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Proceeding Paper

Sensitivity to Geometric Detail in Fatigue Simulation of Electronic Components of Vehicles †

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Abstract: Solder joints strongly determine the lifetime of electronic components subjected to temperature fluctuations. The lifetime predictions obtained by finite element analysis (FEA) are uncertain due to the significant variation in solder geometry. It is unclear how realistic a geometric model is needed for problems of impartial complexity. A balance must be found between modeling effort and simulation accuracy. Six geometric models of the solder joint of a gullwing lead were built with different complexity, from the simplest to the most realistic, including a realistic reference model obtained by the Surface Evolver simulation software. The FEA results considering linear elastic and plastic material models were compared for the different solder geometries. We conclude that manually created solder geometry is a sufficient alternative to physics-based realistic geometries.

Keywords: fatigue; solder joint reliability; virtual testing; finite element analysis; sensitivity

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1. Introduction

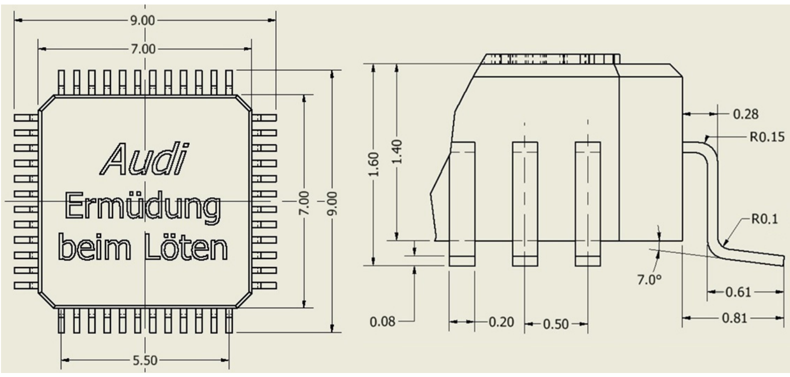
The lifetime estimation of solder joints has become essential in the vehicle industry since the number of printed circuit boards (PCBs) increases in passenger cars. The loads on PCBs are mainly thermal and vibration loads. The lifetime estimation is based on both physical experiments and virtual tests. Virtual tests require finite element analysis (FEA) of the PCB. FEA provides input for the solder joint fatigue life estimation models, such as the models reviewed in paper [1]. The choice of the proper fatigue model in a certain case is not straightforward [1,2], and the estimated fatigue life is subjected to several factors, out of which the geometry of the solder joint is a crucial one. The solder pad size is a fundamental geometric property of which the effect is investigated in [3] using a manually created FEA model and experiments. The solder geometry is also created manually in computer-aided design (CAD) software in [4]. FEA analysis and fatigue life estimation were carried out for three different resistors having different geometric dimensions. It is proven that the geometry largely affects lifetime. The PhD thesis [5] carries out thorough FEA and experimental analysis of solder joints. It is shown that the geometric shape can be modified due to manufacturing uncertainties even for ball grid array (BGA) joints, which have the simplest geometry among solder joint types. FEA models were created in [5] manually to gain results on the strain and stress distributions and fatigue lifetime of various solder joint geometric changes. An important aspect of the simulations is that the FEA-based stress and strain values are not evaluated at one FEA node only but averaged for a certain domain of the solder joint. A variety of solder geometry is analyzed in [6] with a focus on the volume where the plastic work is averaged. The literature suggests that (1) the manual creation of solder geometry is widely used, but there is no comparison between manually created and physics-based or scanned geometry; (2) the weak point of the virtual fatigue lifetime estimation is the uncertainty of the choice of the averaged volume: some stress and strain indicators, such as average strain energy, are used in the fatigue life estimation models, but there are no clear instructions on how to choose the volume of averaging.

