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Title:	Developing an Abaqus *HYPERFOAM Model for M9747 (4003047) Cellular Silicone Foam
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Developing an Abaqus *HYPERFOAM Model for M9747 (4003047) Cellular Silicone Foam

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Summary

This report documents work done to develop an Abaqus *HYPERFOAM hyperelastic model for M9747 (4003047) cellular silicone foam for use in quasi-static analyses at ambient temperature. Experimental data, from acceptance tests for "Pad A" conducted at the Kansas City Plant (KCP), was used to calibrate the model. The data includes gap (relative displacement) and load measurements from three locations on the pad. Thirteen sets of data, from pads with different serial numbers, were provided. The thirty-nine gap-load curves were extracted from the thirteen supplied Excel spreadsheets and analyzed, and from those thirty-nine one set of data, representing a qualitative mean, was chosen to calibrate the model. The data was converted from gap and load to nominal (engineering) strain and nominal stress in order to implement it in Abaqus. Strain computations required initial pad thickness estimates. An Abaqus model of a right-circular cylinder was used to evaluate and calibrate the *HYPERFOAM model.

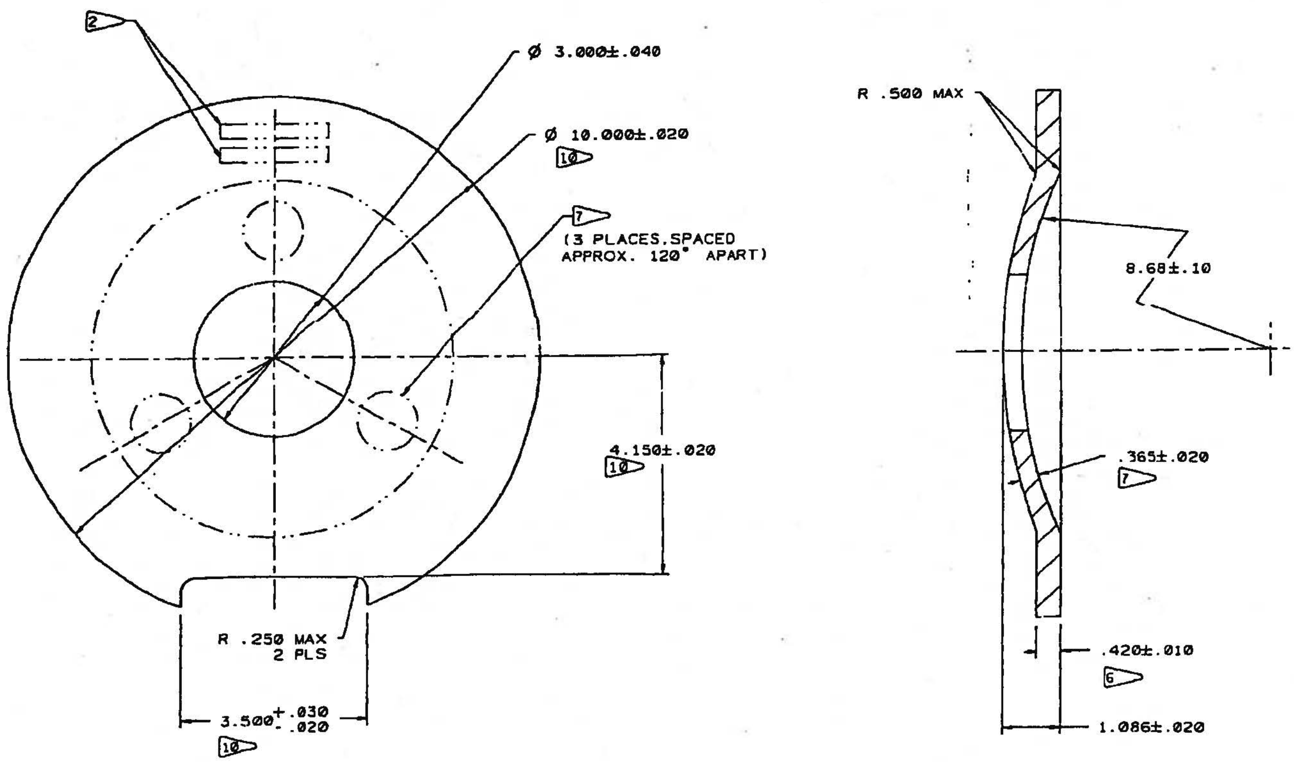


Figure 1: Portion of engineering drawing AY321889 showing Pad A.

1 Pad A Acceptance Test Data

Figure 1 shows the portion of drawing number AY321889, found in `AY321889-1-W.tif` and Appendix A, that contains the engineering drawing of Pad A. The top view of the pad shows the three test locations, specified by note 7 in Figure 1, where two platens are used to compress the pad. The side view shows the curvature of the pad where the measurements are taken.

The pads, tested at the Kansas City Plant (KCP), were made of M9747 (4003047) cellular silicone foam. Data from the acceptance tests of part number 321889-103 were provided for use in calibrating the material model for M9747. Table 1 lists thirteen Pad A serial numbers, when the pads were tested, and the identification number of the operator who conducted the tests. The table shows that data was collected over approximately a four-year period of time, and by three different operators. KCP provided the data for each serial number in Excel and PDF files with filenames `321889_xxxx_Data_Retrieval.xls` and `321889_xxxx_Complete_Part_Load_Vs._Deflection.pdf`, respectively, where `xxxx` represents the serial numbers in Table 1. Each of the thirteen sets of data contained three gap-load curves—one for each position on the pad—with gap reported in inches and load reported in pounds-per-square inch. The gap values referred to the distance between the two test platens. The reported load values were positive for compressive forces. Data was collected during the compressive portion of the first loading cycle.

The data supplied by KCP was used to calibrate a material model in Abaqus. Abaqus typically accepts experimental data in the form of pairs of nominal (engineering) strain and nominal stress from appropriate experiments, therefore the supplied data was extracted from the Excel spreadsheets, analyzed, and converted for implementation in Abaqus.

Table 1: List of data sets in order of increasing serial number.

Serial No.	Date	Operator No.
4100	12/01/99	433016
4137	04/14/00	433029
4156	05/17/00	433029
4163	09/13/00	437016
4200	10/20/00	433016
4252	05/08/01	433016
4299	07/16/01	433001
4337	09/14/01	433001
4383	08/20/02	433001
4445	02/05/03	433001
4478	05/19/03	433001
4494	09/08/03	433016
4542	10/16/03	433001

