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Albuquerque, New Mexico 87185

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to: M. Guthrie

from: E. Corona

subject: MLEP-Fail calibration for 1/8 inch thick cast plate of 17-4 steel

Introduction

The purpose of the work presented in this memo was to calibrate the Sierra material model *Multilinear Elastic-Plastic Hardening Model with Failure* (MLEP-Fail) for 1/8 inch thick cast plate of 17-4 steel. The calibration approach is essentially the same as that recently used in a previous memo [1] using data from smooth and notched tensile specimens. The notched specimens were manufactured with three notch radii $R = 1/8$, $1/32$ and $1/64$ inches. The dimensions of the smooth and notched specimens are given in the prints in Appendix A. Two cast plates, Plate 3 and Plate 4, with nominally identical properties were considered.

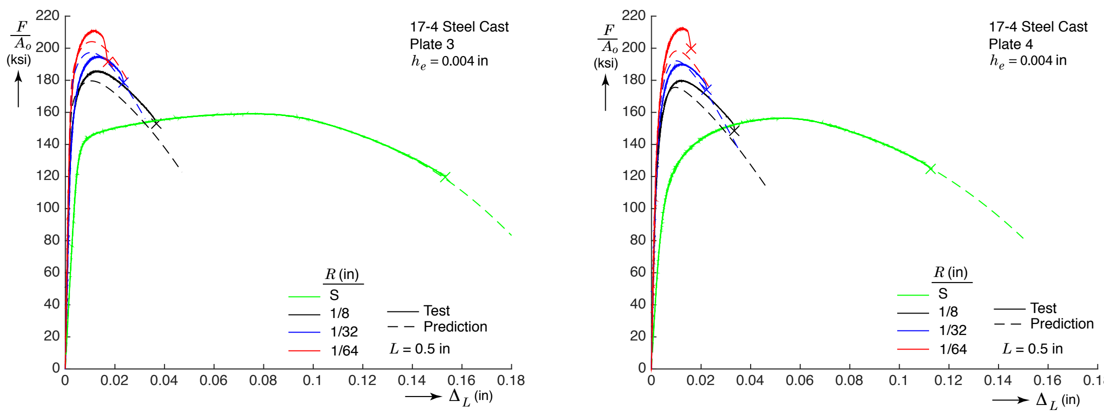
Tensile Test Data

Smooth Specimens

All smooth specimens were quasi-statically pulled to failure at a nominal strain rate of approximately 1.6×10^{-4} s^{-1}. Figures 1 (a) and (b) show the engineering stress vs. strain curves in solid line (labeled "S") obtained from the tests for each of the two plates. The axial displacement was measured with an extensometer with one inch gage length. Clearly in spite of nominally being the same material, the shapes of the curves are somewhat different.

Notched Specimens

The notched specimens were pulled with a nominal speed of 0.05×10^{-3} inches per second. In each test, the axial displacement across the notch (Δ_L)was measured with two extensometers, opposite to each other across the thickness. The gage lengths of the two extensometers (L) were one and 1/2 inches. Figure 1 shows the measured tensile load-deflection responses in solid lines using the 1/2 inch extensometer. The force F has been normalized by the initial,



(a) (b)

Figure 1. Measured and calculated load-deflection curves for smooth and notched specimens. (a) Plate 3 and (b) Plate 4.

nominal cross-sectional area of the notch (A_o). As expected, as the notches get sharper, the displacement to failure decreases and the maximum load increases.

Calibration

Hardening Function

The calibration of the hardening function was obtained using the script developed by Tim Shelton (1542), which utilizes an implicit quasi-statics finite element model of the specimen's test section. The form of the hardening function is multilinear. The basic properties of the engineering stress-strain curves for Plate 3 and Plate 4 curve are given in Table 1. The simulations used selective deviatoric elements.

It is well known that the determination of the hardening function can depend on the size of the element (h_e) if the specimen necks. Figure 2 shows the calibrated true stress vs. strain curve, or hardening curve, using three models of the uniaxial specimens with element sizes of 0.02, 0.01 and 0.004 inches. As expected, the smaller the element, the higher the true stresses (σ_t) in the fit. The hardening functions obtained with $h_e = 0.01$ in. were adopted for the calibration procedure of the failure criterion. The inputs for Sierra/SM are shown in Appendices B and C for Plate 3 and Plate 4.

