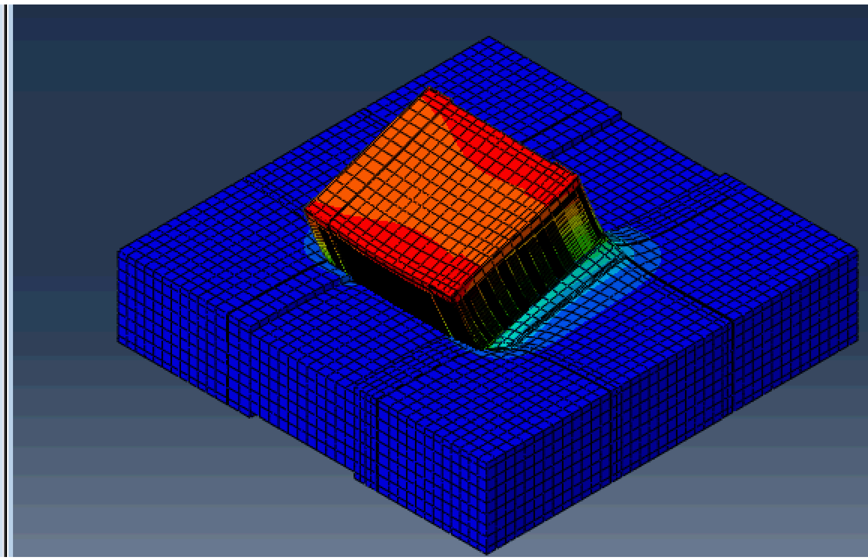


1st mode, natural frequency of 111.29 kHz

Fixed Circuit Board with Corner Crack

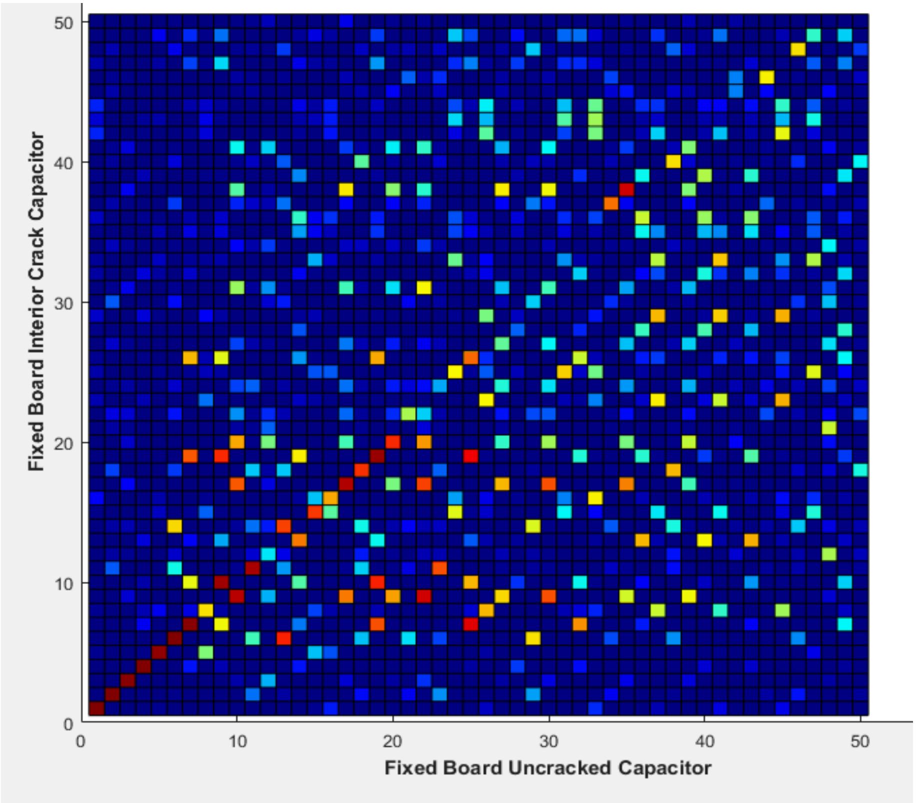


1st mode, natural frequency of 112.085 kHz

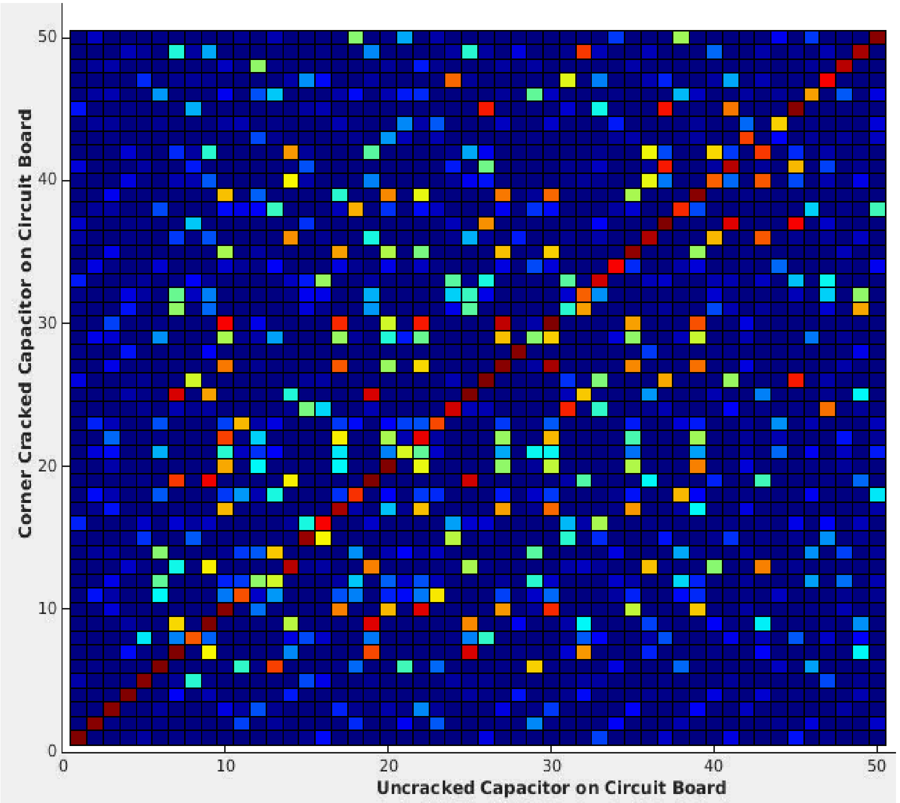


1st mode, natural frequency of 109.788 kHz

Circuit Board Boundary Condition



Interior Crack



Corner Crack

Conclusions

- Able to find mode shapes with a high MAC coefficient that exhibited large differences in natural frequencies for different crack cases
- Further confirmed that endcap cracks have little effect on the natural frequencies for comparable mode shapes across all boundary conditions
- Corner crack modes seemed to be most sensitive to the boundary conditions, possibly because of its proximity to them
  - Results show some promising differences that can be used to classify a seemingly well performing capacitor as having a corner crack

Acknowledgments

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