The present work focuses on a variety of solder joint modeling approaches. The question is the level of geometric complexity of the model, which is an important aspect in industrial applications. The solder can be specified using geometric primitives [3,7]. With a bit more work, the shapes can be rounded by considering the effect of the flux or solder paste on the solder spreading over the wetted surfaces. More accurate geometries are generated by physics-based simulations, e.g., computational fluid dynamics tools or the so-called Surface Evolver software [8]. Modeling realistic geometry is possible by 3D scanning the solder. Although this possibility is not considered in this work. In industry, human effort in modeling must be minimized, as a single PCB can have hundreds of solder joints. On the other hand, the FEA model's solder geometry must be realistic enough to ensure accurate lifetime estimations. The goal is to determine the necessary complexity of solder joint geometry that provides realistic FEA outputs, i.e., what accuracy and detail of geometry input is required to make the simulation results match the results of physical fatigue experiments. As a secondary goal, we investigate the effect of the choice of the section where the stresses and strains are averaged, serving as an input for the lifetime estimation models. A novel aspect of this work is that the analysis is carried out for the so-called gullwing geometry leads, which are still used in surface-mounted electronic technology.

2. Methodology

2.1. Solder Geometry Variations

We compare six solder geometries based on complexity, shear area size, and volume. The 3D model of a 48-lead gullwing package was created based on the standard [9]. Figure 1a shows the geometric data; Figure 1b shows the model. As Figure 2 shows, six different solder geometries from i to vi were created with increasing complexity. Model i is a minimal geometry, ii is a geometry where the solder is half the height of the lead, iii is a solder geometry where the solder surrounds the lead on all sides, iv is a slightly curved geometry not only bounded by straight lines, and geometry v is the closest to reality among the manually created models. Model vi serves as a reference and was generated by the Surface Evolver. The distance between the lead and the copper pad is set to 0.02 mm for all models. Table 1 aggregates the data on the shear area and the solder volume.



(a)

(b)

Figure 1. CAD model of the investigated electronic package: (**a**) data required to create the part; (**b**) subpart created in a 3-dimensional environment.