1.1 Data Extraction

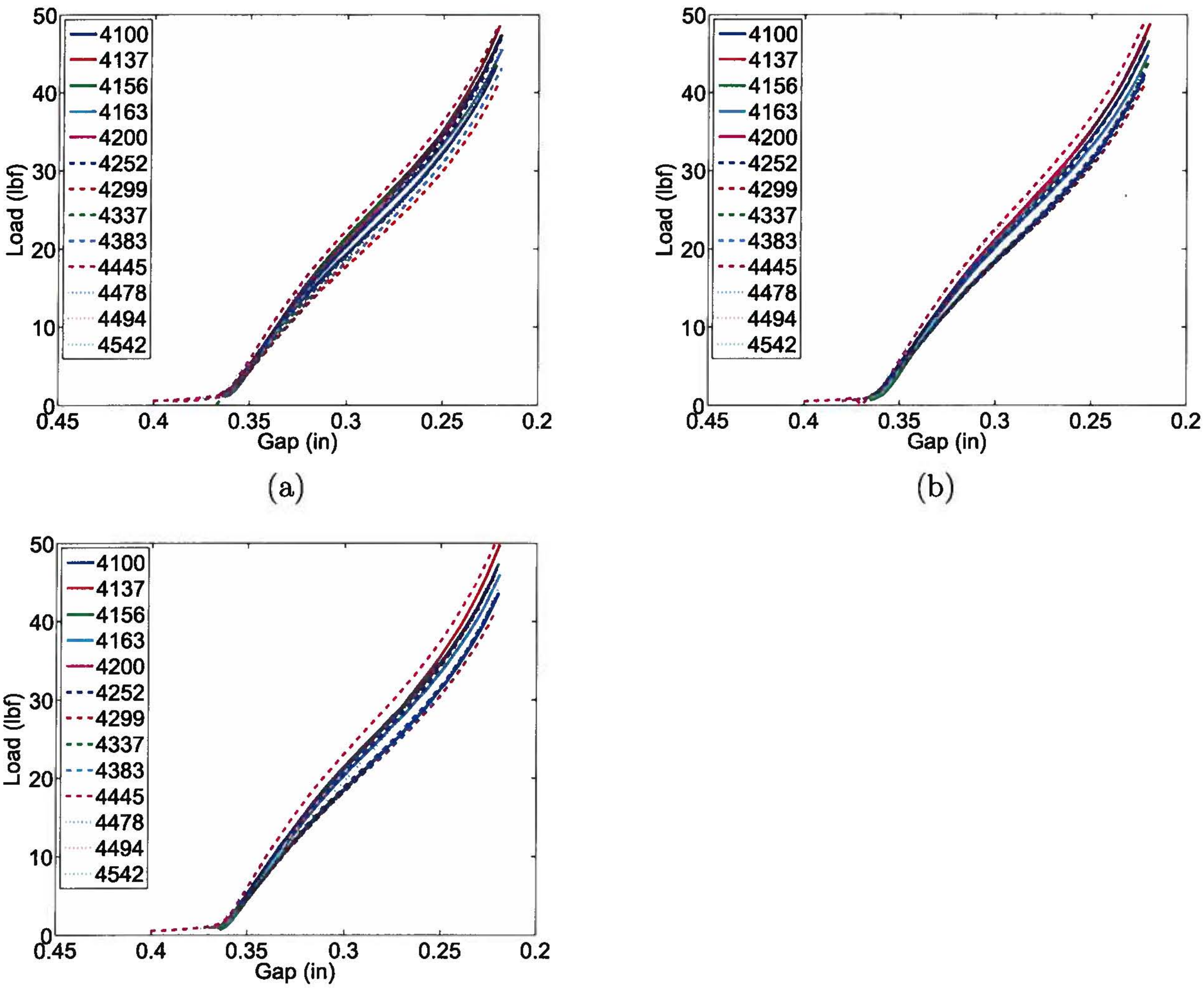
Matlab was chosen for conducting the data analysis, which required that the data first be extracted from the Excel spreadsheets. The Matlab script `import_data.m`, shown in Appendix B, was written to extract the data, arrange it in a desirable structure, and save it for further analysis. The inputs to the script are the serial number (`ser_num`) of the pad for which the data will be extracted, the columns (`col1`, `col2`, `col3`) in the spreadsheet where the gap-load data for each position resides, and the initial (`row1_i`, `row2_i`, `row3_i`) and final (`row1_f`, `row2_f`, `row3_f`) rows of the data for each position. The script begins by constructing the Excel filename in the form `321889_xxxx_Data_Retrieval.xls`, where `xxxx` is specified by the variable `ser_num`. The inputs for the columns and rows are used to construct arrays specifying the range of data for each position. The Matlab command `xlsread(name,range)`, which reads the data from an Excel spreadsheet whose filename is specified by `name` and with desired data in `range`, is used to extract the data for each position. Next the script `extract.m`, shown in Appendix C, is used to separate the gap and load data from each column of alternating gap-load data. Finally the gap data, load data, and the ranges in the corresponding Excel file they were imported from are stored in a Matlab structured array `data_321889_xxxx` and saved as a Matlab data file `321889_xxxx_gap_load.mat`.

Though a copy-paste operation combined with the script `extract.m` could have been used to bring the data into Matlab and sort it, `import_data.m` has the advantage of automating the saving of the data and it provides a means to trace back to the source of the data.

1.2 Raw Data

Figure 2 shows plots of the extracted data for the three test positions and all serial numbers. The data is plotted with load[1] on the vertical axis and gap on the horizontal axis, with gap plotted in reverse order. Some important qualitative comments can be made regarding the trends in the data.

[1]A 1 in^2 platen was used during the acceptance test, therefore the load reported by KCP in pounds-per-square-inch (psi) is equivalent in magnitude to load in pounds-force (lbf) shown in Figure 2.



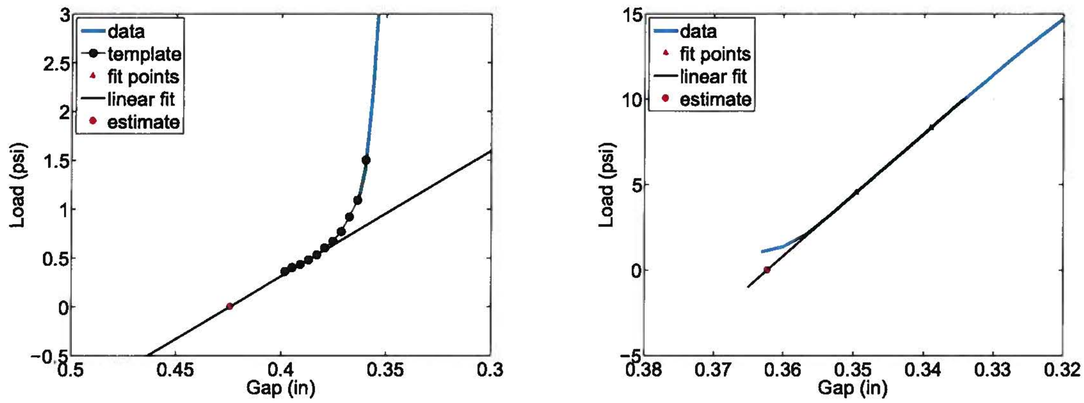
(a) (b) (c)

Figure 2: Plots of the raw gap-load data for positions (a) one, (b) two, and (c) three on Pad A.

For a gap range of about 0.36–0.4 inches a few of the curves start with a linear region with small slope. The slopes of the curves increase at a gap of around 0.36 inches, and for a gap range of about 0.32–0.36 inches the curves have a region of linear growth. Next the slopes of the curves decrease and for a gap range of about 0.26–0.32 inches the curves have a linear region with a smaller slope relative to the previous linear region. Finally for a gap smaller than about 0.26 inches the slopes of the curves increase.

These qualitative observations can also be stated in terms of how the pad resists the applied load. In the gap range of about 0.36–0.4 inches the pad offers little resistance, from about 0.32–0.36 inches it resists the load much like a linear elastic material, it then softens and from about 0.26–0.32 inches the pad again behaves like a linear elastic material, and finally for gaps smaller than about 0.26 inches the pad becomes increasingly stiff.

The early response of the pad, in the gap range of about 0.32–0.4 inches, was of particular interest since the data trends in that range helped estimate the initial pad thickness, which was



(a) (b)

Figure 3: Examples of initial pad thickness estimates using options (a) one, and (b) two on the data for serial number 4163.

necessary for computing strain from gap data.[2] The estimates varied greatly depending on whether the trend in the data in the range of 0.36–0.4 inches was considered or ignored.

