

Fracture analysis of the battery cans for Implantable Pulse Generators

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Abstract: The stresses in a battery housing used in Implantable Pulse Generators (IPGs), also known as pacemakers, were investigated using Abaqus/Standard. There were three levels of analysis: the global level, the three-dimensional submodel level and the plane strain submodel level. The output of the global analysis was fed into the three-dimensional submodel analysis and subsequently the output of the three-dimensional submodel analysis was fed into the plane strain submodel analysis. The simulation results of the global model were used to drive the more detailed three-dimensional submodels on long and short sides of the battery models. The material properties of the heat affected zone and fusion zone were incorporated into the more detailed three-dimensional submodels. The geometry for the battery housing was also enhanced in the three-dimensional submodel. From the three-dimensional submodel analyses, the displacements of several key points were recorded and imposed on the plane strain submodels. The plane strain submodel included details of the notches, whereas the three-dimensional submodels did not. Ultimately, the finite-strain fracture analyses were conducted on the plane strain submodels and J-integral values were extracted. The J-integral results on the long and short sides were compared and it was found that the J-integral values on the long-side are higher than the corresponding values on the short-side. This was consistent with the experimental observations.

Keywords: Pacemaker, Global-local modeling, submodeling, Fracture mechanic, Implantable Medical Device, Biomedics, Experimental Verification, Welding.

1. Introduction

Medtronic CRDM designs and manufactures cardiac rhythm management products, such as pacemakers and Implantable Cardioverter Defibrillators (ICDs). Both pacemakers and ICDs make use of an internal battery to provide power to the devices. The battery cases can be subjected to internal pressure which can cause stress risers at the weld locations in the battery cases. This pressure develops after end-of-service of the device, when access anode material reacts with the electrolyte in the battery. Although this phenomenon happens only after the battery has been discharged to the point where device replacement is recommended, Medtronic ensures that the device is still safe for the patient. Hence, minimizing potential fracture in the battery cases is of great interest to Medtronic. Numerical modeling was used to analyze the mechanics of the battery

pressurization process and to study the stress intensity factors that occur in the weld region of the battery case. Five different models were built at three analysis levels, which are global, three-dimensional submodel and plane strain submodel levels. The following sections describe the battery case geometry, the analysis methodology, the models built at each level and results of the different analyses that were conducted. The main conclusions of the study are provided at the end of the paper.

2. Model description

Figure 1 shows the battery can geometry. The model consists of two main components: the battery case and battery cover. The battery case and cover are welded together. The following paragraphs discuss the details of the analysis methodology and different models that were built.

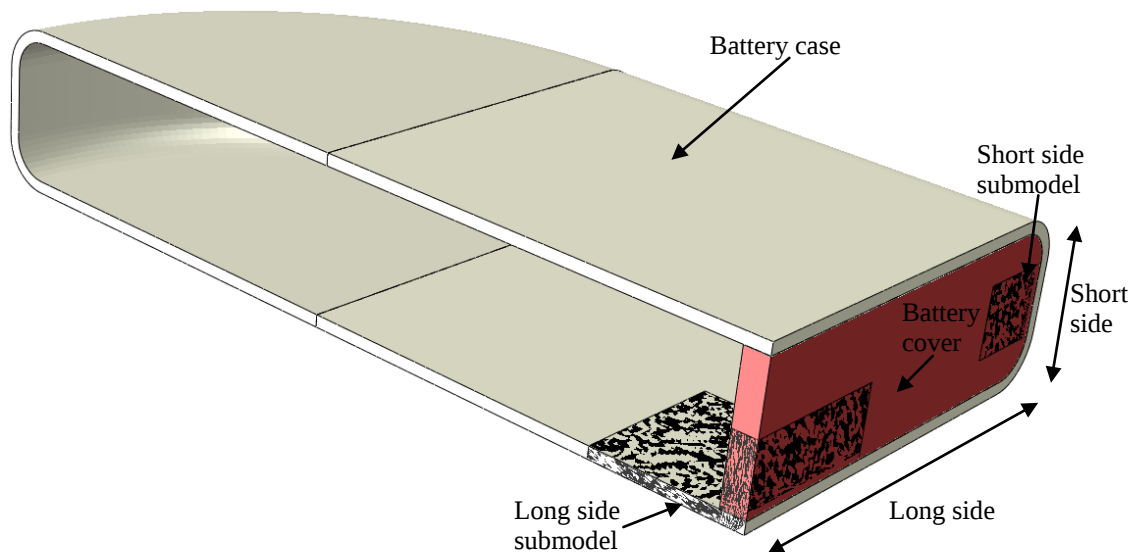


Figure 1. Battery can geometry

2.1 Analysis methodology

A nonlinear general static analysis was conducted in Abaqus/Standard. The analysis consisted of three levels of idealization: the global level, the three-dimensional submodel level and the plane strain submodel level. The output of the first level was used in the second level and the output of second level was used to analyze the third level model. Global model displacements were used to drive the more detailed three-dimensional submodels on long and short sides (see Figure 1) of the battery can. The displacements obtained from the three-dimensional submodels were used to drive the plane strain submodels.