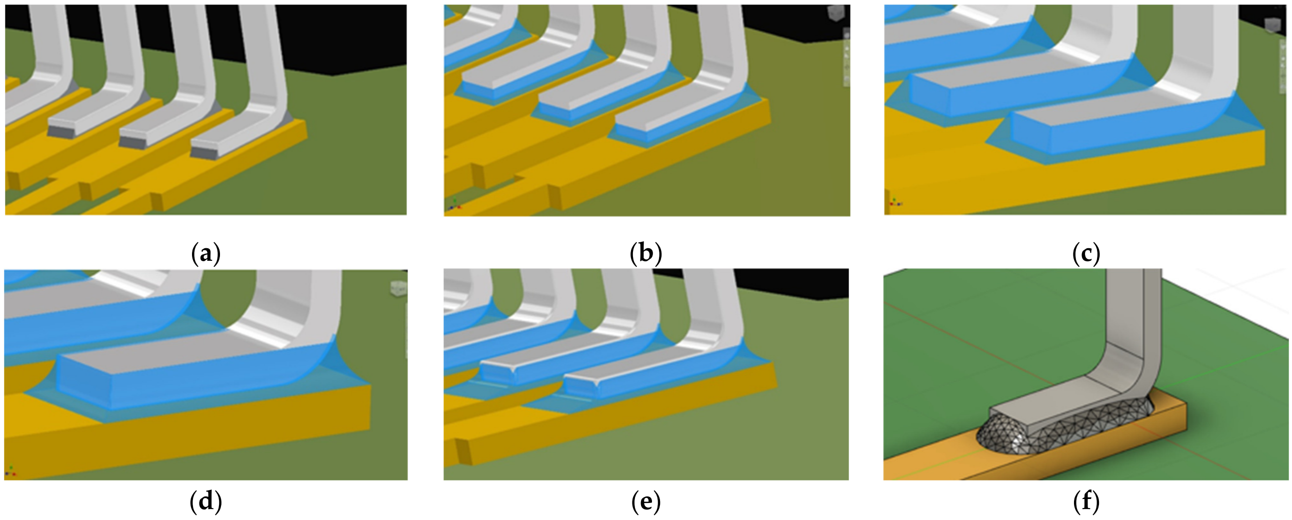


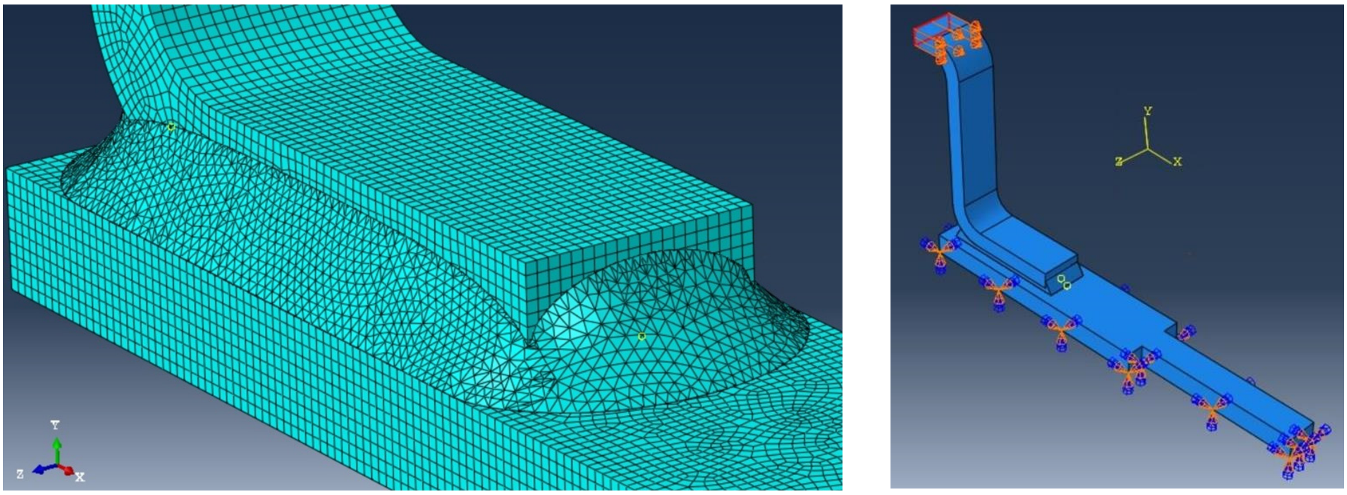
Figure 2. The different soldering geometries: (**a**) geometry type i; (**b**) geometry type ii; (**c**) geometry type iii; (**d**) geometry type iv; (**e**) geometry type v; and (**f**) geometry type vi.

Table 1. Comparison of FEA results for geometries i–vi.

Geometry (#)	V (mm^3)	A (mm^2)	Cr. sec. (V./H.)	Mat. Model (E./P.)	σ_{eq} (MPa)	γ_{xy} (10^{-3})	τ_{xy} (MPa)	PEEQ (10^{-3})	σ_{eq} av. (MPa)	γ_{xy} av. (10^{-3})	τ_{xy} av. (MPa)	PEEQ av. (10^{-3})
i	3×10^{-3}	0.122	V.	E.	1170	27.2	1170	-	62.8	0.503	7.19	-
				P.	93.5	69.5	53.5	166	39.8	0.400	5.97	3.27
			H.	E.	273	4.37	62.4	-	47.6	0.686	9.80	-
				P.	82.4	17.7	45.6	13.5	37.7	0.417	7.12	1.09
ii	4×10^{-3}	0.157	V.	E.	1250	15.9	227	-	61.8	0.339	4.84	-
				P.	107	55.4	50.4	181	38.4	0.253	5.89	3.31
			H.	E.	185	4.26	60.8	-	42.4	0.362	5.17	-
				P.	85.1	19.0	45.5	10.5	34.9	0.235	4.74	0.802
iii	8×10^{-3}	0.202	V.	E.	1130	22.5	321	-	58.5	0.732	10.4	-
				P.	93.1	158	45.1	161	39.9	1.87	10.0	1.88
			H.	E.	118	2.45	35.0	-	31.3	0.289	4.13	-
				P.	85.4	4.24	40.1	3.19	30.2	0.180	3.79	0.098
iv	6×10^{-3}	0.191	V.	E.	850	10.2	145	-	64.3	0.395	5.64	-
				P.	86.1	139	45.3	140	40.5	1.89	8.65	2.80
			H.	E.	131	2.97	42.4	-	35.7	0.264	3.77	-
				P.	86.6	3.69	41.3	4.2	32.9	0.124	4.12	0.179
v	6×10^{-3}	0.189	V.	E.	796	7.38	105	-	58.2	0.387	5.53	-
				P.	93.2	97.7	46.2	104	38.9	1.16	6.46	2.10
			H.	E.	145	4.14	59.2	-	33.7	0.265	3.79	-
				P.	84.5	6.51	45.2	4.95	30.4	0.0827	3.53	1.70
vi	6×10^{-3}	0.188	V.	E.	697	10.6	151	-	67.1	0.582	8.31	-
				P.	84.9	110	45.3	117	40.8	2.12	9.87	2.79
			H.	E.	144	3.33	47.5	-	34.4	0.289	4.13	-
				P.	88.0	4.72	42.8	4.79	31.9	0.0868	3.62	0.211