1.3 Estimating Initial Pad Thickness

The initial pad thickness was estimated as the gap value when the load reached zero, which required extrapolating the data until zero load was reached. Two options were considered for extrapolating the data. For the first option the initial data in the range of 0.36–0.4 inches was considered relevant, and it was assumed, due to a limited amount of data, that all the curves had the same slope in that range. Extrapolations with this option employed a template, using the data for serial number 4445 in the range 0.36–0.4 inches, that was manually fit to all the curves and then extrapolated to zero load using a linear fit through two selected data points. For the second option trends in the data above a gap of about 0.36 inches were ignored, and the assumption was made that all the data should begin in the linear range for a gap of about 0.32–0.36 inches. Extrapolations with this option were made by manually choosing two points in the linear region of each curve, using those two points to define a line, and extrapolating that line to zero load. Figure 3 shows examples of the two extrapolation options applied to the data for serial number 4163. Figure 3(a) shows how the template was used to extend the data, and how a linear fit of the linear portion of the template was used to extrapolate to zero load and estimate the initial thickness. Figure 3(b) shows how the linear fit was used to extrapolate the data and estimate the initial thickness while ignoring the trend at larger gap values.

Appendix E contains a table showing the initial pad thickness estimate results using both options as compared to the actual thickness reported by KCP. Table 2 lists only the pad thickness estimates

[2]The KCP data sheets state "Actual Thickness" of the pad at each test position. These values were used to compute strain, but the resulting strain-stress curves, shown in Appendix D, were inconsistent with the expected results. Ideally the strain-stress curves should be linear for small strains and pass through zero stress at zero strain. However most of the curves in Appendix D would not pass through zero stress at approximately zero strain when extrapolated. Though not tested, similar results were anticipated if the nominal pad thickness was used to compute strain.

Table 2: List of initial thickness estimates, using second option to extrapolate data, compared to actual thickness values reported by KCP.

	Position 1		Position 2		Position 3	
Serial No.	Est. 2 (in)	Act. (in)	Est. 2 (in)	Act. (in)	Est. 2 (in)	Act. (in)
4100	0.365	0.363	0.363	0.363	0.364	0.364
4137	0.364	0.364	0.363	0.363	0.363	0.363
4156	0.363	0.365	0.361	0.365	0.362	0.365
4163	0.362	0.363	0.362	0.364	0.363	0.363
4200	0.365	0.363	0.364	0.362	0.365	0.362
4252	0.365	0.363	0.365	0.362	0.365	0.364
4299	0.364	0.361	0.365	0.362	0.364	0.362
4337	0.365	0.367	0.365	0.373	0.364	0.367
4383	0.365	0.390	0.365	0.380	0.366	0.370
4445	0.365	0.400	0.364	0.400	0.365	0.400
4478	0.366	0.364	0.366	0.362	0.366	0.364
4494	0.367	0.365	0.366	0.364	0.367	0.365
4542	0.366	0.374	0.365	0.375	0.365	0.374

from the second extrapolation option. Since the test positions, as shown in Figure 1, are on a curved section of the pad and assuming that the platens are flat, the data in the gap range of about 0.36–0.4 inches represented the pad being flattened between the platens, as opposed to being compressed. Therefore the experimental results in the range of 0.36–0.4 inches did not represent uniaxial compression, and as a consequence the extrapolations using the first option greatly overestimated the initial pad thickness. Extrapolations made with the second option did a good job estimating the thickness of 0.365±0.020 in shown in the engineering drawing.

1.4 Computing Strain and Stress

Engineering (nominal) strain (ϵ) was computed as

$$\epsilon = \frac{d_o - d}{d_o} \tag{1}$$

where d_o is the initial thickness of the specimen and d is the thickness of the specimen subject to a load. This expression for ϵ produced positive values of strain during compression, and was chosen such that the sign convention of compressive strains would correspond with the sign convention of the compressive stresses reported by KCP. Engineering strain in the pad was found using the initial pad thickness estimates 2 for d_o, and the KCP gap values for d. Nominal stress (σ) is, by definition

$$\sigma = \frac{P}{A} \tag{2}$$

where P is an applied load and A is the area over which the load is applied. The applied load was given in the data from KCP. The area over which the load was applied, which corresponded to the surface area of the platen used in the KCP tests, is 1 in^2—platen of 1.128 inch diameter—as stated in the text for note seven in the engineering drawing AY321889 shown in Appendix A.

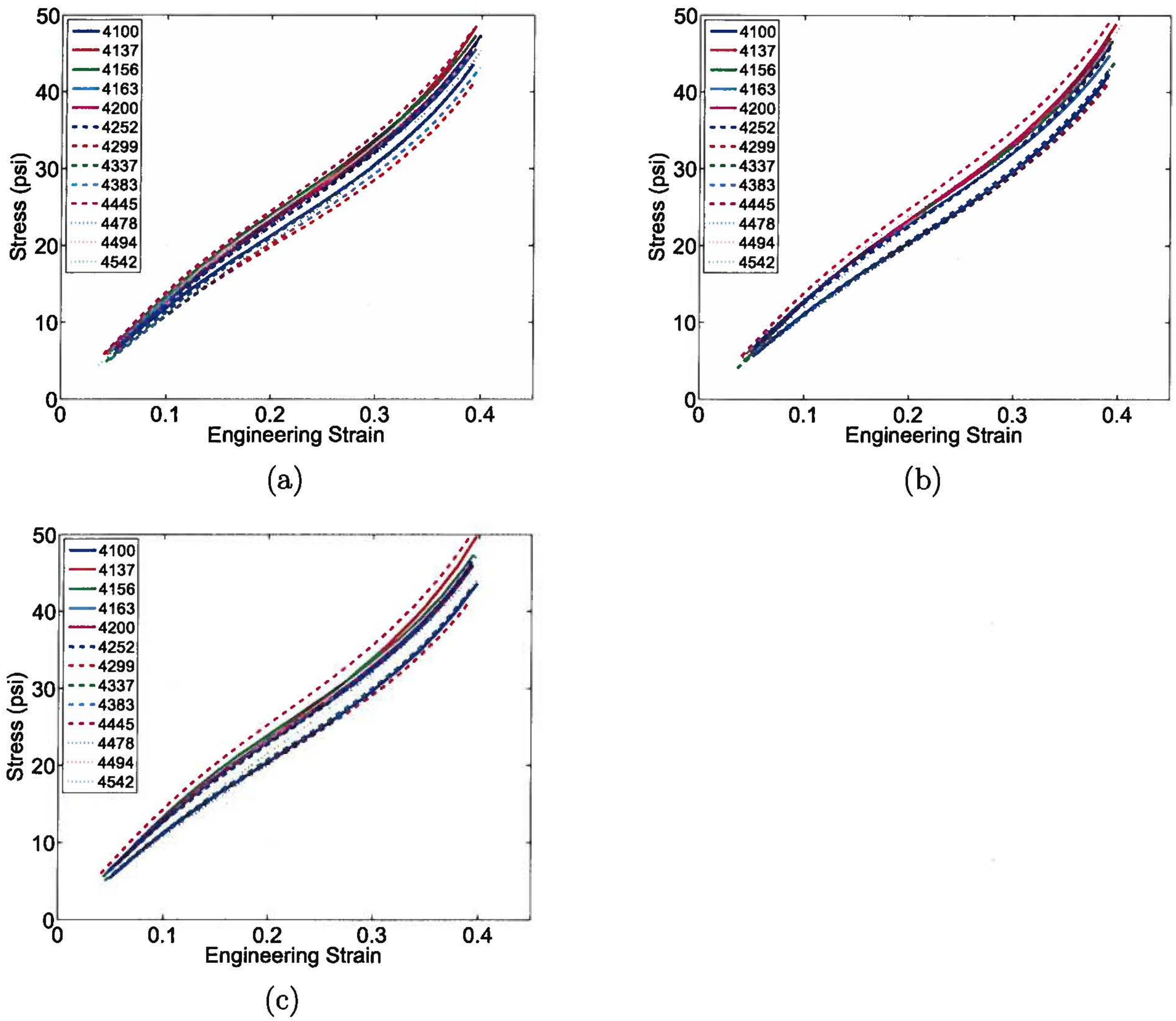


Figure 4: Strain-stress plots for positions (a) one, (b) two, and (c) three.