The material properties of the heat affected zone and fusion zone were incorporated into the detailed three-dimensional submodels. The geometry for the battery can was also enhanced in the

three-dimensional submodel. Several key points in the three-dimensional submodels were recorded and imposed on the plane strain submodels. The plane strain submodel included notch details not present in the global models or three-dimensional submodels. Ultimately, the finite-strain fracture analyses were conducted on the plane strain submodels and J-integral [1, 2] values were extracted. The plane strain models considered notches on the short and long sides. The following paragraphs describe details of each model that was built for analysis.

2.2 Description of global model

The model was built in Abaqus/CAE by importing the CAD data from Pro-Engineer. The model shown in Figure 1 is one-half of the full model. Due to symmetry, only one-half model was sufficient for analysis. The material of both the cover and case was titanium. Elasto-plastic material properties were used. The Young's modulus was 105 GPa and Poisson's ratio was 0.37. The plastic properties in the form of true yield stress versus logarithmic plastic strain are given in Table 1 below.

Table 1. Material properties of Ti

Yield Stress (MPa)	Logarithmic Plastic Strain
209.64233	0
258.08234	0.00909
328.25939	0.03121
376.2469	0.06401
398.07743	0.09598
416.58123	0.12698
429.37101	0.1571
440.07512	0.18635
446.36659	0.2148
454.5024	0.24245

The battery case and cover are welded together. Hence, a tie constraint was used for rigidly connecting the battery case and cover. The battery case and cover were connected only to the extent that the actual welding fuses the surfaces together. Information about the amount of area in contact was obtained by the micrographs of the battery cross-section. Figure 2 shows micrographs of the cross-section of the battery on the long-side (Figure 2(a)) and short-side (Figure 2(b)). It can be seen that the battery and case are connected together through a distance of 0.007 inch and 0.0075 inch on long-side and short side respectively. The remaining distance has a gap between battery case and cover.

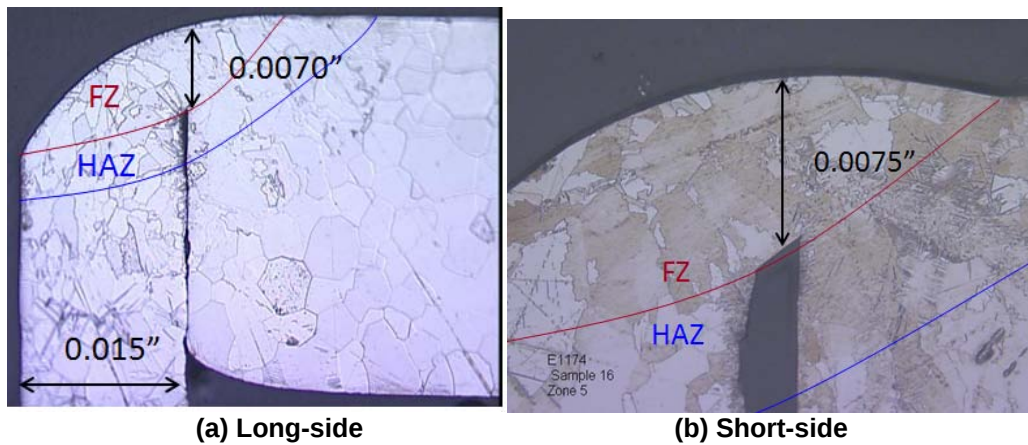


Figure 2. Micrographs of the cross-section of the battery can

In above requirement testing, the battery housing has been subjected to hydrostatic pressurization to a maximum of 3.45 MPa. Hence, during analysis, the battery can was pressurized to 3.45 MPa. The mesh for the global model is shown in Figure 3 and consisted of 158,367 nodes and 127,150 C3D8R elements. A nonlinear static analysis was conducted using Abaqus/Standard. Field and history output was requested at every 0.1 MPa applied pressure.

