Fatigue Failures of Vehicle Components

by

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1. **Introduction**
   Criteria for the design, classification of vehicle components and product liability requirements.

2. **Influences for the failures**
   2.1. Design and service loading
   2.2. Material and manufacturing
   2.3. Usage conditions (Assembly, Environment)
   The individual influences will be discussed on examples and the means to avoid failures presented.

3. **Conclusions**
   Requirements concerning the procedures for the design validation of vehicle components.
Recalls in Car Industry

Source: German Traffic Office 2004

Die Zahl der Pkw-Rückrufe wächst – nicht allein bei Mitsubishi. GRAFIK: DPA
Automotive Failures-Occurrence and Costs

Generalized Overview

- 80% of Failures Originated

- Design Failures

- Production Failures

Failure Probability Distribution

Cost per Failure

- Failure Occurrence

- Failure Detection*

- After study
  Daimler Chrysler/
  Fraunhofer Society-IPT

DEVELOPMENT MANUFACTURING ASSEMBLY USAGE
Classification of Components Concerning Reliability Requirements

**Classification**
- Primary - Components
  - Safety Components
    - Fracture not allowed
    - Fracture leads to accident and danger for user and environment
      - Wheel
      - Hub
      - Spindle
      - Steering knuckle
      - Suspension arm
    - Functional Components
      - Fracture to be avoided
      - Fracture interrupts the function
    - Examples
      - Connecting rod
      - Crankshaft
      - Starter
      - Cooler
      - Gears
  - Fracture influences neither the safety nor the function
    - Car body local areas
    - Internal accessories

**Influence**
- Secondary - Components
  - Fracture influences neither the safety nor the function

**Examples**
- Wheel
- Hub
- Spindle
- Steering knuckle
- Suspension arm
- Connecting rod
- Crankshaft
- Starter
- Cooler
- Gears
- Car body local areas
- Internal accessories
Relation between Operational Stresses and Durability Life

Fatigue Life under Constant Amplitude (Woehler - Curve)

Fatigue Life under Variable Amplitude (Gassner - Curve)

\[ N_i = N_x \left( \frac{\bar{S}_{a,x}}{\bar{S}_{a,i}} \right)^k \]

Stress Amplitude \( S_a \) or \( S_{a,x} \)

Static Strength

Safety-Factor

Stress Spectrum

Endurance Limit

\[ 1 \quad 10^3 \quad N_{D,CA} \quad 2 \times 10^6 \quad 10^7 \quad N_{D,S} \]

Durability Life (log)

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Wheel/Hub Assembly of Commercial Vehicles with Drum Brakes

1. Hub
2. Bearing
3. Spindel
4. Brake Drum
5. Bolts
6. Wheel
Influence of Wheel Design on Hub Stresses
Load Condition: Cornering

Aluminum Wheel
Steel Wheel

Wheel 22.5 x 9.00

Relative Stress Amplitudes

1.0

0.5

0.0

1 2 3 4 Measuring Point

Steel Wheel
Aluminum Wheel
Fatigue Fractures on Trailer Hubs

Wheel: 22.5 x 11.75; Tyre: 385/65R22.5 Bridgestone; Wheel rated load: $F_{z,\text{stat}} = 55 \text{ kN}$

Fracture in Biaxial Wheel/Hub Test Facility
Load Programme „Eurocycle“
Test Life $\approx 7 \text{ 000 km}$

Fracture after $\approx 200 \text{ 000 km}$ Service usage
Fatigue Fracture on Cast Hubs for Commercial Vehicles (Nodular Iron GGG 50)
Truck Overloaded
Measurements on roads in Hubei – Province (China)
Measuring Vehicle
Pothole Test Track MAO JIAN
Comparison of Test Spectra ($L_t = 15\,000\,\text{km}$) Hub, Area Gage 3

Calculated Damage $D_t$

- "Chinacyle" : 1.65
- "Eurocycle" : 0.19

**Graph Details:**
- **Y-axis:** Ratio of Stress Amplitude
- **X-axis:** Number of Cycles

**Graph Elements:**
- Chinacyle
- Eurocycle
- S-N Curve (modified)
Influence of Design Spectra on Required Design Modifications