Figure 4 shows the results of computing strain and stress using the KCP supplied gap-load data, the initial pad thickness estimates in Table 2, and the information regarding the platen area from the engineering drawing. The data presented in Figure 4 has been manually truncated such that the curves are linear for small strain, which removes the data collected during flattening of the pad. If these curves were to be extrapolated they would cross zero stress at approximately zero strain. Such truncation has also removed any negative values of strain. This strain-stress data is representative of uniaxial compression of a hyperelastic foam.

Note that while the plots in Figure 4 show positive values of strain and stress the experimental results are for compression tests and therefore those values would be negative based on the positive-in-tension sign convention used by Abaqus.

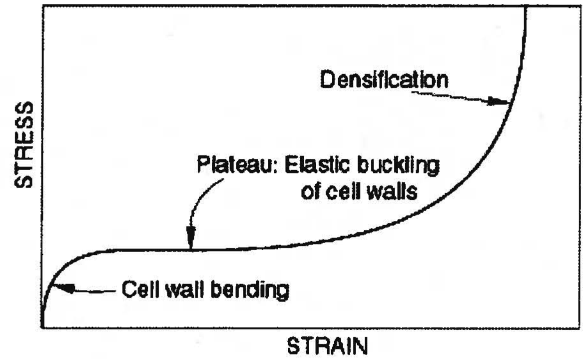


Figure 5: Qualitative strain-stress curve of foam in compression taken from [1, sec. 19.5.2].

2 Abaqus *HYPERFOAM Model

The Abaqus *HYPERFOAM model is a nonlinear, isotropic material model that is valid for cellular solids with porosity that permits large volumetric changes, and is suitable for hyperelastic foams [1, sec. 19.5.2]. The model, whose details are discussed in [1, sec. 19.5.2] and [3, sec. 4.6.2], implements a strain energy potential (U) of the form

$$U\left(\hat{\lambda}_1, \hat{\lambda}_2, \hat{\lambda}_3\right) = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left[\hat{\lambda}_1^{\alpha_i} + \hat{\lambda}_2^{\alpha_i} + \hat{\lambda}_3^{\alpha_i} - 3 + \frac{1}{\beta_i}\left(\left(J^{el}\right)^{-\alpha_i\beta_i} - 1\right)\right]$$

to find the constitutive model relating strain to stress. The parameter N dictates the number of terms in the model. The terms α_i, β_i, and μ_i are material parameters. The independent variables $\hat{\lambda}_1$, $\hat{\lambda}_2$, and $\hat{\lambda}_3$ are principal stretches, and are related to the strain in a continuum. The term J^{el} is the elastic volume ratio, and is a function of the principal stretches. Furthermore, β_i is related to the Poisson's ratio ν_i by the expression $\beta_i = \frac{\nu_i}{1-2\nu_i}$. The model order, $N = \{1, 2, 3, 4, 5, 6\}$, must be chosen and the material parameters α_i, β_i, and μ_i can either be specified, or computed by Abaqus using a least squares fit that minimizes the error in the computed stress when given experimental data. The Poisson's ratio can also be specified or computed. The types of experimental data that are acceptable for this model are uniaxial, biaxial, planar, simple shear, and volumetric. All data needs to be input as nominal (engineering) values, with the appropriate sign following a positive-in-tension convention.

Figure 5 shows a qualitative sketch of the performance of a hyperelastic foam during compression. The sketch highlights the three general ranges of behavior and shows how initially stress increases as a function of strain, next the stress levels off and stays nearly constant for a range of strain, and lastly the stress increases nonlinearly as a function of strain. In the first range the foam acts like a linear elastic solid. In the second range the cell walls bend and weaken, which makes the foam soften and lose strength. Lastly, the weakened cells are crushed and the foam behaves nearly incompressible. Section 1.2 discussed qualitative characteristics exhibited by Pad A during acceptance tests. The pad initially behaved like a linear elastic solid, it then softened, and finally became increasingly stiff. These qualitative behaviors agreed well with those of the *HYPERFOAM model, which made the model a suitable candidate for modeling M9747 cellular silicone foam.

3 Developing the M9747 Material Model

Once the appropriate Abaqus material model was chosen, work was done to select the inputs to Abaqus to create an appropriate model. The KCP acceptance tests were used to produce data for uniaxial compression, as discussed in Section 1, and that was the only data available to supply to Abaqus. Furthermore, the decision was made to first implement the model with a Poisson's ratio of zero for all N. Aside from choosing which set of data to supply to Abaqus, this left N as a free parameter to vary in order to find the best model.

3.1 Choosing the Uniaxial Compression Data

One available option for choosing the data set to supply to Abaqus was to use the average of all the data sets. However, the data was not collected at the same increments in stress or strain—even for simultaneous data acquisition on each position of the same pad—which made computing the average more difficult and time consuming.[3] The option used for this work was to choose a curve from Figure 4 that represented the qualitative mean of all the data. The strain-stress curve for position one of serial number 4252 was chosen based on this criteria.

This data, as input into to Abaqus, is shown in Appendix F. Nominal stress is in mega-Pascals (MPa). The Abaqus command `*UNIAXIAL TEST DATA`, which signifies that data from a uniaxial tension/compression test is being provided, was used to supply the data for the analysis. The first column of data contains (nominal) stress, and the second column of data contains engineering (nominal) strain. The negative sign on the data signifies compressive stress and strain.

3.2 Other Material Parameters

Abaqus also required a density to go along with the *HYPERFOAM model. The density of M9747, as listed in 'Item 46' of the table in drawing 18Y-309210, found in `18Y-309210-RevB_Mod4-assembly.pdf`, is 0.639 g/cc.[4]

3.3 Model Calibration: Testing Values of N

A representative test specimen was used to simulate the performance of the *HYPERFOAM model for different values of N. The specimen was chosen as a right-circular-cylinder with a thickness equivalent to the nominal Pad A thickness (0.365 in, 28.67 mm), and diameter equivalent to the diameter of the acceptance test platens (1.128 in, 9.27 mm). An Abaqus simulation was made using an axisymmetric model with a radius of 14.3 mm and height of 9.27 mm. The bottom edge of the specimen model was fixed in the axial and radial directions to simulate a fixed bottom platen. The top edge of the specimen model was fixed in the radial direction and a constant compressive 10 g acceleration, which is equivalent to the loading used in the analysis that the model was developed for, was applied in the axial direction to simulate a platen compressing the specimen.[5] These

[3] The model developed by this work was used in exploratory analyses, so this option was not considered in the interest of time.