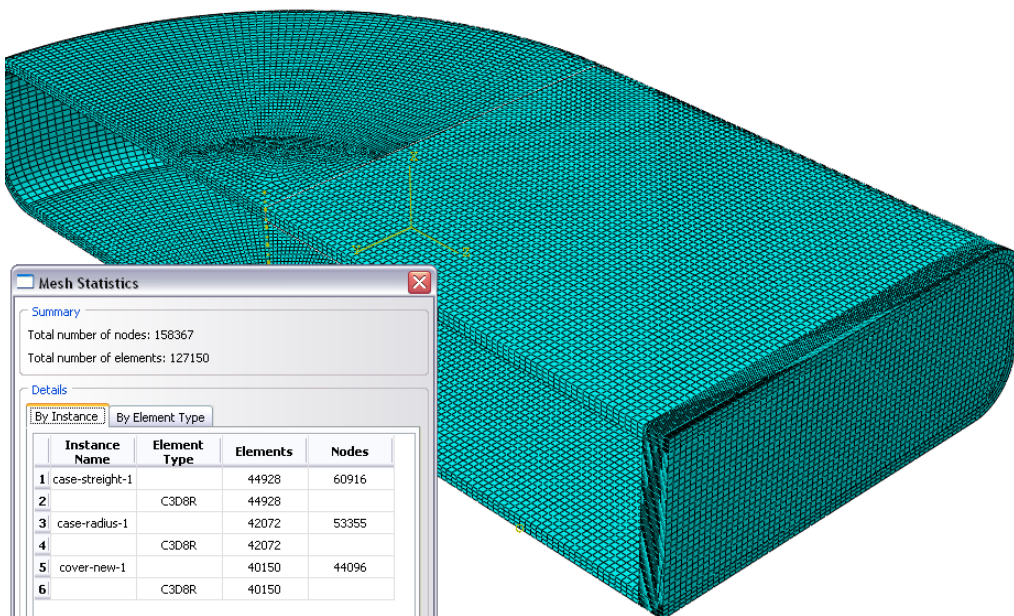


Figure 3. Mesh for the global model

2.3 Description of three-dimensional submodels

The three-dimensional submodel on the long-side is shown in Figure 4. The model consists of a small portion of the global model. The location of the three-dimensional submodel is shown by superimposing it on the global model in Figure 1. The three-dimensional submodel has more detailed information about the actual geometry as shown in Figure 4. Welding is done from the outside, where battery case and cover meet. A round was created in this region to represent the weld.

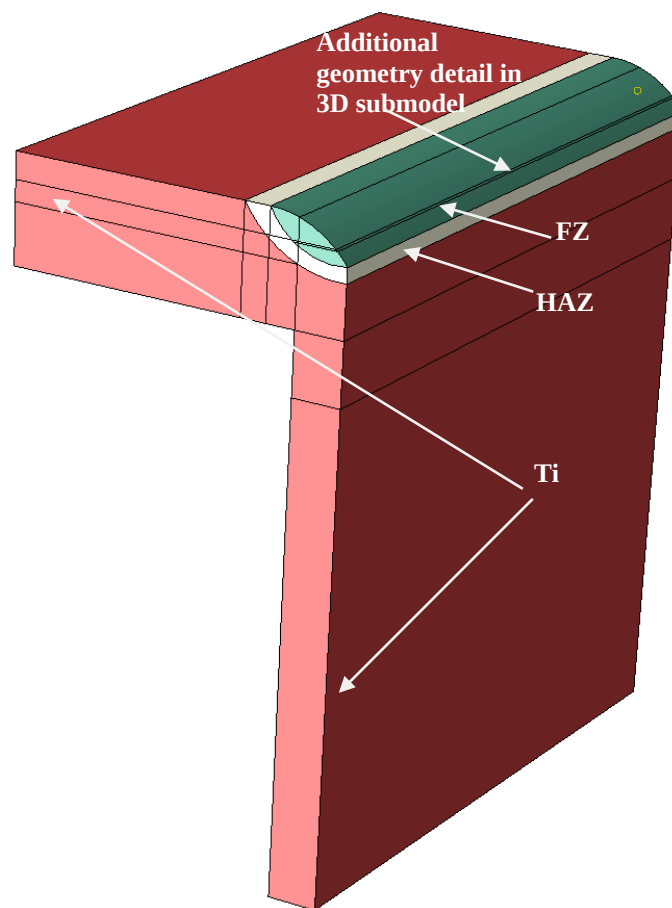


Figure 4. 3D submodel on the long-side

The welding process changes the properties of the case material near the weld area. In reality, the properties of the region near the weld area may change smoothly. However, for simulation purposes, three different zones were assumed. The region where welding creates a fused zone is labeled as Fusion Zone (FZ) in Figure 4. The intermediate zone between the original properties and FZ is labeled as Heat Affected Zone (HAZ) in Figure 4. The material properties for the rest of the model remained unchanged. The original properties of Ti material were used for the entire three-dimensional submodel except for the FZ and HAZ regions. All three zones are shown in Figure 4 for the long-side 3D submodel.

