National Science Foundation
Earth-Energy Systems
IGERT

A Physics Based Model for the Ductile Failure of Metals

Geoffrey F. Bomarito and Derek H. Warner

Structural Reliability Program

Introduction

From the millions of miles of aging pipelines to the intricate workings of a wind turbine, ductile metals are ubiquitous. Of paramount importance in both the design and upkeep of structures composed of these materials is a predictive capability for their failure.

[1]

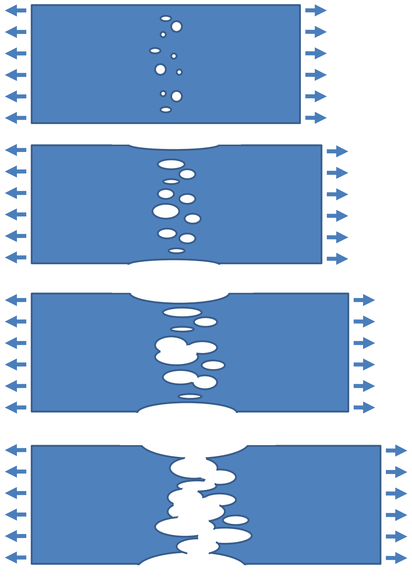
[2]

Traditionally, the failure of metals is modeled using phenomenological relationships that are fit to experimental testing data. In contrast, a **physics based failure model**, consistent with both the underlying failure mechanisms and experimental data, can provide a more robust and transferable alternative. Physics based models:

- rely less on expensive and complex experimental tests
- help illuminate important microstructural phenomena
- can extend the range of model applicability beyond the limits of experimental tests

Background

Although failure of metals occurs on a scale that is visible by the human eye, it is really the microscopic structure of the material that controls its occurrence. Thus, physics based models that **simulate the microstructure** can offer great insight into how and why failure occurs. The microstructure of ductile metals consists of countless **microscopic voids**. The mechanism for failure follows the stages below:



Micro-voids **nucleate** from particles or different phases in the material.

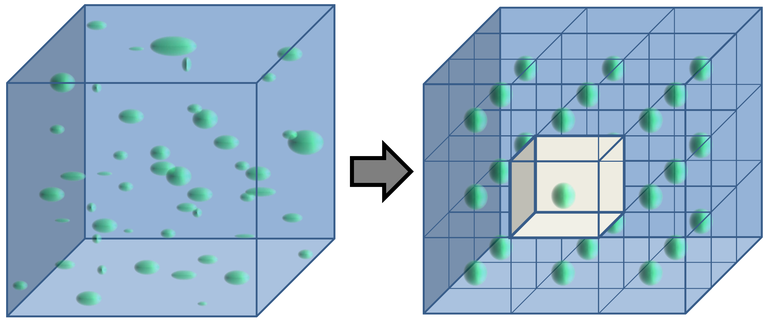
The voids **grow** significantly through loading of the material.

Eventually, the voids start to **coalesce** with each other.

Finally, failure occurs through large scale **fracture** of the material.

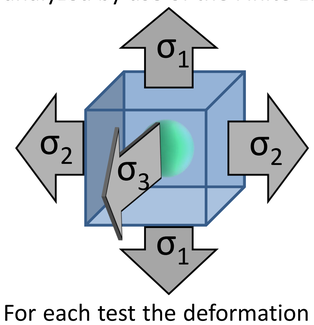
Methods

In the material, the size, spacing, and orientation of the **micro-voids have random distributions.** For simplification, a model was created that assumes the voids are periodically spaced; it has the same void volume fraction and average void size as the real microstructure.



True microstructure **Model microstructure**

By modeling the distribution of voids as a periodic array, **a single unit cell can be used to simulate the entire microstructure**. The unit cell is analyzed by use of the Finite Element (FE) method.



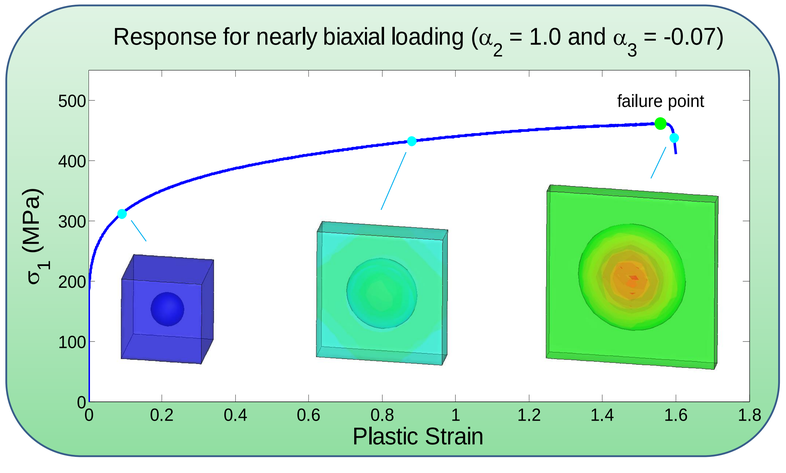
Deformations are applied to each face such that the stress loading ratios α_2 and α_3 are kept constant.

