Cast Iron Fatigue

Professor Stephen D. Downing
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

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Outline

1. Comparison to Wrought Metals
2. Conceptual Models
3. Stress-Strain Behavior
4. Fatigue Behavior
Cast Iron vs. Wrought Steel

- Cast iron is a composite material
  - Steel matrix
  - Graphite particles of different shapes
- Graphite makes cast iron
  - More prone to surface cracking
  - Stiffer in compression than tension
- New methods need to account for differences
Microstructure

- **Nodular Iron**
  - Spheroidal graphite
  - Fairly consistent size
  - Behavior similar to steel

- **Gray Iron**
  - Graphite flakes
  - Behavior very different from steel

- **Compacted Flake Iron**
  - Intermediate behavior
Strain-Life – Wrought Metals

Major Assumptions:

- Local stresses and strains control fatigue behavior
- Accurate determination of $K_f$
Similitude

\[ \Delta \sigma, \Delta \varepsilon \]

Plastic Zone

\[ \Delta S \quad \text{Nominal stress} \]

\[ \Delta \sigma, \Delta \varepsilon \]

\[ \Delta \sigma, \Delta \varepsilon \]
Fatigue Analysis: Strain-Life

Material Data
- $\varepsilon N$ curve
- $\sigma \varepsilon$ curve

Component Geometry
- $K_f$

Service Loading
- $\Delta S, S_m$

Analysis

Fatigue Life Estimate
Cyclic Hardening / Softening

(a) Fully annealed
$$\Delta \varepsilon = 0.0084$$
$$2N_f = 8060$$ reversals

(b) Partially annealed
$$\Delta \varepsilon = 0.0078$$
$$2N_f = 4400$$ reversals

(c) Cold worked
$$\Delta \varepsilon = 0.0099$$
$$2N_f = 2000$$ reversals
Stable Hysteresis Loops

\[ \sigma, \frac{\Delta \sigma}{2} \]

\[ \varepsilon, \frac{\Delta \varepsilon}{2} \]

\[ \Delta \sigma \]

\[ \Delta \varepsilon \]
Stable Hysteresis Loops

\[ \frac{\Delta \sigma}{2} \]

\[ \frac{\Delta \varepsilon}{2} \]
During cyclic deformation, the material deforms on a path described by the cyclic stress strain curve:

\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left( \frac{\Delta \sigma}{2K'} \right)^{1/n'}
\]
Cyclic Stress Strain Curve

- 350 MPa
- 0.01
- 2024-T4
- 7075-T6
- Man-Ten steel
- SAE 4340 (350 BHN)
- Ti-811
- Waspaloy A
Stable Hysteresis Loop

Hysteresis loop

Cyclic $\sigma \varepsilon$

Masing behavior

Symmetrical
Strain-Life Data $\Delta \varepsilon - 2N_f$

\[ \frac{\Delta \varepsilon}{2} = \frac{\sigma_f'}{E} (2N_f)^b + \varepsilon_f' (2N_f)^c \]

2 Reversals, $2N_f = 1$ Cycle, $N_f$
Cyclic Deformation

Loading history

Stress-strain response
Neuber’s Rule

\[ K_T = \sqrt{K_\varepsilon K_\sigma} \]

\[ K_f^2 \Delta S \Delta e = \Delta \sigma \Delta \varepsilon \]
Mean Stresses

Smith Watson Topper

\[ \sigma_{\text{max}} \frac{\Delta \varepsilon}{2} \]

For \( R = -1 \) loading only,

\[ \sigma_{\text{max}} = \frac{\Delta \sigma}{2} = \sigma_f (2N_f)^b \]

leads to a formulation in terms of the standard strain-life curve

\[ \sigma_{\text{max}} \frac{\Delta \varepsilon}{2} = \frac{\sigma_f^2}{E} (2N_f)^{2b} + \sigma_f \varepsilon_f (2N_f)^{b+c} \]
Elastic-plastic behavior in stress concentrations control fatigue life.

Rainflow counting is used to determine damaging events corresponding to closed elastic-plastic hysteresis loops.

Mean stresses are tracked according to input loading sequences.

Smith-Watson-Topper parameter accounts for mean stress.

Neuber' Rule is used to determine notch root stress and strains.