The material properties for the Ti are provided in Table 1. The FZ and HAZ had the same elastic properties as regular Ti. The plastic material properties for the FZ and HAZ were different and are listed in Table 2. The three-dimensional submodel on the short-side was very similar to the one on long-side. The only difference between the two was in terms of the welded area and model dimensions. The micrograph of the cross-section of the battery can on the short-side is shown in Figure 2(b).

Table 2. Material properties of FZ and HAZ

FZ		HAZ	
Yield Stress (MPa)	Logarithmic Plastic Strain	Yield Stress (MPa)	Logarithmic Plastic Strain
320.8	0	277	0
357	0.03	347	0.03
400	0.07848	390	0.07848
450	0.1571	440	0.1571
475	0.24205	460	0.24205

Both the Y-symmetry and fixed line boundary conditions were applied on the three-dimensional submodel, similar to the global model. The three-dimensional submodel, however, had an additional boundary condition to drive the displacements of the submodel from the global model. This submodel boundary condition is shown in Figure 5. The region on which the submodel boundary condition was imposed is highlighted in red in the figure.

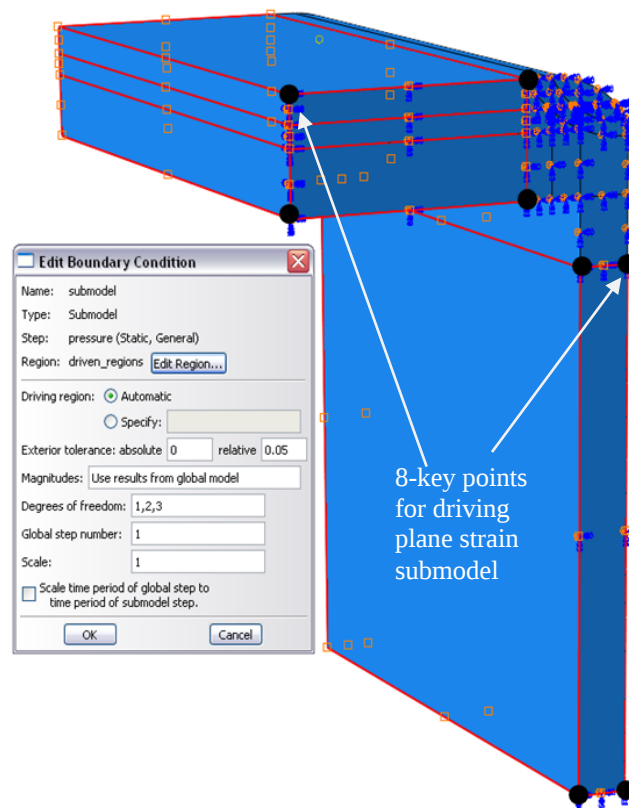


Figure 5. Submodel boundary condition for the 3D submodel on the long-side

The three-dimensional submodels were meshed with C3D8R elements, as in the global models. Similar to the global model, the same type of nonlinear static analysis was conducted for the three-dimensional submodel. Output was requested at every 0.1 MPa. Eight key output points are highlighted in Figure 5. Displacement history output was requested for these key points. These points were used to drive the plane strain submodels, which are described below.

2.4 Description of plane strain submodels

The fracture analysis was conducted using the plane strain submodels. Creating refined meshes to model the notches would have required a very large model size and would have been cumbersome for fully three-dimensional models. The plane strain analyses allowed the fracture analyses to be conducted economically with a reasonable model size. The plane strain submodels were driven by the displacements obtained from the three-dimensional submodels. It should be noted that the default global coordinate systems for the three-dimensional submodels and plane strain submodels were different from each other. The displacements were transformed from one coordinate system to the other and were imposed correctly.