[4] This value differs from the 0.615 g/cc nominal density, and is outside the range of 0.60–0.63 g/cc, listed in the material specification sheet for M9747 (4003047) found in `40030471-4003049_D.pdf`.

[5] A simulation was also run with a 1 g acceleration and the differences were negligible.

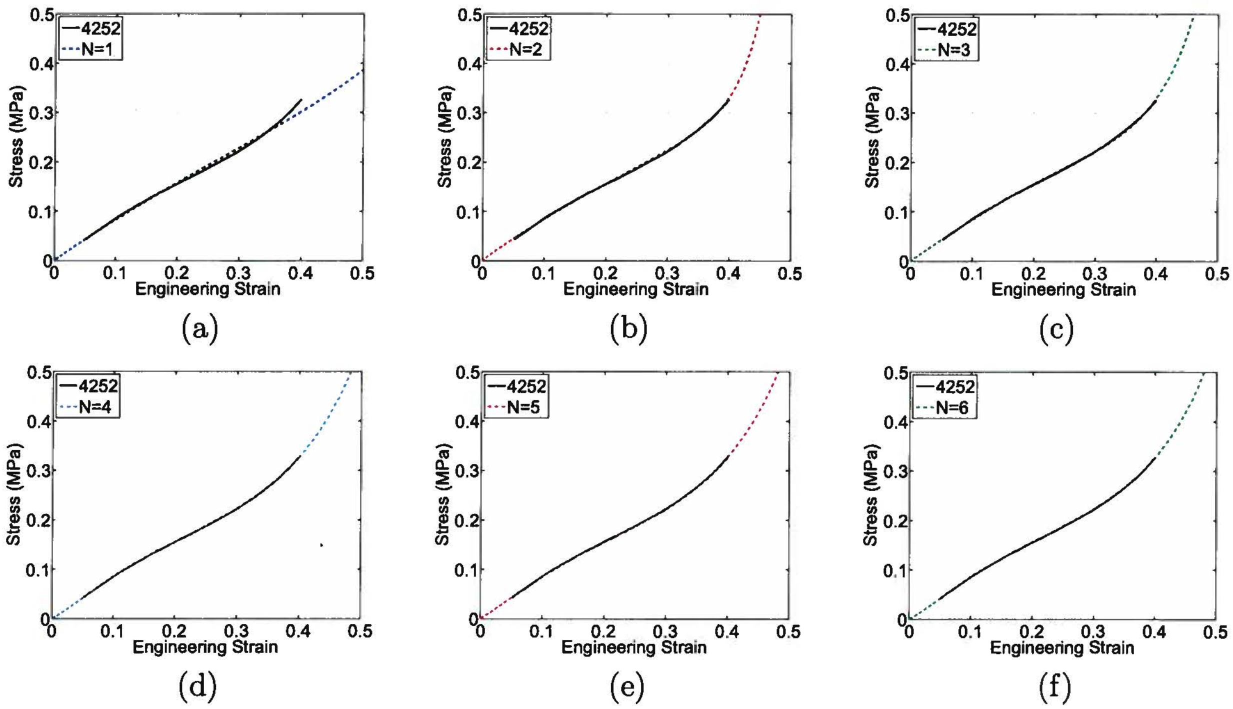


Figure 6: Comparison of the strain-stress data for position one of serial number 4252 and the Abaqus result for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, (d) $N = 4$, (e) $N = 5$, and (f) $N = 6$.

boundary conditions assumed that no slipping occurred between the platens and the specimen. Boundary conditions were also used to fix the radial direction along the axis of symmetry and the outer edge of the specimen, which helped improve the quality of the simulations by resolving issues with element distortion and allowing the simulations to run for higher strains and higher N. The reaction force introduced by the boundary condition on the outer edge was negligible compared to the reaction force along the top of the specimen. Four-node bilinear axisymmetric continuum elements with reduced integration and hourglass control (CAX4R) were used to mesh the part. This simulation was run in Abaqus explicit, as dictated by the analysis that the material model was developed for.

Figure 6 shows comparisons of the strain-stress data for position one of serial number 4252 and the Abaqus results for the six values of N. These plots show the simulation's ability to reproduce the data used to compute the *HYPERFOAM material parameters α_i, β_i, and μ_i. For $N = 1$ the computed strain-stress can reproduce the general behavior of the experimental data, but not the nonlinearity in the data. For $N =$ 2–6 the simulation is able to capture the nonlinear behavior of the data. Table 3 shows the root-mean-square (RMS) error percentage between the experimental strain-stress data used to compute the *HYPERFOAM model parameters and the simulated strain-stress, and lists whether the resulting model is stable or not. The RMS values in the table quantify the observations from the plots in Figure 6 and show that $N = 1$ produces the worst fit, while the fit improves for $N =$ 2–4. No improvement in fit is achieved with $N = 5$, and $N = 6$. The stable models ($N =$1–3) are stable for all loading conditions and strains considered by Abaqus. The unstable models ($N =$4–6) are stable for strains captured by the experimental data, but unstable beyond those strains.

Table 3: Root-mean-square (RMS) error between experimental and simulated strain-stress curves and stability (s: stable, u: unstable) of model for each N.

N	1	2	3	4	5	6
RMS Error (%)	2.66	1.22	0.92	0.10	0.10	0.10
Stability	s	s	s	u	u	u

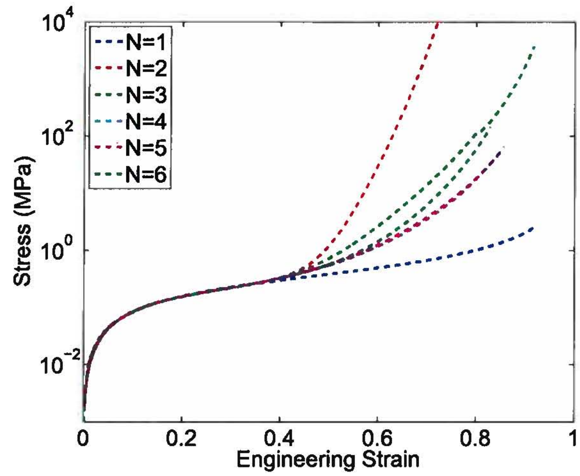


Figure 7: A comparison of the simulated strain-stress curves for all N.

The curves in Figure 6 all exhibit different behavior for strains larger than that of the experimental data. Figure 7 compares the simulated strain-stress curves for all N. The data is plotted on a logarithmic scale for the vertical axis. All the curves exhibit a nonlinear increase in stress for strains higher than about 0.4, which is expected from the *HYPERFOAM model and its qualitative response shown in Figure 5. This higher strain behavior is important because it dictates how the material becomes increasingly stiff at higher strains. For $N = 1$ the material model can undergo very large compressive strains while exhibiting very little stiffening. The $N = 2$ case produces a material model that has the earliest stiffening with respect to compressive strain. For $N = 3$–5 the stiffening behavior is comparable.

Figure 8 shows comparisons of the experimental gap-load data for position one of serial number 4252 and the Abaqus results for $N = 1$–6. These plots show the simulation's ability to reproduce the original gap-load data. Similar to the results shown in Figure 6, the $N = 1$ case captures the general behavior of the data but not its nonlinearities, while the $N = 2$–6 cases do well to match the acceptance test data. These results increase confidence in the assumptions made in modeling the Pad A acceptance test using a representative specimen that is flat, does not extend beyond the platens, and is assumed to not slip relative to the platens. As with the strain-stress data, the simulated gap-load results also capture the stiffening of the pad with trends similar to in Figure 7.