Damage Relation: \( D_{\text{China}} \approx 5 D_{\text{Europe}} \)

Design Life Relation: \( L_{\text{China}} \approx 1/5 L_{\text{Europe}} \)

Required Design Modifications

\[
t_{\text{China}} = t_{\text{Europe}} \cdot \left( \frac{D_{\text{China}}}{D_{\text{Europe}}} \right)^{\frac{1}{k \cdot n}}
\]

- \( t \) – thickness
- \( k \) – slope of S-N-Curve
- \( n \) - ratio of Loading mode
  - \( n = 2 \) (pure bending)
  - \( n = 1 \) (pure tensile/compression)

Required thickness for China compared to Europe for the same operational life and unchanged design of the wheel hub (\( n = 1.8, k = 7 \)) for hub manufactured from nodular iron:

\[
\frac{t_{\text{China}}}{t_{\text{Europe}}} \approx 1.14
\]

- e.g. from \( t_0 = 12 \text{ mm} \) to \( t_{\text{new}} = 13.7 \text{ mm} \)
Proof Test in Biaxial Test Facility Load Program CHINACYCLE
Fatigue Damage on a Cast Nodular Iron Hub for Dual Wheels
Classification of Allowable and Non-Allowable Pores in Nodular Cast Hubs (GGG 50)

b. Non-allowable flange shrinkage

c. Non-allowable outer pore in bearing seat area
Areas of Shrinkage and Porosity on Cast Hubs for Commercial Vehicles
Allowable Shrinkage and Porosity on Highly Stressed Areas of Nodular Iron Hubs for Commercial Vehicles

<table>
<thead>
<tr>
<th>Area</th>
<th>Percentage of pores</th>
<th>Size of single pores Ø in mm</th>
<th>No. of areas with pores of 1 cm² +)</th>
<th>Porosity according to ASTM E 155 (Cast Aluminium)</th>
</tr>
</thead>
</table>
| A    | • Machined flange to wheel seat / brake disc  
     • Bearing seat | 0 | ≤ 0,1 | 0 | 0 |
| B    | • Non - machined hub radii | ≤ 5 | < 1 | < 3 | p ≈ 8 |
| C    | • Higher circumferential stress on outer bearing seat | ≤ 3 | < 0,5 | < 1 | p ≈ 4 |
| D    | • Internal areas with mainly bending stress | < 5  
     Surface distance > 5 mm | < 1  
     at 3 cross sections (max.) | p ≈ 0 - 4 |

+): These areas of defects are allowed, if their distances along the circumference are ≥ 5 cm
Operational Stresses (Cornering) and Fracture Modes on Steel Wheels

\( \sigma_r \) = radial stress
• \( \sigma_t \) = tangential stress
\( \sigma_e \) = equivalent stress
\( \sigma_{e,3} \leq 0.95 \sigma_{e,2} \)

\( \alpha \) = angle of rotation
0° corresponding to load input
Fatigue Crack on Welding between Disc and Rim

rim

disc
Fatigue Cracks on Wheels with Large Rims (>7 inches) and Low Profile Tyres Operational Usage 60,000 – 100,000 km

Wheels: 8J x 17; 9,5 x 16 (240 TR 415); 10,5 x 18
Tyres: 245/40 ZR 17 280/45 VR 415 295/35 ZR 18
Procedure for Pre-Loading of Wheels for Durability Approval

Static Pre-Loading:
Vertical Force: \[ F_v = 2.5 \cdot F_{v,\text{stat}} \]
Tyre pressure: \[ p_l = 0.6 \cdot p_{l,n} \]
Half tyre width (inside section)
Obstacle radius \[ r = 12 \text{ cm} \]

Plastic deformation: \( \Delta D = 0.9 \text{ mm} \)

Fatigue Crack after validation test

Strain \( \varepsilon \) 1000 \( \mu \text{m/m} \)

Wheel forces

Plastic deformation on rim strain gauges
Fatigue Cracks at Durability Approval on Wheels after Pre-Loading