$$\alpha_2 = \frac{\sigma_2}{\sigma_1} \qquad \alpha_3 = \frac{\sigma_3}{\sigma_1}$$

$$\sigma_1 \geq \sigma_2 \geq \sigma_3$$

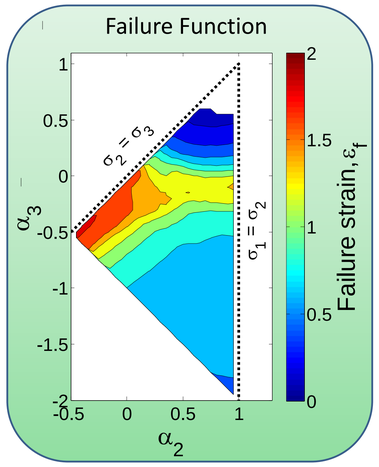
Many simulations, each with a given set of load ratios, were performed.

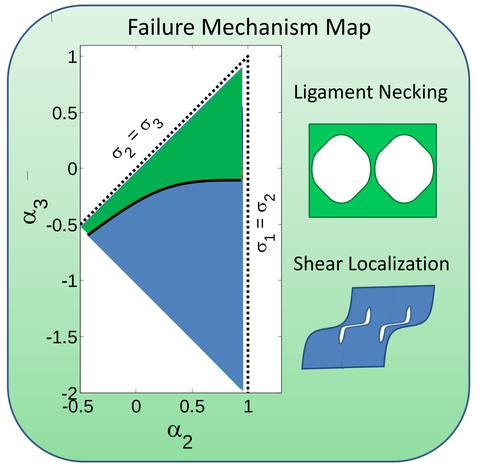
For each test the deformation is increased until failure occurs. **The failure point is defined as the point at which a maximum stress state is reached.** The plastic strain at which failure occurs is called the **failure strain (ε_f).** The failure point for each simulation is recorded and combined to give **failure as a function of loading.**



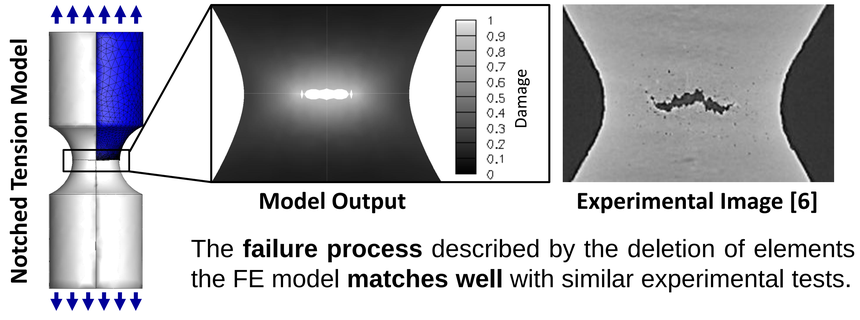
Results

The resulting failure function has two distinct regions that are separated by a ridge of high failure strain. The two regions correspond to two different failure mechanisms: **ligament necking** and **shear localization.** The shape of the failure function matches well with experimental data [3][4][5].





The failure function is incorporated into a larger scale FE model of a round notched tension test. The **failure function is used to predict the failure of the individual elements** of the model.



The **failure process** described by the deletion of elements in the FE model **matches well** with similar experimental tests.

The rate at which the process occurs, however, is significantly different than experiment [7]. The proposed **model over predicts the ductility** (elongation to failure) of the notched bar **by nearly 60%**. The reasons for the over prediction were investigated and it was found that:

- Effects of **heterogeneity** in the microstructure account for most of the error.
- Absence of **nucleation** in the model accounts for most of the remaining error.

Conclusion

The proposed physics based model is able to capture the qualitative effects of the failure of metallic materials; however, the model over predicts ductility. Further refinement and the incorporation of nucleation and heterogeneity will greatly enhance the model's predictive capabilities. The model will offer a valuable supplement to experimental tests and will offer increases in efficiency, reliability, and applicability of metals and their alloys.

References:: [1] Engineers Australia, Url: http://www.engineersaustralia.org.au/sites/default/files/fracture_control.jpg .
[2] Rochester Solar technologies, Url: http://www.solarrochester.com/Wind%20Turbine%20information.asp .
[3] G. R. Johnson and W. H. Cook, Engineering Fracture Mechanics 21, 31 (1985), ISSN 0013-7944.
[4] Y. Bao and T. Wierzbicki, International Journal of Mechanical Sciences 46, 81 (2004), ISSN 0020-7403.
[5] I. Barsoum and J. Faleskog, International journal of solids and structures 44, 1768 (2007).
[6] C. Landron a, E. Maire a, J. Adrien a, O. Bouaziz, Optical Measurements, Modeling, and Metrology, Volume 5 (2011).
[7]J. Zhou, X. Gao, M. Hayden, and J. A. Joyce, Engineering Fracture Mechanics (2012).