Table 1. Basic properties of fitted engineering stress-strain curve.

Plate	Young's Modulus (Msi)	Poisson's Ratio [not measured]	0.2% Yield Stress (ksi)	Ultimate Stress (ksi)	Failure Strain
3	29	0.3	139	159	0.153
4	26	0.3	110	156	0.113

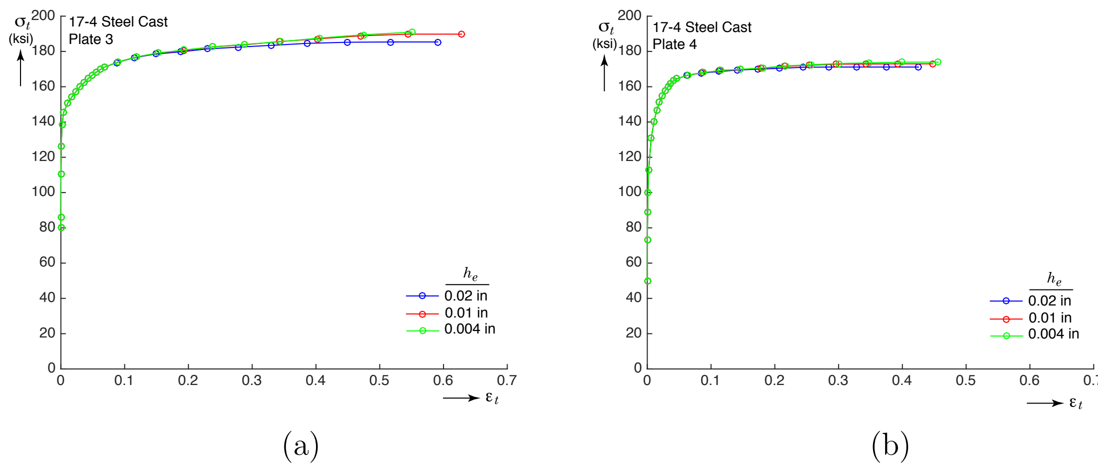


Figure 2. Hardening functions as function of element size. (a) Plate 3 and (b) Plate 4.

Failure Criterion

The calibration of the failure criterion is based on data obtained from tension tests conducted on smooth and notched specimens. The first step is to simulate the notched tension tests using the hardening function chosen above. For consistency, the element size in all subsequent simulations was 0.004 in. Figures 1(a) and (b) show the results of the simulations for Plates 3 and 4 in dashed lines. Whereas the simulation results for the smooth specimens are very close, as expected, the results for the load-deflection responses of the notched specimens were not as good when compared to the test data. The trends are correct, but the predicted peak loads are lower than the test measurements for the specimens with notch radii of 1/8 and 1/64 in. The reasons for the discrepancy have not been determined. Up to this point no failure criterion has been used in the simulations.

The failure criterion in the MLEP-Fail model (the tearing parameter) assumes that the material accumulates damage (t_p) according to

$$t_p = \int_0^{\varepsilon} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^m d\varepsilon_p \tag{1}$$

where <> are Macaulay brackets, σ_1 and σ_m are the maximum principal and mean hydrostatic stresses, and $d\varepsilon_p$ is an infinitesimal increment in equivalent plastic strain. The upper limit of integration represents the current value of equivalent plastic strain. The parameters of the model to be calibrated include the failure exponent, m and the critical value of t_p when material failure occurs, given by t_p^{crit}. The objective of the calibration procedure is to find values for m and t_p^{crit} to best match the failure displacements in the tests.

Procedure

The calibration procedure consists of measuring the values of Δ_L^* in the tension tests at which failure occurred. The next step consists of running finite element models of the tension tests on smooth and notched specimens and keeping a record of the values of σ_1, σ_m and ε_p at each solution step for the elements likely to be most critical. These elements are located in the narrowest part of the notches, or neck in the case of the smooth specimen. The selective deviatoric elements used have 8 integration points. In the calibration procedure, the average values of σ_1, σ_m and ε_p over the 8 integration points were used to calculate t_p. Models with $h_e = 0.004$ gave reasonably well converged results for even the sharpest notch used here, as shown in a previous memo [2]. Once the simulations are done, the values of σ_1, σ_m and ε_p can be used in a simple script to calculate t_p at all critical elements, given a guess of m. The value of t_p^{crit} can then be determined by trial and error by minimizing the difference between the values $\bar{\Delta}_L$ calculated from the guessed values of the two parameters above and the corresponding measurements from the tests. Here, the objective function to be minimized is

$$e = \sum_1^N \left| \frac{\bar{\Delta}_L - \Delta_L^*}{\Delta_L^*} \right|, \tag{2}$$