2.2. Finite Element Model

The hexagonal meshing of the models was mapped in the lead and in the simple solder geometries i, ii and iii. However, for cases iv, v and vi, automatic meshing was used with tetrahedral elements. In case vi, the Surface Evolver already results a surface mesh, with which the solder geometry is defined. However, remeshing was necessary with element size close to other parts of the model, see Figure 3a. The preferred element size was set to 0.01 mm, which is in correspondence to the 0.02 mm solder layer between the lead and the copper pad. Mesh density tests showed that the mesh provides accurate results. Figure 3b depicts the boundary conditions. The copper pad is fixed in all directions. A displacement of 0.1 mm in x direction was set for the top of the lead. This represents the heat expansion difference between the package and the PCB.



(**a**) (**b**)

Figure 3. FEA model: (**a**) meshing of the model; (**b**) specifying loads.

Two types of material models were used: a linear elastic material model, which allows infinitely high stress, and a bilinear elastoplastic material model, which goes off from the first linear strain-stress characteristic above 80 MPa von Mises equivalent stress. Above the 80 MPa yield strength, a 10% elongation was associated to any additional 1 MPa rise. The plastic material model indeed increased the computational requirements. These two material models are denoted by letters E. and P. in Table 1.

The stress and strain values, which are the inputs of the fatigue life models, are usually not evaluated only in a single node, but they are averaged on a certain volume. We defined two sections: a vertical one in the plane of symmetry and a horizontal section at 0.01 mm height as Figure 4 shows. These are denoted by V. and H. in Table 1.

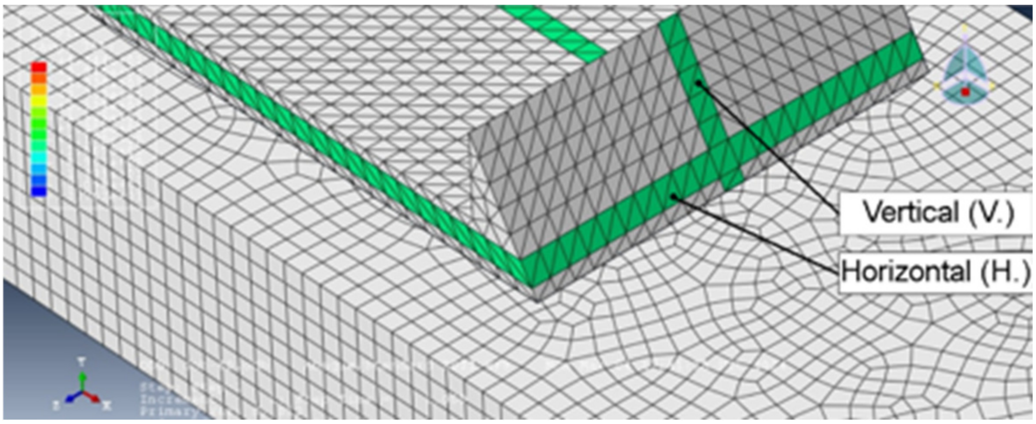


Figure 4. Definition of the sections: horizontal and vertical sections.

3. Results and Discussion

Table 1 contains FEA results for each geometry. The indicated values are the volume V of the solder, the shear area A in the horizontal section, the cross-section type, the material model, the von Mises equivalent stress σ_{eq}, the shear strain γ_{xy}, the shear stress τ_{xy}, and the equivalent plastic strain PEEQ peak value within the section. The section-averaged values of σ_{eq}, γ_{xy}, τ_{xy}, and PEEQ are also shown. The volume V gradually increases for the first three models (i, ii, and iii), reaching the highest volume for geometry iii. Models iv, v, and vi have approximately the same volume. The shear area A is also the highest for geometry iii and the lowest for i. The solder volume is a fundamental parameter, since the larger the volume, the more deformation energy the solder joint can absorb without damage. Similarly, the greater the shear area, the lower the shear stress. Prior to the FEA analysis, one could therefore expect that geometry iii will provide the longest estimated lifetime (the most unsafe estimation of lifetime—there is the greatest chance that the real lifetime is shorter than the estimated). For the same reason, geometry i is expected to provide the shortest estimated lifetime (safest lifetime estimation).