Figure 6 shows plane strain submodel on the long-side. Different material regions are identified in the figure. The dimensions of these regions were consistent with the material regions in the three-

dimensional submodel shown in Figure 6. Notches were created in the plane strain submodels as shown in Figure 6. The notch width is 0.02 mm. The length of the notch in the submodel was consistent with the area not in contact in the three-dimensional submodel. The total number of elements in the long-side plane strain submodel was 81,496 and total number of nodes was 204,702. Linear plane strain elements (CPE4R and CPE3) were used in most of the model. Quadratic plane strain elements (CPE8R and CPE6) were used in the regions near the notch so that this region could be enriched.

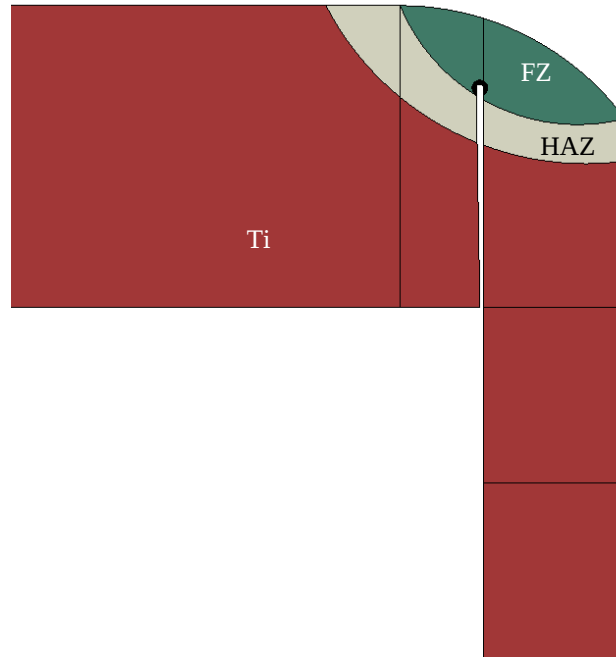


Figure 6. Plane strain submodel on the long-side

It should be noted that since the model experiences finite strain deformation and has elasto-plastic materials, a linear elastic fracture analysis would not have sufficed. Hence, a finite strain analysis was conducted. Notch geometries were created for that purpose. For conducting the fracture analysis, a crack front and crack tip were defined for the notch region as shown in Figure 7. For sharp cracks, using degenerate elements and adjusting mid-side node parameter can help enhancing stress singularity. Since the notches were modeled explicitly in the plane strain submodels, this was not required. Hence, the 'no degeneracy' option was specified on the singularity tab and mid-side node parameter was set to be 0.5.

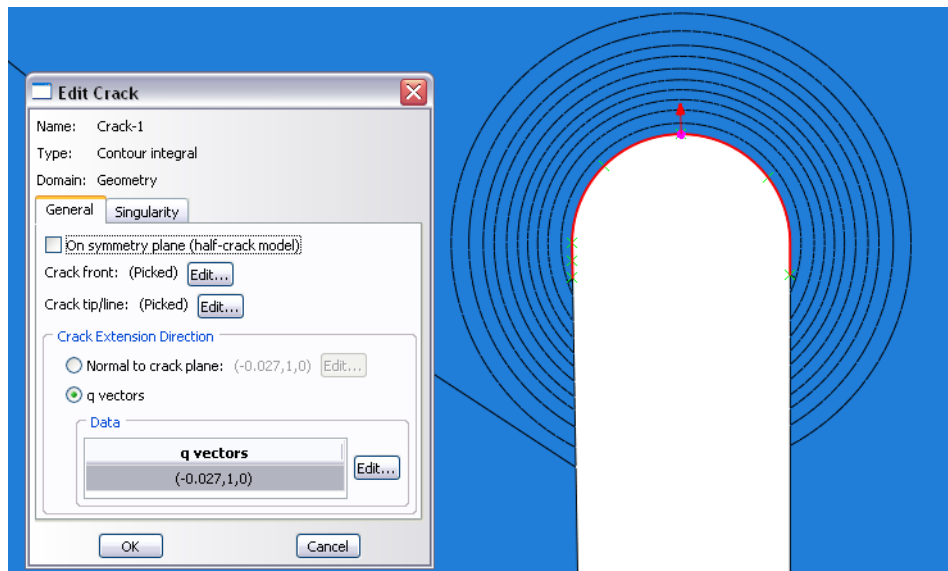


Figure 7. Crack front & crack tip for contour integral calculations

The plane strain model for the short-side was very similar to the model for the long-side. One key difference was in the width of the notch. Using micrographs of the cross-sections, the existence of a bigger notch width on the short-side than on the long-side was noted. The notch width in the short-side models was increased accordingly.