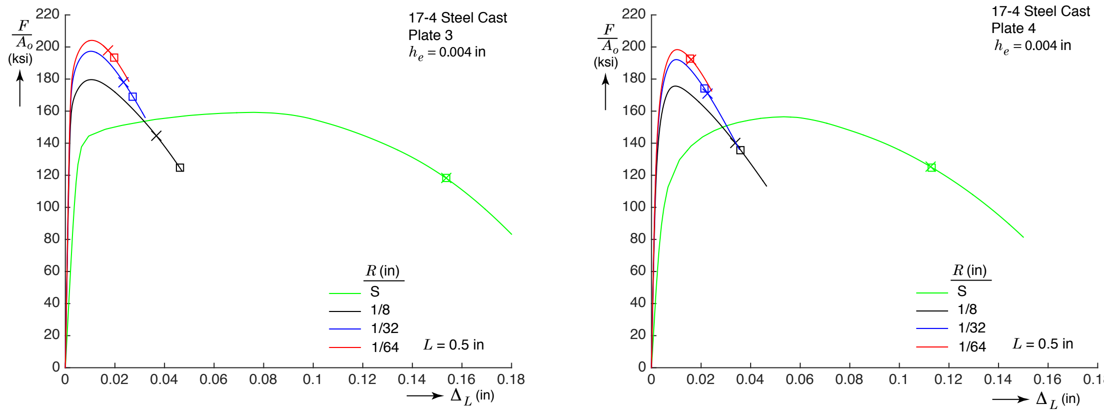
where N is the number of calibration tests considered, which is four in the present calibration.

Results

The simple, traditional method of using a constant value of equivalent plastic strain based on the failure of a smooth uniaxial specimen will be considered first. Note that the constant equivalent plastic strain failure criterion is equivalent to the tearing parameter in (1) with $m = 0$. Figure 3(a) and (b) show the result of applying this criterion to the simulation of the notched tension tests for Plates 3 and 4. The figures show plots of the calculated load vs. deflection curves for all specimen geometries. The symbol $\times$ marks the displacement at which failure occurred in the tests while the symbol $\square$ represents the point at which failure would be predicted based on equivalent plastic strain. The two symbols necessarily coincide for the smooth specimen. From here, the critical value of equivalent plastic strain was $\bar{\varepsilon}_p = 0.83$ for Plate 3 and 0.595 for Plate 2. Note that the simulations of pulling the notched specimens overestimate the displacements at failure for Plate 3 but are very close to the failure data from the tests for Plate 4.

Minimizing the objective function in (2) should give the optimum values of m and t_p^{crit} that best fit the test data. The procedure followed here consisted of fixing the value of m to an integer value and then finding the value of t_p^{crit} that minimized the objective function. This value was found within ± 0.012. The results are shown in Table 2 for both plates. Figure 4 shows the failure points marked on the predicted load-deflection responses for both plates. Clearly the failure points are clustered around the test data and all fits are reasonable, which brings up the question: which one should be chosen? One approach is to pick the ones that gave the overall lowest value of the objective function. If this is the case then the best fits are $m = 3$ with $t_p^{\text{crit}} = 1.80$ for Plate 3 and $m = 1$ with $t_p^{\text{crit}} = 0.80$ for Plate 4, respectively.

The issue of which fit could be potentially more appropriate can not be categorically settled with the information that we have so far. Although the calculated failure points in Fig. 4 are clustered around the test data, there are significant differences in the failure details, similar to those discussed in [1].