A new model for stress-strain response is needed.
Gray Iron Hysteresis Loop
Monotonic Behavior – Nodular Iron

**FIG. 6**  EXPERIMENTAL AND PREDICTED MONOTONIC STRESS/STRAIN RESPONSE OF NODULAR IRON
Monotonic Behavior – Gray Iron

Much stiffer in compression

No linear region

FIG. 4  EXPERIMENTAL AND PREDICTED MONOTONIC STRESS/STRAIN RESPONSE OF GRAY IRON
1. Curvature in the tensile stress/strain curve is not only associated with elastic and plastic deformation of the matrix, but is also due to volume increase in the spaces occupied by the graphite.

2. This volume increase is most pronounced on the specimen surface where graphite flakes, oriented perpendicularly to the load can actually crack or debond from the matrix.

3. Gray iron is stiffer in compression than tension because the spaces occupied by the graphite do not see corresponding decreases in volume.
Inspiration

Displacement, $\delta$

Load, $P$

Elastic

Fully Plastic

Elastic - Plastic

$\sigma_{ys}$

$\varepsilon$
Inspiration - Add Broken Bars
Inspiration - Add Broken Bars

Fig. 4 Load/deflection response of bar model with broken elements
Strategy – Divide and Conquer
Problem - Elastic Modulus

![Diagram of stress-strain curve with labels](image-url)
Secant Modulus

\[(E_S)_{linear} = E_0 + m\sigma\]

\[\varepsilon_S = \sigma / (E_S)_{linear}\]

\[= \sigma / (E_0 + m\sigma)\]

\[\varepsilon = \varepsilon_S + \varepsilon_R\]
Remaining Plastic Strain

\[ \varepsilon = \frac{\sigma}{E_0 + m\sigma} + \left(\frac{\sigma}{K}\right)^{1/n} \]

New stress-strain equation

\[ \varepsilon_R = \left(\frac{\sigma}{K}\right)^{1/n} \]

Graph showing stress (MPa) vs. remaining plastic strain.
Monotonic Behavior – Gray Iron

\[ \varepsilon = \frac{\sigma}{E_0 + m_C \sigma} + \left( \frac{\sigma}{K_C} \right)^{1/n_C} \]

\[ \varepsilon = \frac{\sigma}{E_0 + m_T \sigma} + \left( \frac{\sigma}{K_T} \right)^{1/n_T} \]

**FIG. 4** EXPERIMENTAL AND PREDICTED MONOTONIC STRESS/STRAIN RESPONSE OF GRAY IRON
Composite Rule of Mixtures

\[ F = \sigma_m A_m + \sigma_g A_g \]
\[ = \sigma_m (1 - A_g) + \sigma_g A_g \]

Elastic
\[ F = \varepsilon \left[ E_m (1 - A_g) + E_g A_g \right] \]
Bulk Response Like Steel?

- Dominated by steel matrix \( E_m \gg E_g \), \( A_g < 0.25 \)
- Symmetric?
- Masing Behavior?
- Material Memory?

\[
\varepsilon = \frac{\sigma_B}{E_0 + m_B \sigma_B} + \left( \frac{\sigma_B}{K_B} \right)^{1/n}
\]

\[
\Delta \varepsilon = \frac{\Delta \sigma_B}{E_0 + (m_B/2) \Delta \sigma_B} + 2 \left( \frac{\Delta \sigma_B}{2K_B} \right)^{1/n}
\]

\[
(\sigma_B)_i = (\sigma_B)_{i-1} \pm \Delta \sigma_B
\]
Symmetric Area

FIG. 10  HYSTERESIS LOOP HEIGHT VERSUS STRAIN FOR SEVERAL GRAY IRON HYSTERESIS LOOPS SHOWING SYMMETRY OF HYSTERESIS AREA WITH RESPECT TO MEAN STRAIN
Internal Graphite Behavior

- Greater stiffness in compression
- Graphite approaches incompressibility
- Compressive stress is transferred to the inherently stiffer matrix

\[ \sigma_G = (\sigma_M)_C - (\sigma_B)_C \quad \text{if} \quad \varepsilon \leq 0 \]

\[ = 0 \quad \text{if} \quad \varepsilon > 0 \]
Surface Behavior

- Debonded graphite in tension
- Unloading modulus provides evidence
Surface Behavior Equations

\[ E_u = E_0 + m_u \sigma \]

\[ A_{\text{eff}} = \frac{E_u}{E_0} = 1 + \frac{m_u \sigma_{\text{max}}}{E_0} \]

\[ (\sigma_M)_T = A_{\text{eff}} (\sigma_B)_T \]

\[ (\sigma_B)_T = \frac{E_0 (\sigma_M)_T}{E_0 + m_u (\sigma_M)_T} \]