3. Results & discussion

In this section, the results of the global model and three-dimensional submodels are discussed in terms of deformed shapes and stress distributions. The fracture analysis results are discussed for the plane strain submodels.

3.1 Deformation of global & three-dimensional submodel

Figure 8 shows the deformation of the global model at applied test condition's pressure of 3.45 MPa. The deformed shape is superimposed on the undeformed shape to clearly show the magnitude of deformation. The deformation scale factor was 1. The figure also shows the Mises stress distribution at applied pressure of 3.45 MPa. It can be seen that the weld locations are the regions of high stress concentrations. The peak stress value is 451 MPa. The maximum swelling in the battery can is of considerable importance and was also investigated. The maximum swelling as a function of applied pressure is plotted in Figure 9. The maximum swelling at extreme test conditions of applied pressure of 3.45 MPa was found to be 5.91 mm.

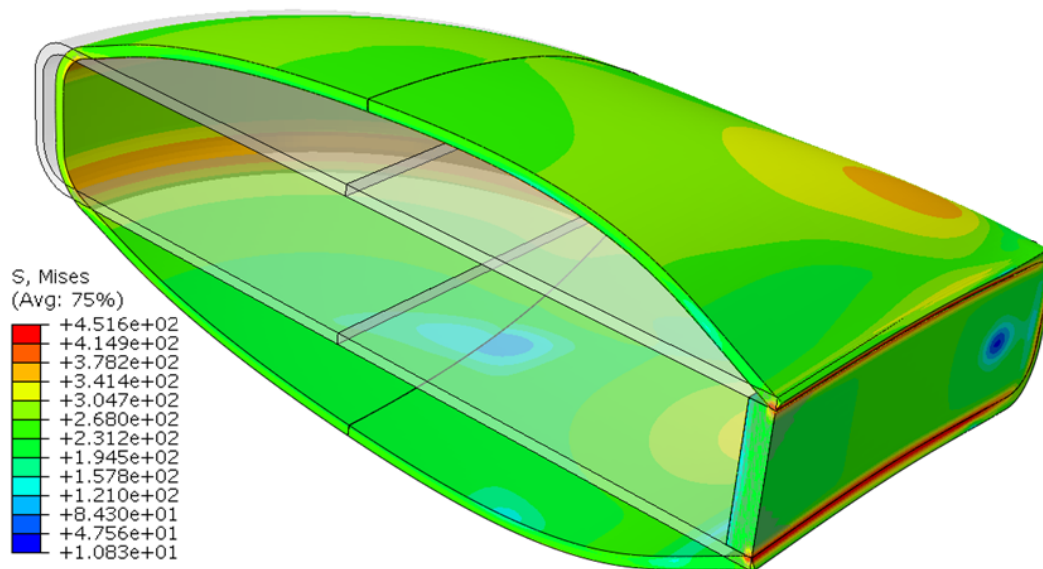


Figure 8. Deformation & stress distribution of the global model at 3.45 MPa is shown by superimposing the deformed shape on the undeformed shape (deformation scale factor = 1)