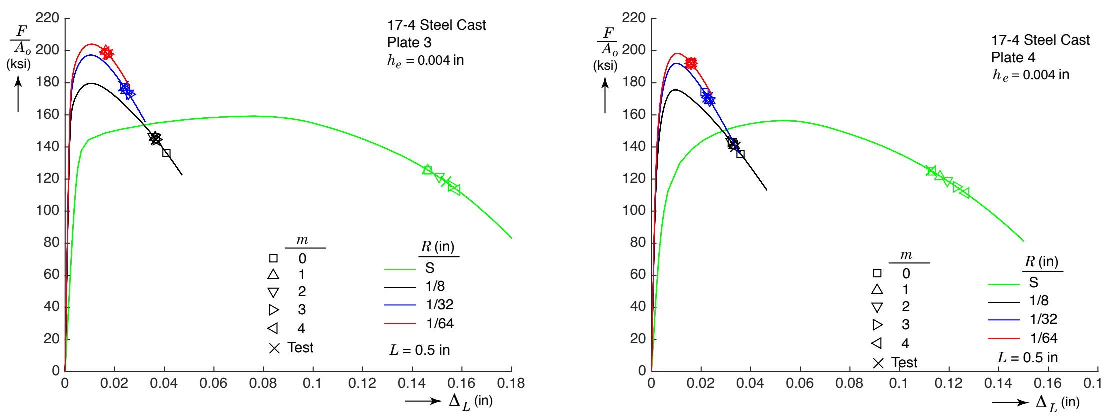


(a) (b)

Figure 3. Comparison of the failure points between test data and predictions by the constant equivalent plastic strain at failure criterion when calibrated to match failure data in a uniaxial tension test. (a) Plate 3 and (b) Plate 4.

Table 2. Combinations of critical tearing parameter and failure exponent that fit the test data reasonably well for meshes with $h_e = 0.004$ and 0.015 inches.

Plate 3		Plate 4	
m	t_p^{crit}	m	t_p^{crit}
0	0.70	0	0.60
1	0.85	1	0.80
2	1.18	2	1.10
3	1.80	3	1.63
4	2.67	4	2.55



(a) (b)

Figure 4. Comparison of failure points for the calibrations presented in Table 2. (a) Plate 3 and (b) Plate 4.

Validation

The results of the calibration were used in Sierra/SM models that calculate the value of the tearing parameter independently of the calibration. All cases for Plate 3 with $m = 2$ and selected results for plates 3 and 4 with $m = 4$ were used to compare the results of the calibration agains the Sierra results. In all cases the agreement was very good. The failure points were all either the same or within one increment in the solution.

Summary and Conclusions

This work concentrated on the calibration of Sierra/SM's MLEP-Fail model for cast 17-4 steel plates with nominal thickness of 1/8 inch. Multilinear forms of the hardening function were obtained employing the script developed by Tim Shelton for this purpose. The curves obtained using the element sizes considered here were very close, but bigger elements could give rise to more substantial differences. Ideally, the smaller the element, the more representative the fit should become of the actual behavior, but it comes at the cost of increased computational time.

The calibration of the failure model (tearing parameter) was conducted based on failure data from smooth and notched tension specimens. The calibration of the failure model was not unique given the data available. The reason for the non-uniqueness is insufficient data. The solution to this issue is to obtain other failure points that are removed from the range of triaxialities achieved in these tests. A possible test is a low-triaxiality, shear dominated test. The feasibility and utility of such tests are currently being investigated.

The calibration of the failure criterion also depends on the element size used to model the specimens [1]. This is an important observation because the combination of geometry and element size used in applications can significantly influence the loads at failure, as has been shown in many previous studies. In other words, the fits obtained here may need to be adjusted depending on the characteristics of models used in applications.

In conclusion, a recommendation for the use of the failure criterion would be to use the fits with $m \leq 2$ since higher values of m give very high values of equivalent plastic strain for shear dominated states of stress. In addition, one must be mindful of the element size used in the applications. Obviously the current state of the calibration does not put guarantee accuracy in predicting ductile failure. Given that demands for failure prediction by computational means will continue, gahtering experience in the calibration and use of ductile failure models will in time improve our abilities to deliver more credible failure assessments. Hopefully, the development of other test geometries to explore a larger range of triaxiality will allow for better calibrations.

Acknowledgments

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on notched specimens. Jack Heister produced the specimen drawings and coordinated the manufacture of the samples.

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References

[1] Corona, E., MLEP-Fail calibration for 1/8 inch thick plate of 13-8 PH steel in the H1150 condition, Memo to D. VanGoethem, November 10, 2017.

[2] Corona, E., Evaluation of Planar Notched Specimens for Failure Model Calibration, Memo to D. VanGoethem, May 9, 2017.

Appendix A: Specimen Prints

Figures 5 and 6 show the manufacturing prints of the specimens used.

