STOCHASTIC SIMULATION APPROACH FOR REALISTIC LIFETIME FORECAST AND ASSURANCE OF COMMERCIAL VEHICLE BRAKING SYSTEMS

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Virtual Lifetime Determination

Durability (t-t₀) 10^6 LC

Failure Probability F(t)

Shape parameter b
Agenda

1. Motivation

2. Application example: brake caliper

3. Simulation process

4. Design of Experiments

5. Result evaluation

6. Summary and Outlook
Virtual Lifetime Determination of commercial vehicle braking systems

1. MOTIVATION
1. Motivation

Real durability tests

Identification of specific product properties:
- Failure mechanism
- Lowest and longest cycle times
- Failure distribution
- Control of correct target-engineering by requirements

Scattering produces a characteristic lifetime distribution
1. Motivation

Motivation:
Realistic lifetime prediction through stochastic simulation of stress and strength

- Endurable nominal load amplitude in operation
- Occurring nominal load amplitude on component
- Nominal load cycles $N_{\text{nom}}$ (log)
- Scatter band of endurable load amplitudes in operation
- Scatter band of the load amplitudes occur on the component
- Scatter band of load cycles $N$
- Cumulative density $F(t)$
1. Motivation

- Parameter variations of the product lead to variations in product properties as a result of internal correlations.
- This can cause functional or structural failure and the deterioration of product quality.

Aim: Realistic forecast of time to failure
1. Motivation

**Parametric CAD-Model**
- Mapping the caliper geometry
- Changes in the geometry

**FEA-Simulation model**
- Mapping of damage-related effects
  - Stress amplitudes
  - Strain amplitudes

**Parameter study**
- Automatic simulation of the established DOE
- Statistical evaluation

Source: Dynardo 2015
Virtual Lifetime Determination of commercial vehicle braking systems

2. APPLICATION EXAMPLE BRAKE CALIPER
2. Application example Brake caliper

- Have to withstand high loads in case of overload
- Therefore tested with high loads
- Failures in Low-Cycle-Fatigue range (LCF)

Application example: Brake caliper

- Pressure cylinder dummy
- Brake caliper
- Piston
- Brake disc
- Brake pads

Probability function of lifetime
Weibull
Full data – ML-Estimation

Standardized lifetime
Percent

0.09 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.99

99 98 97 96 95 94 93 92 91 90 89 88 87 86 85 84 83 82 81 80 79 78 77 76 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

99 98 97 96 95 94 93 92 91 90 89 88 87 86 85 84 83 82 81 80 79 78 77 76 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

0,1 0,15 0,2 0,25 0,3 0,35 0,4 0,45 0,5 0,55 0,6 0,65 0,7 0,75 0,8 0,85 0,9
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3. SIMULATION PROCESS
3. Simulation process

Loadcase simulation

Definition of claim and the associated amplitudes

Load definition

Material properties

Stochastic Simulation

for variance determination

Deterioration

Strength

Carrying Capacity

Lifetime distribution

The level of deterioration related stress and strain amplitudes

Identification and consideration of non-homogeneous loading states

Characterization of the relevant material properties

Source: maschinenbau-wissen 2015

Source: Haibach 2005

Source: SOFEA 2015

Source: Haibach 2005
3. Simulation process – load definition

Real force flow in the brake caliper

Simulated force flow in the brake caliper

Contact surface

System simulation to determine deterioration

Contact surface

Same damage state

Clamping force causes high FE-calculation time

Bolt pretension for lower FE-calculation time
3. Simulation process – load definition

- There are variations in the clamping force occurring through hysteresis effects
- Load spectrum is determined from test reports
- Best-Fit: Lognormal distribution
3. Simulation process

- **Loadcase simulation**
  - Load definition
  - Material properties

- **Stochastic Simulation**
  - Deterioration
  - Strength
  - Carrying capacity
  - Lifetime distribution