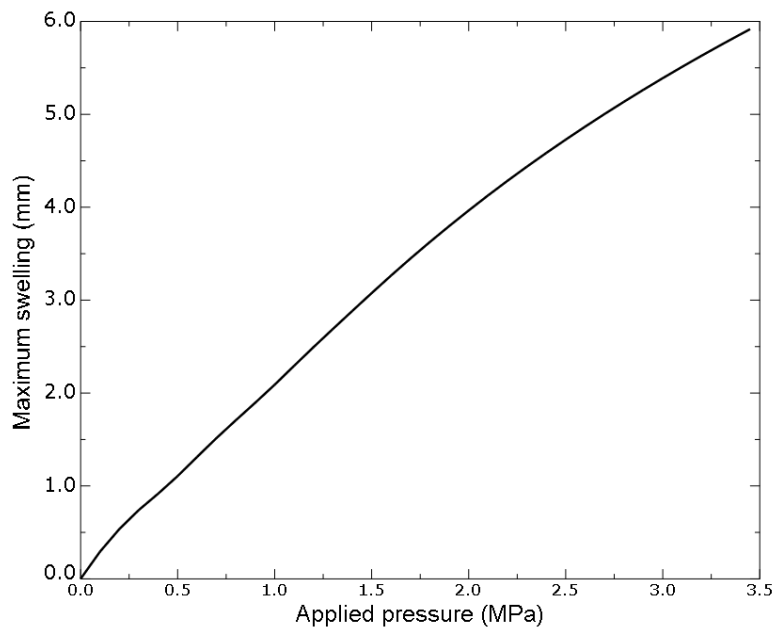


Figure 9. Maximum swelling (twice the maximum deformation) vs applied pressure

The three-dimensional submodel was driven by the displacements of the global model. The deformed shape and contour plot of the long-side three-dimensional submodel was superimposed on the global model and it was found that the deformation of the three-dimensional submodel was consistent with that of the global model. The Mises stress distribution in the long-side three-dimensional submodel at an applied pressure of 3.45 MPa is shown in Figure 10. The peak stress value is 475 MPa and is more than the corresponding value in the global model. This is due to the reason that the three-dimensional submodel captures geometry and material properties closer to reality. The peak value of Mises-stress in the short-side three-dimensional submodel at an applied pressure of 3.45 MPa was also found to be 475 MPa.

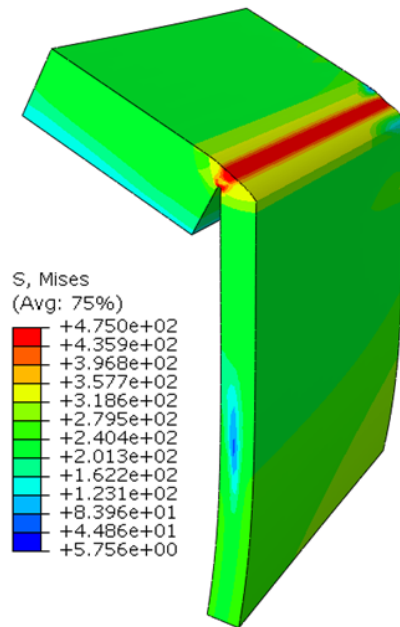


Figure 10. Mises stress distribution in the long-side 3D submodel at 3.45 MPa

3.2 Variation of J-integral on the long-side & short side

Figure 11 shows the Mises stress distribution for the long-side plane strain submodel at an applied pressure of 3.45 MPa. The displacements obtained from the three-dimensional submodel were imposed on several points of the plane-strain submodel. Hence, the deformation obtained is consistent between the models. The plane strain submodels had additional details of the notches and cracks to capture the fracture behavior. Up to 10 contour integrals were used for the plane strain submodel on the long-side. The contour integral domain for contours 1 through 10 is highlighted in Figure 12.

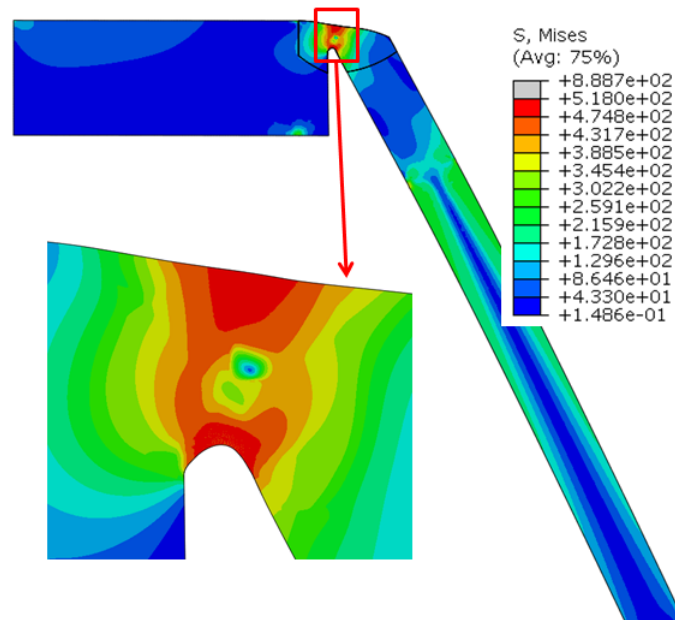


Figure 11. Mises stress distribution in the long-side plane strain submodel at 3.45 MPa

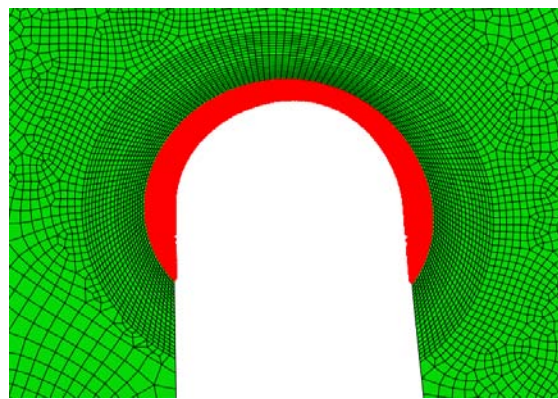


Figure 12. Contours 1 through 10 for the long-side plane strain submodel

The variation of the J-integral with applied pressure is shown in Figure 13. The average J-integral value at an applied pressure of 0.8 MPa is predicted to be 3.759 mJ/mm² for the long-side plane strain submodel. The pressure value of 0.8 MPa is one of the other test pressure conditions and is closer to reality. This is the reason that the J-integral values between short side and long side models will be compared at this pressure.