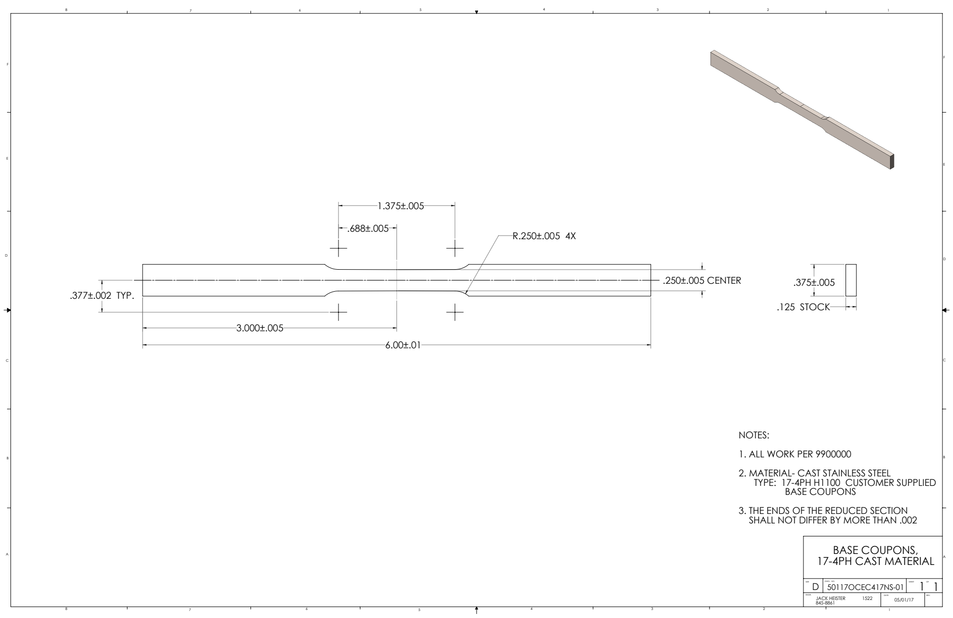
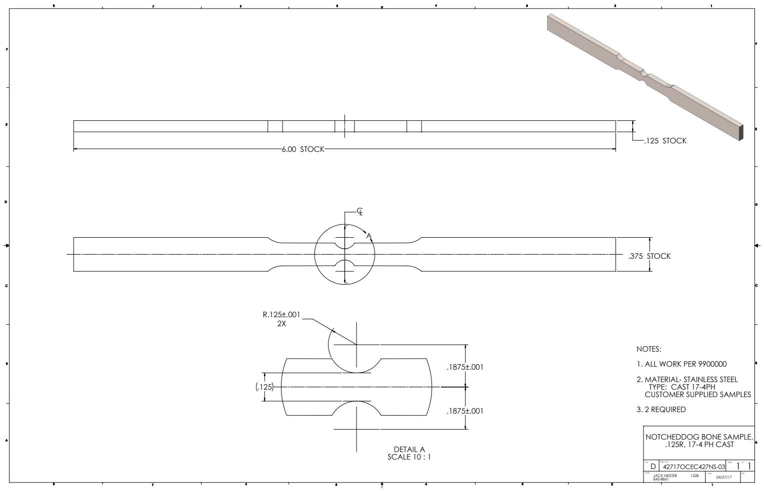
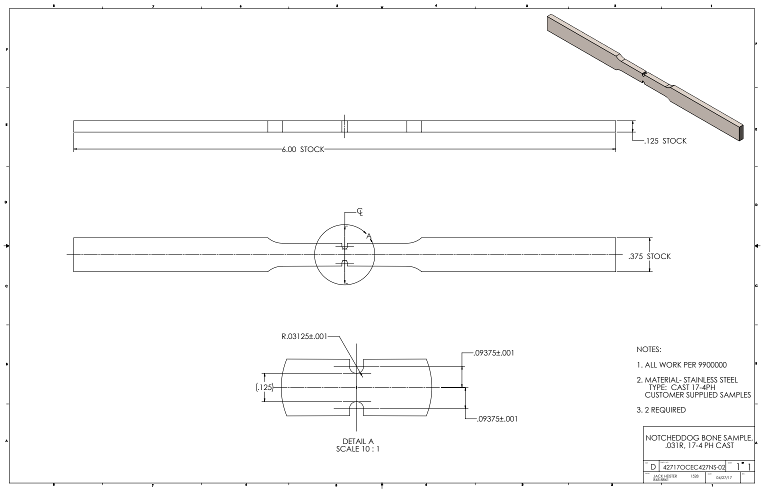