**Characterization of the relevant material properties**

**Stress / Strain Wöhler curve**

**Stress / Strain hysteresis**

**Definition of claim and the associated amplitudes**

**The level of deterioration related stress and strain amplitudes**

**Identification and consideration of non-homogeneous loading states**

**Strength Identification and consideration of non-homogeneous loading states**

**Characterization of the strength model**

**Dehnungswöhlerlinie**

**Stress / Strain**

**Wöhler curve**

**Identification and consideration of non-homogeneous loading states**

**Characterization of the strength model**

**Load definition**

**Material properties**

**Carrying capacity**

**Lifetime distribution**

**Stress / Strain**

**Characterization of the relevant material properties**
3. Simulation process – material properties

Material behavior GJS-600-6

Mathematical modeling using Ramberg-Osgood-equation:

\[ \varepsilon_{a,t} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K}\right)^{\frac{1}{n}} \]

- **Significantly higher cyclic yield strength** \( R_e' = 500 \text{ MPa} \)
- **Material shows clear solidifying behavior**

\( R_e = 370 \text{ MPa} \)

\( R_e = \text{first load yield strength} \)
\( R_e' = \text{cyclic yield strength} \)

General Ramberg-Osgood-equation:

\[ \varepsilon_{a,t} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K}\right)^{\frac{1}{n}} \]

Modelling the fist load curve:

\[ K = 1160 \]
\[ n = 0.19 \]

Modelling the first discharge curve:

\[ K'' = 1300 \]
\[ n'' = 0.17 \]

Modelling the cyclic curve:

\[ K' = 924.9 \]
\[ n' = 0.1 \]

Nominal material behavior
3. Simulation process – material properties

Material behavior GJS-600-6

General Ramberg-Osgood-equation:

$$\varepsilon_{a,t} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K}\right)^{\frac{1}{n}}$$

Modelling the first load curve:

$$K = 1160$$
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Modelling the first discharge curve:

$$K'' = 1300$$
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Modelling the cyclic curve:

$$K' = 924.9$$
$$n' = 0.1$$

Nominal material behavior
3. Simulation process – material properties

- Only data from the static tensile test available
  - Mathematical derivation of the scattering of $n$ and $k$

- Determination of the limits and the distribution of $n$, and $k$:
  - Using two interpolation points solving Ramberg Osgood iteratively for $n$ and $k$

\[
\varepsilon_{0,2i} = \frac{R_{p0,2i}}{E} + \left( \frac{R_{p0,2i}}{K} \right)^{\frac{1}{n}}
\]

\[
\varepsilon_{gj} = \frac{R_{mj}}{E} + \left( \frac{R_{mj}}{K} \right)^{\frac{1}{n}}
\]

Diagram:
- Generation of point clouds using monte carlo simulation with $m$ samplings
- Loop to $j$, $i = m$
3. Simulation process – material properties

- Determination of the variance of $K$ and $n$ using 1000 Monte Carlo Samplings
- Best fit for initial loading $K$ and $n$ with Weibull distribution
- Proportionate transfer of variance at $K'$, $K''$, $n'$ and $n''$
3. Simulation process

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Stochastic Simulation

for variance determination

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Carrying Capacity

Lifetime distribution

The level of deterioration related stress and strain amplitudes

Definition of claim and the associated amplitudes

Identification and consideration of non-homogeneous loading states

Characterization of the relevant material properties

Stress / Strain hysteresis

Stress / Strain Wöhler curve

Characterization of the strength model

Stress / Strain

Source: Haibach 2005

Source: maschinenbau-wissen 2015

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Source: maschinenbau-wissen 2015

Source: Haibach 2005

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3. Simulation process – deterioration

First load simulation:

\[ \varepsilon_{a,t} = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{K} \right)^{\frac{1}{n}} \]

Cyclic operation load simulation:

\[ \varepsilon_{a,t} = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{K'} \right)^{\frac{1}{n'}} \]

Nearly elastic operating load hysteresis

Formation of residual compressive stress

Correct mapping of the location of the hysteresis

\[ \rightarrow \text{Mean stress influence} \]

First discharge load simulation - Masing behavior:

\[ \varepsilon_{a,t} = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{K''} \right)^{\frac{1}{n''}} \]

Local notch strain \( \varepsilon \) [%]

Local notch stress \( \sigma \) [MPa]

Abstract representation

Accelerated Representative Simulation Process (ARSP) for deterioration calculation at constant load
3. Simulation process