Each solder geometry has 28 values obtained from FEA in Table 1. These serve as inputs for different lifetime estimation models [1,2]. The more realistic the geometry, the lower the peak von Mises stress σ_{eq} developed. The highest value is for the vertical section with elastic material model. The peak values of the shear strain γ_{xy} and stress τ_{xy} show similar tendencies; however, they do not monotonically decrease with the complexity of the geometry. The peak PEEQ clearly correlates with the solder volume. A very important observation is that the stresses are much lower and the strains are higher for the elastoplastic material model, as one would expect.

Since the peak values might be affected by the mesh quality and numerical issues, the literature suggests using the averaged values instead in lifetime prediction [1,2,5,6], which are shown in the last four columns of Table 1. The averaged values are obviously much lower than the peak values. Furthermore, a significant difference is observable between the vertical and horizontal cross sections. The plastic material model yields lower average stresses in most cases. However, the plastic averaged strain γ_{xy} is many times higher than the averaged strain from the elastic model. Figures 5 and 6, respectively, show the comparison of the von Mises stress distribution developed in the vertical and horizontal sections.

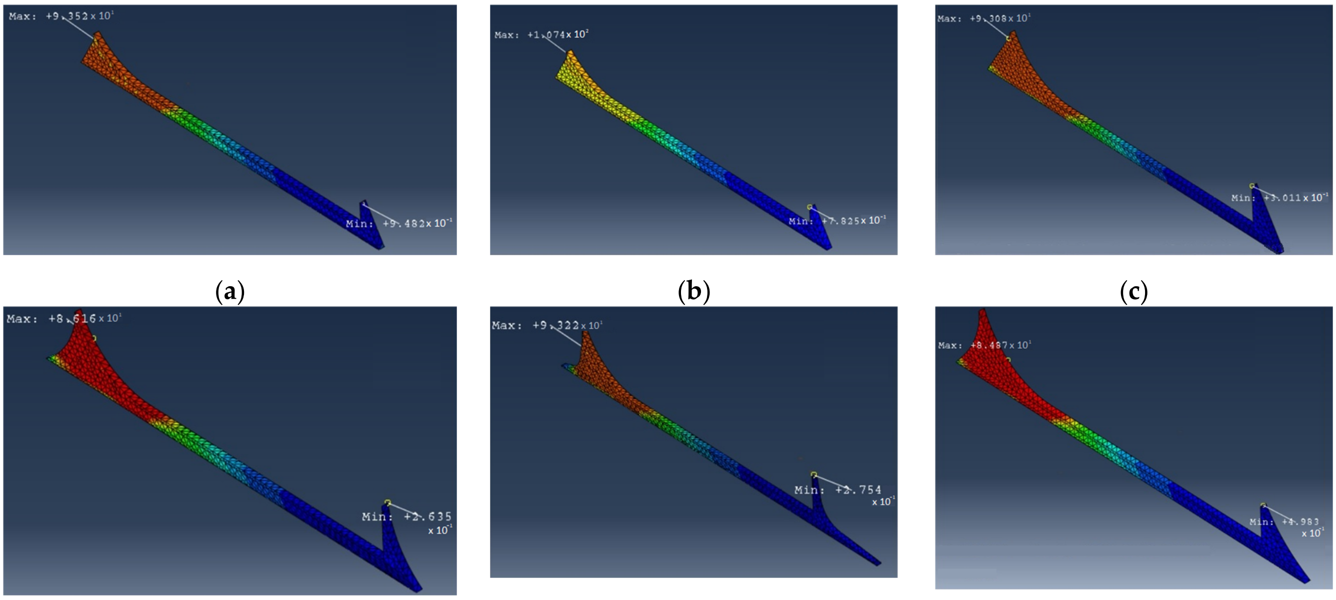


Figure 5. Von Mises stresses developed in the vertical sections in case of the different geometry types: (**a**) geometry type i; (**b**) geometry type ii; (**c**) geometry type iii; (**d**) geometry type iv; (**e**) geometry type v; and (**f**) geometry type vi.