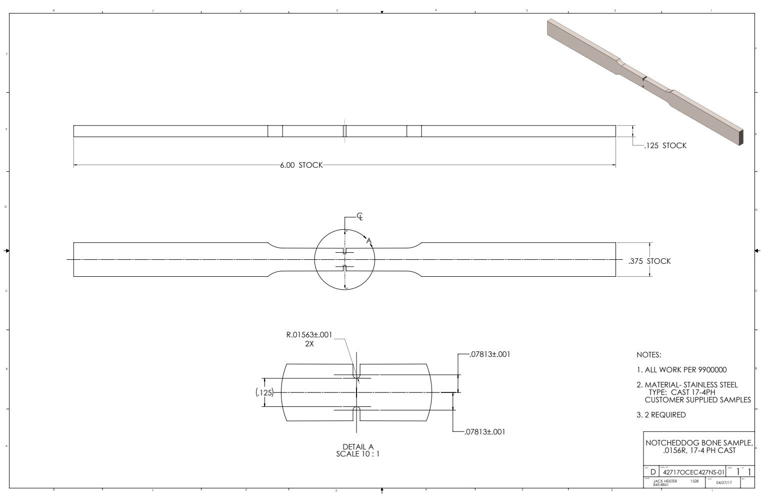
Figure 5. Smooth specimen.



(a)



(b)



(c)

Figure 6. Notched specimens. (a) 1/8 inch notch radius, (b) 1/32 inch notch radius, (c) 1/64 inch notch radius.

Appendix B: Material properties for Plate 3.

```
   begin definition for function function_174P3
    type is piecewise linear
    begin values
0.0, 80000.0,
3.39683974561e-05, 85910.5011574,
0.000180884719535, 110556.400198,
0.000628233034888, 126479.23844,
0.00171433687783, 138306.123473,
0.0043632784702, 145517.387819,
0.010793835555, 150744.631178,
0.017243740696, 154197.873075,
0.02365543327, 157121.045437,
0.0299998795888, 160013.559375,
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0.342271605887, 185582.995366,
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0.469442920884, 188847.37118,
0.544150331618, 189806.207946,
0.628485021762, 189806.207946,
5.000000000000, 189806.207946,
    end values
  end definition for function function_174P3


  #---------- Materials ----------

  begin property specification for material 17_4P3
    density = {0.29/(32.174*12)}
    begin parameters for model ml_ep_fail
      youngs modulus =  29.e6
      poissons ratio =  0.3
```

```
      yield stress =  80000.0
      beta = 1.0
      hardening function = function_174P3
      critical tearing parameter = 1.18
      critical crack opening strain = 0.0
      failure exponent = 2.
    end parameters for model ml_ep_fail
  end property specification for material 17_4P3
```

Appendix C: Material Properties for Plate 4.

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  begin definition for function function_174P4
    type is piecewise linear
    begin values
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0.000187917904561, 73020.1770589,
0.000576031007582, 88853.272088,
0.00113435696231, 100241.740848,
0.00223281105994, 112962.703773,
0.00618322971799, 130798.987318,
0.0104456285533, 140092.461169,
0.0147965681476, 146547.16597,
0.0192007284036, 151185.768103,
0.0236210961064, 154876.374449,
0.0280628669071, 157725.797148,
0.0325134063266, 160007.062639,
0.0369601474522, 161938.833201,
0.0414856622031, 163374.594294,
0.0461441155758, 164494.526855,
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0.447705839796, 172973.772207,
5.000000000000, 172973.772207,
    end values
  end definition for function function_174P4
```

```
#---------- Materials ----------

begin property specification for material 17_4P4
  density = {0.29/(32.174*12)}
  begin parameters for model ml_ep_fail
    youngs modulus =  26.e6
    poissons ratio =  0.3
    yield stress =  50000.0
    beta = 1.0
    hardening function = function_174P4
    critical tearing parameter = 1.10
    critical crack opening strain = 0.2
  end parameters for model ml_ep_fail
end property specification for material 17_4P4
```

Internal Distribution:

J. Gearhart	1528
A. Jones	1528
M. Guthrie	1553
E. Fang	1554
B. Lester	1554
W. Scherzinger	1554
D. VanGoethem	1554
J. Ostien	8343