Wheel Design: 10\(\frac{1}{2}\) J x 18
Tyre: 295/35 ZR18

Fatigue Cracks on Rim Flange

Stress-Time-History

\[ S \text{ due to } +F_l \]
\[ S \text{ due to } -F_l \]
## Influence of the Rim Design on Plastic Deformation and Durability

<table>
<thead>
<tr>
<th>Design</th>
<th>Weight [kg]</th>
<th>Plastic Deformation $\Delta D$ [mm]</th>
<th>Durability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10.9</td>
<td>-0.85</td>
<td>cracks at 4,979, $\approx 0.5$</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>-0.55</td>
<td>cracks at 10,141, $\approx 1.0$</td>
</tr>
<tr>
<td>C</td>
<td>11.35</td>
<td>-0.35</td>
<td>without cracks 14,920, $&gt; 1.5$</td>
</tr>
</tbody>
</table>

* After Preloading: $F_v = 2.5 \cdot F_{z,stat}$; $p_l = 0.6 \cdot p_{l,n}$
Fracture of Washer (1), Hub (3) and Drive Shaft (2)
Assembly of Drive Wheel

- hub carrier
- spindle
- driving shaft
- wheel
- brake disc
- central nut
- washer
- hub
- bolt
Fatigue Failure of Drive Wheel Assembly

1. Washer
2. Spindle End
3. Hub
Typical Cracks on Steering-Knuckle Arms

rust out

corroded

GrubiTokio-Oct2004.ppt

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Design Load Spectrum and Test Results with corroded Steering-Knuckle Arms

Result of tests with 36 specimens in usage 5 to 8 years and 32,000 to 129,000 km

Design Load Spectrum

\[ T_N = \frac{N_{90\%}}{N_{10\%}} = 1:7 \]

\[ P_s = 99\% \quad P_s = 50\% \]

Track Rod Load $\pm F$ [kN]

Load Spectrum without parking maneuvers

Load Spectrum at parking including extrem loads from curbstone impression

Cycles $N$ (log)

Load Spectrum 3 x $10^5$ km, $P_s \leq 1\%$

Result of tests with 36 specimens in usage 5 to 8 years and 32,000 to 129,000 km

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Reliability Requirements for Safety Components

Design Spectrum

- Probability of Occurrence $P_o \leq 1\%$
- Stress Amplitudes $S_a\,(\log)$

- Scatter of Operational Stresses
- Scatter of Allowable Stresses

Durability Life Curve

- Probability of Survival $P_s$
- Design Life $L_D$
- Theoretical Probability of Failure $P_F \leq 10^{-3}$ or $P_F \leq 10^{-4}$

Safety Factor $S_F = \frac{\sigma_{a,50\%}}{S_{a,50\%}} \approx 1.7$ or $2.2$

- Design Spectrum $S_a,50\%$
- $S_{a,max}$
- $P_s = 90\%$ or $99\%$
- Failure Rate

Operational Life

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Realibility Requirements at Durability Life Approval

Probability of Survival $P_s$

Scatter of total production

Test sample

$90\% \hspace{1cm} 90\%$

Load

Test Spectrum

$R_F = \left(\frac{1}{T_N}\right)^{\frac{1}{\sqrt{4n}}}$

$T_N = L_{90\%}L_{10\%}$

$n = \text{number of tests}$

$L_p$ – Life at test corresponding to $L_0$

$L_T$ – Required test life $L_T = L_p \cdot R_F$

Durability Life (log)
CODEX HAMMURABI (18 Century b.C.)

- If the wall of a house tumbles down, the house builder must repair it with a stronger wall on his own cost.

- If the house collapses because it is not properly built and his owner is killed, the house builder will be killed, too.
In every development a certain amount of risk remains. If we try to eliminate risks completely, it would be a totally unrealistic goal. But we have to take into account in the approach we apply to determine the operational strength and durability, whether or not a safety item is under consideration and to what degree the function of vehicle is influenced by possible failure. For such cases the procedures we apply have to **guarantee the whole functionality under operational usage and we are responsible for the methods we apply to prove it.**