4 Results

The poorest performing model, in terms of capturing the nonlinearity of the acceptance data and becoming stiff at higher strain, was the model with $N = 1$. The models with $N = 5$ and $N = 6$

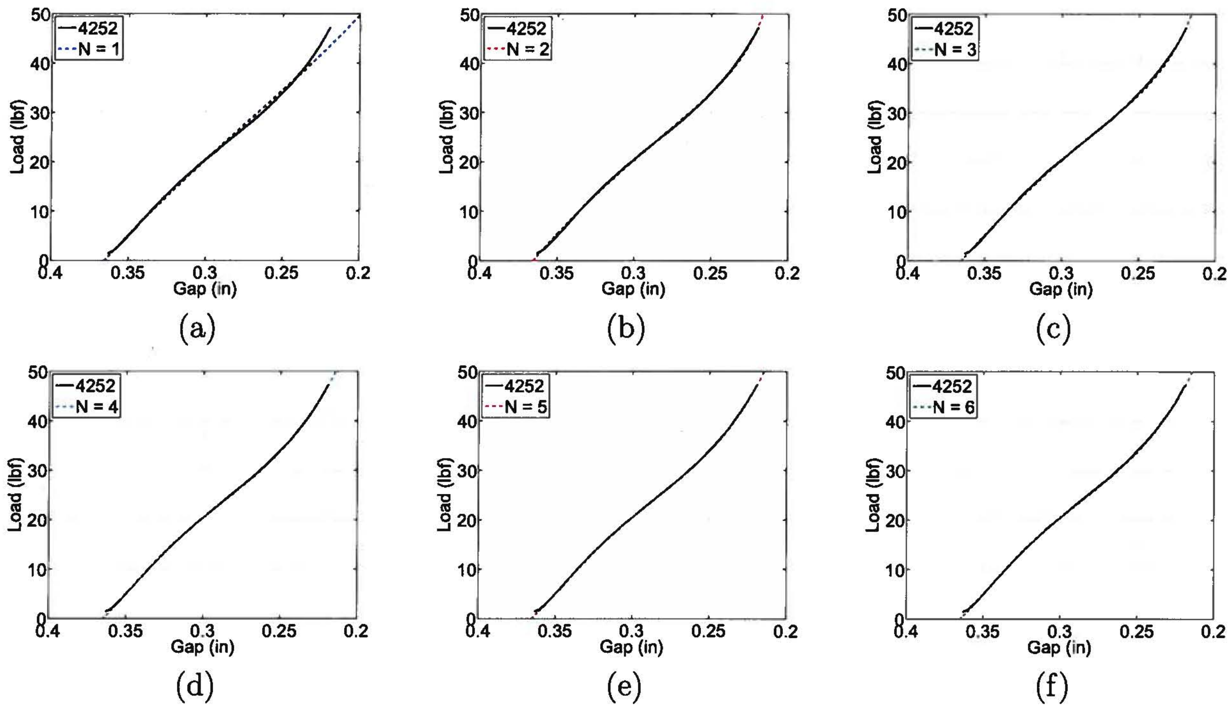


Figure 8: Comparison of the gap-load data for position one of serial number 4252 and the Abaqus result for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, (d) $N = 4$, (e) $N = 5$, and (f) $N = 6$.

provided no improvement in the fit of the strain-stress data, as shown in Table 3, and their behavior beyond a strain of 0.4 did not vary much compared to $N = 4$. Furthermore, the models with N =4–6 were unstable at levels of strain beyond the experimental data. Therefore, $N = 1$, 4, 5, and 6 were removed from consideration. From the two remaining models, $N = 3$ produced the best fit but also stiffened at higher strain as compared to $N = 2$. The model with $N = 2$ has less terms, which may aid computation times.

More experimental data is necessary to properly complete the modeling process. At least, data at compressive strains larger than 0.4 should be used to correctly model the stiffening of the material, instead of relying on the behavior of the model for different N to capture that behavior. Different types of testing—biaxial, planar, volumetric, and simple shear—should be performed in order to improve the capabilities of this model beyond uniaxial compression. Ideally, lateral strain data and/or volumetric test data should be supplied so that Abaqus may compute the Poisson's ratios for each term [2, *HYPERFOAM]. Pressure-volume-temperature (PVT) data would also be valuable.

The models developed in this work assume a single Poisson's ratio for all terms, and furthermore $\nu = 0$. This model was developed for implementation in quasi-static simulations at ambient temperature.

References

[1] Abaqus Analysis User's Manual (6.10), Simulia.

[2] Abaqus Keywords Reference Manual (6.10), Simulia.

[3] Abaqus Theory Manual (6,10), Simulia.

A Pad A Drawing

See next page.

UNCLASSIFIED

NOTES:

1. MATERIAL: CELLULAR SILICONE PER 4003050 OR 4003047.

2▷ MARK DESIGN AGENCY PART NO., MANUFACTURER'S CODE, SERIAL NO., AND DATE CODE (TYPE-1A) PER 9919100, CLASS A-1, .12 INCH CHARACTERS. LOCATE APPROXIMATELY AS SHOWN.

(U) 3. MINIMUM PACKAGING OF ACCEPTABLE PARTS SHALL CONSIST OF SEALING THE PART IN A BAG OF WATER VAPOR PROOF FLEXIBLE BARRIER MATERIAL PER 601477 WITH A MINIMUM OF 2 UNITS OF DESICCANT PER 8500000 FOR EACH 50 GRAMS OF MATERIAL FOR THIS PART.

ACCEPTANCE CRITERIA.
AFTER FINAL ACCEPTANCE PACKAGE AS FOLLOWS, USING THE FOLLOWING MATERIALS:

1	REQ'D	1471207	SUPPORT
1	REQ'D	1471208	COVER
AS	REQ'D	9500070	TAPE
2	REQ'D	8500000	DESICCANT
1	REQ'D	601477	SLEEVE
1	REQ'D	605872	HUMIDITY INDICATOR
1	REQ'D	1445644	LABEL

PLACE PAD ON SUPPORT. PLACE DESICCANT UNDER ROUND CAVITY IN SUPPORT AND SECURE WITH TAPE. SECURE COVER IN PLACE WITH TAPE. PLACE PROTECTED PARCEL WITH HUMIDITY INDICATOR IN SLEEVE AND SEAL SLEEVE. MARK THE FOLLOWING INFORMATION:

(DESIGN AGENCY PART NUMBER)
PAD, COMPRESSION-A
SERIAL (MFG'S CODE, SERIAL NO., AND DATE CODE FROM PART).

4. ALL CORNERS .06 MAX R OR CHAMFER.

5. DELETED.

6▷ PART DIMENSIONS AND TOLERANCES, EXCEPT FOR THE .420±.010 THICKNESS ARE FOR MOLD CONSIDERATION ONLY. FOR OPEN SET UP INSPECTION OF FINISHED PARTS, THE TOLERANCES REFLECTED ON THIS DRAWING SHALL BE MULTIPLIED BY A FACTOR OF TWO (2).