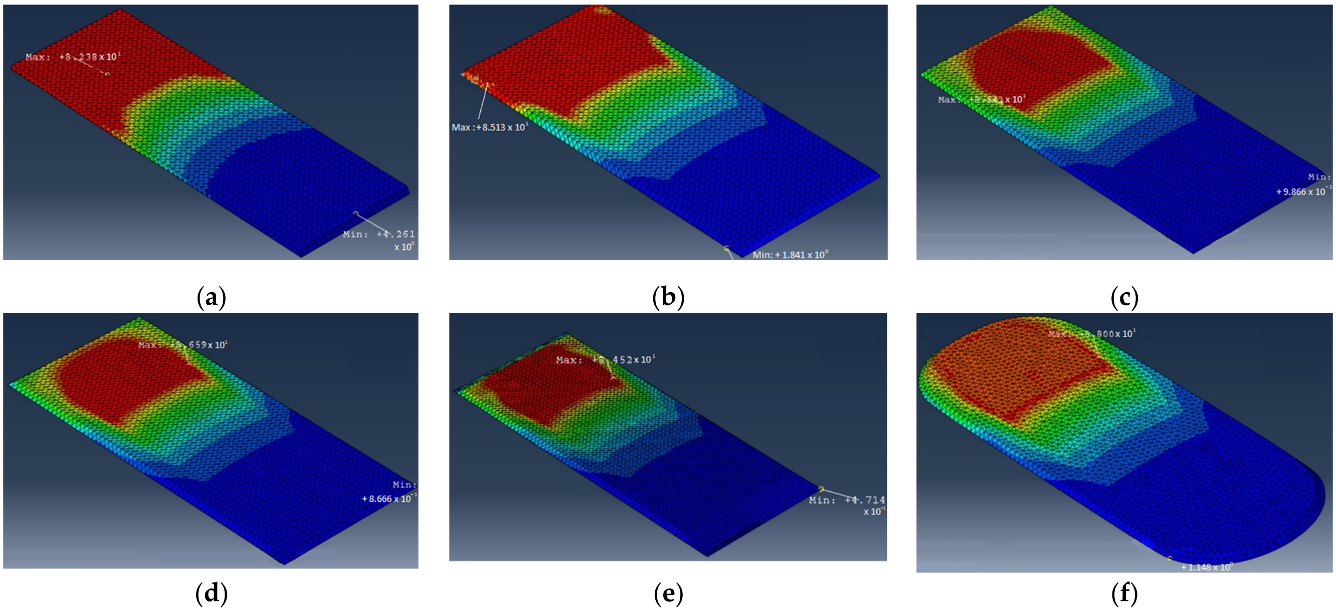


Figure 6. Von Mises stresses developed in the horizontal sections in case of the different geometry types: (**a**) geometry type i; (**b**) geometry type ii; (**c**) geometry type iii; (**d**) geometry type iv; (**e**) geometry type v; and (**f**) geometry type vi.

4. Conclusions

Six geometric models were created for a gullwing lead solder joint to address the effect of geometric modeling complexity on the developed strains and stresses in response to loads originating from thermal expansion differences. It can be concluded that the geometric shape of the solder has a fundamental effect on the FEA results. The geometry iv, which has rounded sides, is closest to the physics-based reference geometry vi. Furthermore, the choice of the section, which is used for stress and strain averaging, has a significant influence on the FEA results and therefore on the predicted lifetime. We found in analogy to the literature that the peak and average FEA results show huge differences. The peak values resulting from the linear elastic material model are not physically meaningful in the context of solder joint thermal loading. When choosing a material model, elastoplastic models are preferable over pure linear elastic models. However, some material models, e.g., the Engelmaier model, expect strains and stresses to originate from linear material models [1,2]. The limitations of the present work include that the question of geometric complexity was investigated on the gullwing joint type only. In more detailed research, not only gullwing but other joint types could be analyzed. Furthermore, a variety of the lead geometry and a variety of solder material types could be analyzed. As another limitation, we point out that the load in the present simulations was a prescribed displacement of the top end of the lead. However, thermo-mechanic simulations could be conducted in future work with the actual simulation of heat expansion. In further research, the FEA results will serve as inputs for lifetime estimation models, and these models will be benchmarked with a variety of geometries.

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