Easier way to get bulk stress
Stress-Strain Model

\[ \sigma = A_{\text{eff}}(\sigma_B + \sigma_G) + (1 - A_{\text{eff}})\sigma_{cc} \]
Crack Closure Stress

\[ \sigma_{cc} = Q(\varepsilon_{\text{max}} - \varepsilon)^q \]

\[ q = -(B_2 / B_1)(\varepsilon_{\text{max}} - \varepsilon') \]

1. If \( |\varepsilon_{\text{max}}| \leq |\varepsilon_{\text{min}}| \), the unloading curve of the hysteresis loop at \( \varepsilon' = \varepsilon_{\text{min}} \) has the same magnitude as the monotonic compressive stress/strain curve at \( \varepsilon' = \varepsilon_{\text{min}} \), and
2. If \( |\varepsilon_{\text{max}}| > |\varepsilon_{\text{min}}| \), the unloading curve of the hysteresis loop at \( \varepsilon' = -\varepsilon_{\text{max}} \) would have the same magnitude as the monotonic compressive stress/strain curve at \( \varepsilon' = -\varepsilon_{\text{max}} \).
Mean Stress

\[ \sigma_{\text{max}} \varepsilon_a = 1.82(N_f)^{-0.25} \]
Life Prediction Procedure

START

CYCLIC STRESS/STRAIN RESPONSE

CLOSED LOOP?

no

yes

MATERIAL PROPERTIES

STRAIN HISTORY

CUMULATIVE DAMAGE ANALYSIS

HISTORY OVER?

no

yes

CALCULATE FATIGUE LIFE

STOP
Stress-Strain Results

Figure 12: Experimental and predicted cyclic stress/strain response of gray iron; $\varepsilon_{\text{max}} = 0.003$, $\varepsilon_{\text{min}} = -0.003$
Stress-Strain Results

FIG. 13  EXPERIMENTAL AND PREDICTED CYCLIC STRESS/STRAIN
RESPONSE OF GRAY IRON; $\varepsilon_{\text{max}} = .003$, $\varepsilon_{\text{min}} = -.001$
Stress-Strain Results

FIG. 14  EXPERIMENTAL AND PREDICTED CYCLIC STRESS/STRAIN
RESPONSE OF GRAY IRON; $\varepsilon_{\text{max}} = 0.001$, $\varepsilon_{\text{min}} = -0.003$
Stress-Strain Results
Model User’s

- John Deere
- Caterpillar
- eFatigue.com
- Safe Technology
- nCode International
Cast Iron Home

The fatigue performance of a particular cast iron depends on the quantity, size, and shape of the free graphite constituent as well as its interaction with the matrix. Tensile and compressive behavior of cast iron can be different. Compressive strength and modulus are greater than the tensile strength and modulus. Fatigue analysis of cast iron requires special considerations of this asymmetric stress strain response. Cast irons may be broadly classified into three types: Ductile iron, compacted graphite or grey iron. Each of these types has different stress strain behavior.

Ductile Iron

In fatigue, graphite nodules, under a tensile load, have been observed to debond from the surrounding matrix. Fatigue cracks initiate not only from nodules but also from casting imperfections such as inclusions, microshrinkage pores, and irregularly shaped graphite clusters. These irregularities initiate cracks at an earlier stage in life than well-formed nodules. As a result, the quality of the casting will have a large influence on the fatigue life of ductile iron castings. Even at long lives, cracks are observed very early in the lifetime of ductile iron.

Compacted Graphite

Compacted Graphite has a graphite configuration between that of ductile iron and gray iron. The fatigue performance is also between that of ductile and gray iron.

Gray Iron

Graphite in gray iron is highly branched and interconnected within a eutectic cell structure. These cell structures are composed of sharp flakes which provide an easy fracture path as well as areas of high stress concentration. Cracks start on the first loading cycle at flakes oriented perpendicular to the applied tensile stress. Since grey iron already contains cracks, it is not very notch sensitive.
Cast Iron Fatigue