7▷ LOAD-DEFLECTION REQUIREMENTS:
USING A 1.0 SQUARE INCH (1.128 DIA) TEST PLATEN, TEST EACH PART AT THREE (3) POSITIONS LOCATED APPROXIMATELY AS INDICATED ON DRAWING. EACH TEST AREA SHALL BE COMPRESSED ONE TIME TO A THICKNESS OF 0.219±.001 INCH USING A LOADING AND UNLOADING RATE OF 0.050±.005 INCH PER MINUTE. THE AVERAGE OF THE THREE (3) TESTS, AS RECORDED ON THE FIRST COMPRESSION CYCLE OF EACH TEST, SHALL BE AS FOLLOWS:

10.5 PSI MINIMUM AT 0.321±.001 INCH THICKNESS.

60.0 PSI MAXIMUM AT 0.226±.001 INCH THICKNESS. IF 60.0 PSI IS EXCEEDED ON THE FIRST CYCLE LOAD READING, THE PART MAY BE LOAD CYCLED THREE TIMES AND WILL BE ACCEPTABLE IF 55.0 PSI IS NOT EXCEEDED ON THE THIRD LOADING CYCLE WHEN READ AT THE 0.226±.001 INCH THICKNESS.

A SAMPLING PLAN OF (15) UNITS PER LOT IS ACCEPTABLE IN LIEU OF 100% TESTING. IF ALL (15) UNITS MEET LOAD DEFLECTION REQUIREMENTS THE REMAINDER OF THE LOT SHALL ALSO BE ACCEPTED; IF NOT, THE REMAINDER OF THE LOT SHALL BE TESTED 100%.

8. VISUAL REQUIREMENTS:

A. SURFACE DISCOLORATIONS, STREAKS, AIR BURNS, SCORCH MARKS, OR MOTTLED APPEARANCE ARE NOT CAUSE FOR REJECTION.

B. THERE SHALL BE NO FLECKS OF FOREIGN MATERIAL GREATER THAN 0.20 INCH DIAMETER AND THE TOTAL AREA OF ALL SUCH FLECKS SHALL NOT EXCEED 0.16 SQUARE INCH. THE TOTAL LENGTH OF ALL EMBEDDED HAIRS SHALL NOT EXCEED 2.0 INCH IN LENGTH.

C. THERE SHALL BE NO CRACKS OR TEARS, AND NO VOIDS WITH A DIMENSION GREATER THAN 0.10 INCH.

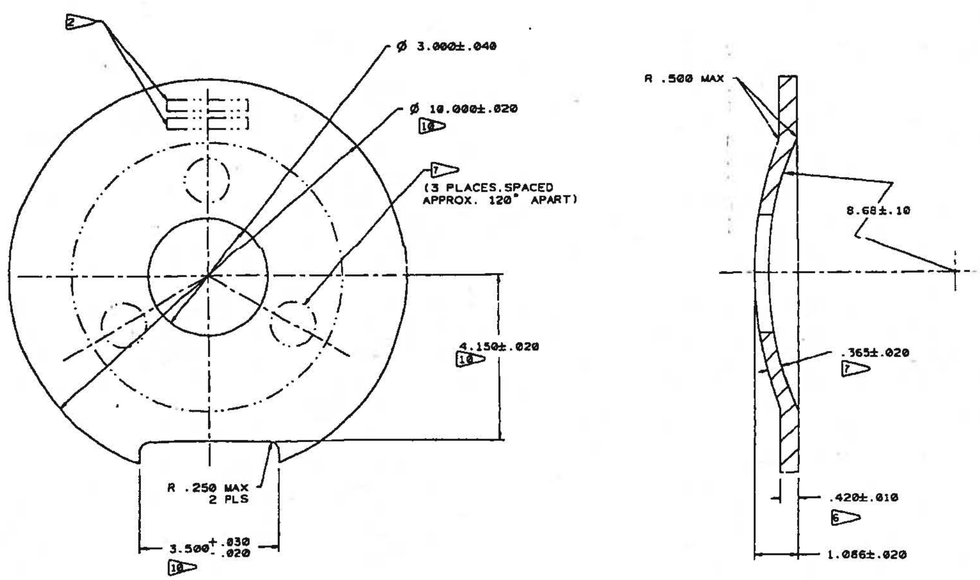
D. THE TOTAL OF ALL DARK AREAS OF INTERNAL DISCOLORATION SHALL NOT EXCEED 6.8 SQUARE INCHES.

9. ALL DIMENSIONS NOT FLAGNOTED CONTROLLED BY MD321889-700.

10▷ DIMENSIONS CONTROLLED BY CERTIFIED TOOL SR321889-002.

DESIGN AGENCY CONTROL NO	ISSUE	SHEET ZONE	DESCRIPTION	PREP	DATE	CHKR	APVD
AY321889-001	W		J. NICHOLS MC5KC B. CONNORS 5311 K. MCKEEHAN MB2KC 960629KC C REV 1		5-23-96	Nichols	[illegible]

Released 5-28-96 PS



PART CODE	
SHEET 1	TITLE
ISSUE W	PAD A (COMPRESSION) (U)
PART CLASSIFICATION: UNCLASSIFIED	
DRAWING CLASSIFICATION: UNCLASSIFIED	FSCM 14213 · DRAWING NUMBER AY321889
ORIGIN KC-ICE-RV2.11	ORIG SIZE E · TIE SA/KC · DWG REL CODE 2
STATUS KC-	ORIG SCALE 1/1 · SHEET 1 OF 1

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B Matlab Script import_data.m

```
clear all
clc

% import data for 321889

    % use serial numbers from Excel files (ex. 4100, 4137, 4156, ...)
        ser_num  = '4542';

    % choose range of data
        %position 1
        col1   = 'B';         % column
        row1_i = '114';       % first row
        row1_f = '199';       % last row
        range1 = [col1,row1_i,':',col1,row1_f];

        %position 2
        col2   = 'C';         % column
        row2_i = '114';       % first row
        row2_f = '199';       % last row
        range2 = [col2,row2_i,':',col2,row2_f];

        %position 3
        col3   = 'D';         % column
        row3_i = '114';       % first row
        row3_f = '201';       % last row
        range3 = [col3,row3_i,':',col3,row3_f];

    % read data from desired file in desired range

        % construct Excel file file-name
        filename = ['321889_',ser_num,'_Data_Retrieval.xls'];

        % read data for each position
        data1 = xlsread(filename,range1);
        data2 = xlsread(filename,range2);
        data3 = xlsread(filename,range3);

    % create corresponding gap (in) and load (psi) vectors from 'data'
        nALL = genvarname(['data_321889_',ser_num]);

        % position 1
        [gap1,load1] = extract(data1);
        eval([nALL '.p1.gap = gap1;']);
        eval([nALL '.p1.load = load1;']);
        eval([nALL '.p1.range = range1;']);
```

```
    % position 2
    [gap2,load2] = extract(data2);
    eval([nALL '.p2.gap = gap2;']);
    eval([nALL '.p2.load = load2;']);
    eval([nALL '.p2.range = range2;']);

    % position 3
    [gap3,load3] = extract(data3);
    eval([nALL '.p3.gap = gap3;']);
    eval([nALL '.p3.load = load3;']);
    eval([nALL '.p3.range = range3;']);

% save
    save_name = ['321889_',ser_num,'_gap_load.mat'];
    save(save_name,nALL)
```

C Matlab Script extract.m

```
% function to extract gap and load

function [gap,load] = extract(data)

    % create gap (in) and load (psi) vectors from 'data'
    n = size(data,1);

    gap  = zeros(n/2,1);
    load = gap;
    for i = 1:n/2
        gap(i) = data(2*i-1);
        load(i) = data(2*i);
    end
```