**Loadcase simulation**
- **Load definition**
- **Material properties**

**Stochastic Simulation**
- **Deterioration**
- **Strength**
- **Carrying Capacity**

**Lifetime distribution**

**Dehnungswöhlerlinie**
- **ε_a**
- **σ_a**

**Stress / Strain Wöhler curve**
- **ε_a = ε_{a,e} + ε_{a,p}**
- **σ_a**

**Characterization of the strength model**
- **Source:** Haibach 2005

**Characterization of the relevant material properties**

**Definition of claim and the associated amplitudes**

**The level of deterioration related stress and strain amplitudes**

**Identification and consideration of non-homogeneous loading states**

**Stress / Strain hysteresis**

**Source:** maschinenbau-wissen 2015

**Source:** SOFEA 2015

**Source:** maschinenbau-wissen 2015

**Source:** Haibach 2005
3. Simulation process – strength

**Stress Wöhler curve**

According to Haibach: modeling of stress levels with normal distribution using Database of FKM

Scattering of endurance strength

Modeled with:

\[ N = N_D \cdot \left( \frac{\sigma}{\sigma_D} \right)^{-k} \]

**Strain Wöhler curve**

Only 2 nominal literature sources. No large database

Uniform Distribution

Modeled with:

\[ \varepsilon_a = \frac{\sigma_f'}{E} (2N)^b + \varepsilon_{f1}' (2N)^c \]

**Determination of scattering of \( k \):**
Monte Carlo Simulation using 3 interpolation points

**Determination of scattering of \( \sigma_{f1}', \varepsilon_{f1}' \):**
Using uniform distribution between \( \sigma_{f1}' \) and \( \varepsilon_{f1}' \)
3. Simulation process – strength

Result for variance of $k$ and $N_D$ of Stress Wöhler curve

Result for variance of $\sigma'_f$, $\varepsilon'_f$, $b$ and $c$ of Strain Wöhler curve

Compatibility condition according to Haibach:

$n' = \frac{b}{c}; \quad k' = \frac{\sigma'_f}{(\varepsilon'_f)^{n'}}$
Virtual Lifetime Determination of commercial vehicle braking systems

4. DESIGN OF EXPERIMENTS
4. Design of Experiments

Spacefilling latinhypercube sampling

- **Design Parameter**
  - Using $3\sigma$ Normal Distribution

- **Material Model**
  - Using Distribution of smallest extreme values

- **Strength Model**
  - Stress: Using Normal Distribution
  - Strain: Using Uniform Distribution

- **Load Spectra**
  - Using Lognormal Distribution and ARSP

Optimal cover of the parameter space

Source: Siebertz 2010
4. Design of Experiments

Spacefilling latinhypercube sampling

Load Spectra
Using Lognormal Distribution and ARSP

Optimal cover of the parameter space

Integration of the load spectrum through parametric study

Source: Siebertz 2010
4. Design of Experiments

Sampling of
- Design Parameter
- Material model

Sending deterioration outputs from FE-Simulation

Sampling of
- Stress strength model
- Calculation of lifetime

Workflow Step 1

Workflow Step 2

Workflow Step 3

Workflow Step 4

Sending back results to Robustness Analysis for Postprocessing

Sampling of
- Strain strength model
- Calculation of lifetime
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5. RESULT EVALUATION
5. Result Evaluation

Probability plot of FKM; PSWT; Real data
Weibull
Full data - ML-Estimation

Variable
- FKM approx.
- PSWT approx.
- Real data
5. Result Evaluation

- Very good approximation using stress based FKM algorithm
- Nearley same Weibull shape parameter b
- Small deviation in characteristic life time $T$
- Larger deviation on upper levels using strain based PSWT

- Pronounced Differences to conservative side for PSWT $\rightarrow$ Additionally insufficient fit
- FKM approximation slightly overestimates the real life time

Reason for this behavior:

**Increasing plastic component of strain amplitude**
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6. SUMMARY AND OUTLOOK
6. Summary and Outlook

- Mapping of systematic uncertainties of
  - Design Parameter
  - Material model
  - Strength model
  - Load

- Development of a Accelerated Representative Simulation Process

- Successfull development of a virtual lifetime distribution
  - Check of reproducibility
  - Future investigations to the influence of plastic compontents in strain amplitudes for deterioration calculation
  - Investigations to the strain based strength model

Increase of maturity level in early design stages!
THANK YOU FOR YOUR ATTENTION!