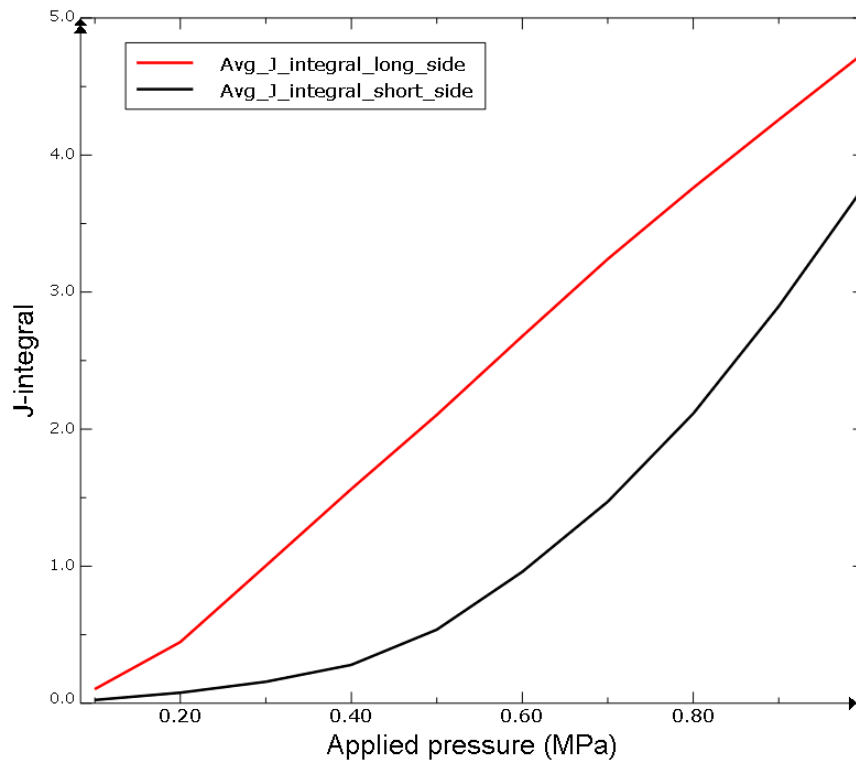


Figure 13. Comparison of J-integral variation between long-side and short-side models

Similarly, the plane strain models on the short side were also analyzed. Note that in the case of the short-side submodel the notch closes during loading. In contrast, the notch on the long-side submodel opens during the applied pressure. The average J-integral variation for the short-side model using several contours is shown in Figure 13. The average J-integral value for the short-side submodel is 2.138 mJ/mm^2 at applied pressure of 0.8 MPa. This is approximately 43% less than the long-side submodel. This observation is consistent with the experimental observations which showed that the long-side of the battery was more susceptible to damage than the short-side. Figure 13 compares the J-integral values for the short-side and long-side plane strain submodels. The plane strain submodels predict a higher J-value for the long-side model as compared to the short-side model at all applied pressures up to 1 MPa. It can also be noted that the J-integral variation for the long-side submodel was almost linear whereas the variation of J-integral for the short-side is bilinear.

4. Conclusions

Based on the analyses described above, the following conclusions can be made:

- The stresses in a battery housing used in IPGs were investigated using three levels of analysis: the global level, the three-dimensional submodel level and the plane strain submodel level. This unique approach allowed including greater geometry and material details in the submodels while keeping the computational time low.
- To estimate the effect of the natural stress raiser at the weld, the energy-release rate was calculated via the J-integral.
- J-integral variation for the long-side submodel was almost linear whereas the variation of J-integral for the short-side is bilinear.
- The average J-integral value for the short-side submodel is predicted to be considerably lower than the long-side submodel. This observation is consistent with the experimental observations. This implies that the long-side of the battery may be more susceptible to fracture damage than the short-side.

5. References

1. J.R. Rice, A Path Independent Integral and the approximate analysis of strain Concentration by Notches and Cracks, *Journal of Applied Mechanics*, **35** (1968) 379-836.
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