D Strain-Stress Curves Using Actual Thickness to Compute Strain

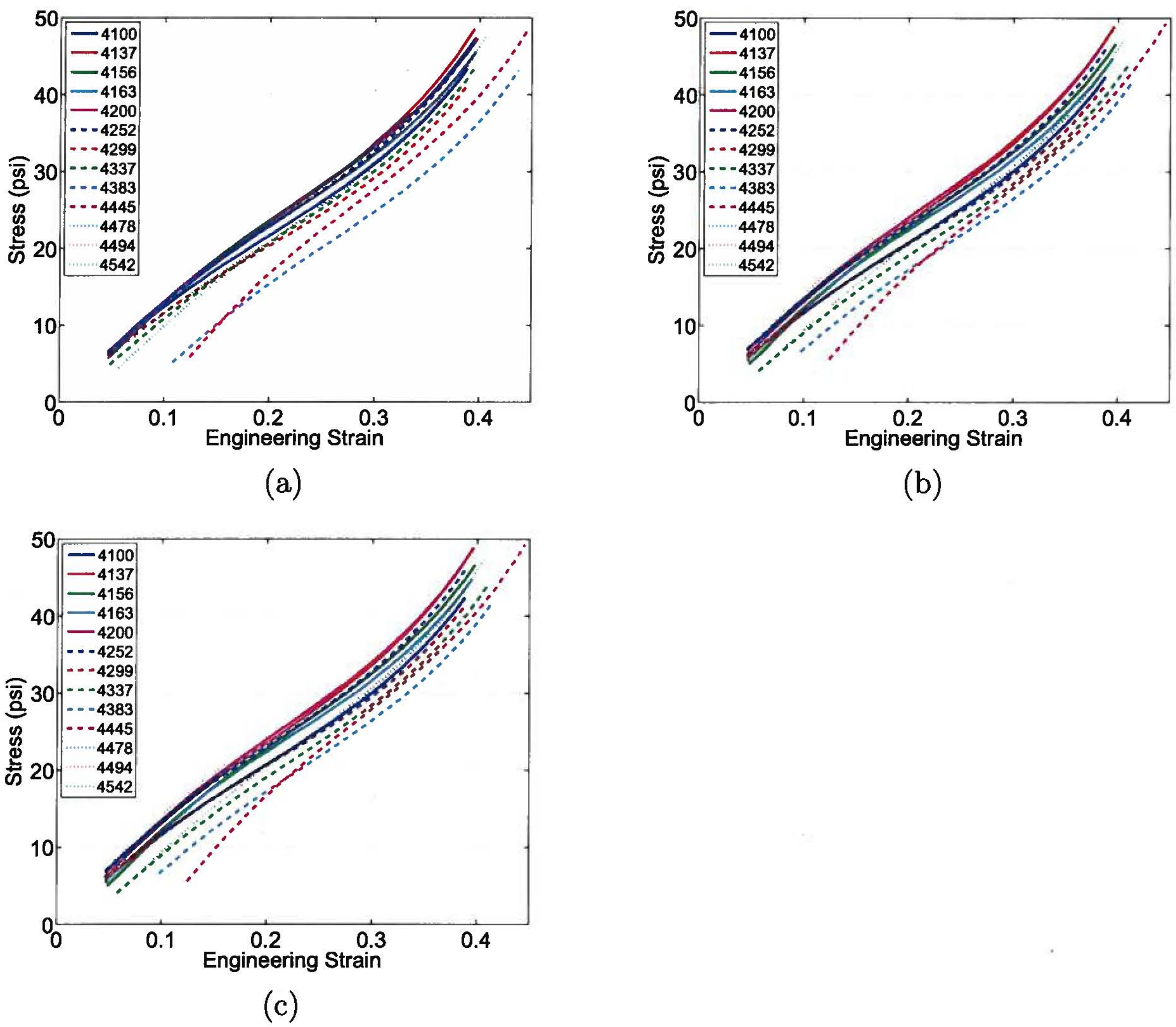

Figure 9: Strain-stress plots for positions (a) one, (b) two, and (c) three, when the actual thickness is used to compute strain.

E Initial Pad Thickness Estimates

Table 4: Initial pad thickness estimates compared to actual thickness reported by KCP.

	Position 1			Position 2			Position 3		
Serial No.	Est. 1 (in)	Est. 2 (in)	Act. (in)	Est. 1 (in)	Est. 2 (in)	Act. (in)	Est. 1 (in)	Est. 2 (in)	Act. (in)
4100	0.439	0.365	0.363	0.403	0.363	0.363	0.397	0.364	0.364
4137	0.426	0.364	0.364	0.425	0.363	0.363	0.427	0.363	0.363
4156	0.470	0.363	0.365	0.395	0.361	0.365	0.414	0.362	0.365
4163	0.424	0.362	0.363	0.413	0.362	0.364	0.416	0.363	0.363
4200	0.460	0.365	0.363	0.430	0.364	0.362	0.425	0.365	0.362
4252	0.446	0.365	0.363	0.440	0.365	0.362	0.421	0.365	0.364
4299	0.441	0.364	0.361	0.439	0.365	0.362	0.420	0.364	0.362
4337	0.435	0.365	0.367	0.430	0.365	0.373	0.424	0.364	0.367
4383	0.431	0.365	0.390	0.426	0.365	0.380	0.432	0.366	0.370
4445	0.440	0.365	0.400	0.440	0.364	0.400	0.437	0.365	0.400
4478	0.432	0.366	0.364	0.440	0.366	0.362	0.432	0.366	0.364
4494	0.449	0.367	0.365	0.448	0.366	0.364	0.434	0.367	0.365
4542	0.434	0.366	0.374	0.430	0.365	0.375	0.436	0.365	0.374

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F Input to Abaqus for *HYPERFOAM Model

```
** M9747
** (model based on KCP Pad A experimental data from position one of serial number 4252)
** (length = mm, mass = Mg, time = s, stress = MPa)
*MATERIAL, NAME=cell-sil
*DENSITY
0.639E-9
*HYPERFOAM, N=2, TEST DATA INPUT, POISSON=0.0
*UNIAXIAL TEST DATA
   -0.0433,   -0.0521
   -0.0519,   -0.0616
   -0.0600,   -0.0712
   -0.0684,   -0.0808
   -0.0767,   -0.0907
   -0.0846,   -0.1003
   -0.0924,   -0.1099
   -0.0998,   -0.1195
   -0.1071,   -0.1293
   -0.1142,   -0.1389
   -0.1209,   -0.1485
   -0.1277,   -0.1581
   -0.1341,   -0.1677
   -0.1403,   -0.1775
   -0,1466,   -0.1871
   -0.1528,   -0.1967
   -0.1589,   -0.2063
   -0.1650,   -0.2162
   -0.1711,   -0.2258
   -0.1773,   -0.2353
   -0.1834,   -0.2449
   -0.1900,   -0.2548
   -0.1964,   -0.2644
   -0.2030,   -0.2740
   -0.2099,   -0.2836
   -0.2168,   -0.2934
   -0.2244,   -0.3033
   -0.2322,   -0.3126
   -0.2401,   -0.3222
   -0.2486,   -0.3321
   -0.2575,   -0.3416
   -0.2668,   -0.3512
   -0.2770,   -0.3608
   -0.2879,   -0.3707
   -0.2995,   -0.3803
   -0.3125,   -0.3899
   -0.3260,   -0.3995
```