Introducing Simcenter™ Portfolio for Predictive Engineering Analytics

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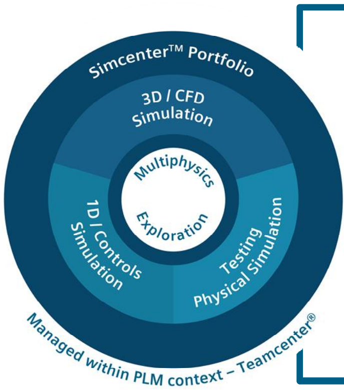

Simcenter™

Durability Agenda

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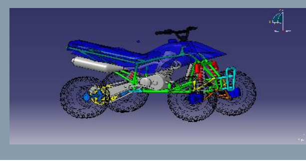
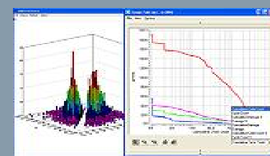
Durability Basics
Fatigue, Stress, Strain

Load Determination
Measurements, Multi-Body Simulation

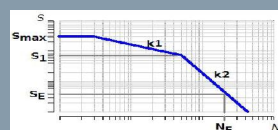


Loads and Damage
S-N Curve, Cycle Counting



Load Characterization
Establishing Durability Targets: Superposition, Extrapolation

Fatigue Life Predictions
Infinite Life, Stress Life, Strain Life



Accelerated Testing & Analysis
RP-Filter, Mission Synthesis

Durability Engineering in Product Development

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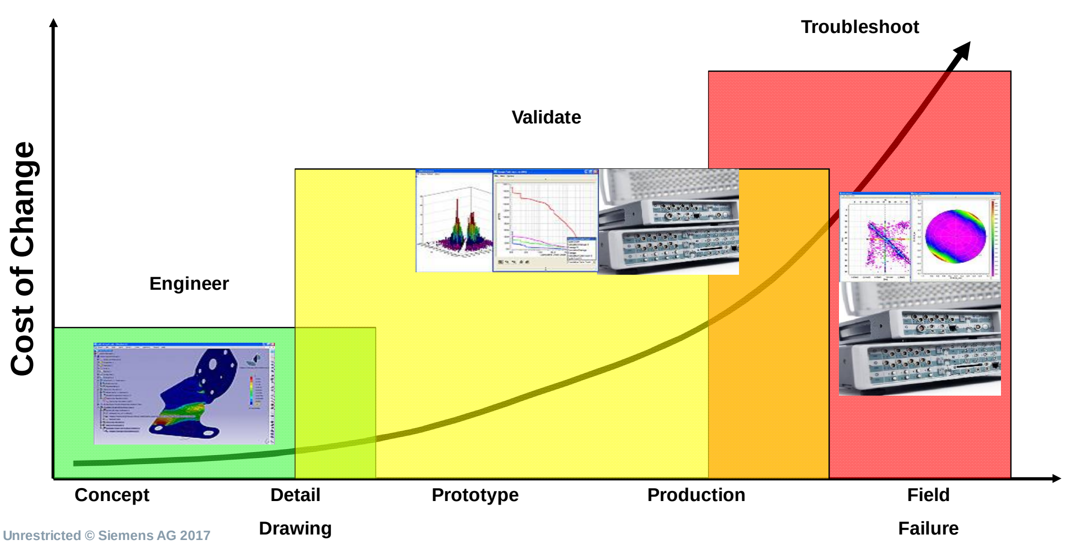

Durability – Why is it important?

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Warranty Costs
- High rate of return is large liability
- Example: Heavy truck

Competitive Advantage
- Reputation for reliability
- Example: Longest lasting appliance, safest aircraft

Performance
- Over-engineering reduces performance
- Example: Fuel economy on heavy car

Manufacturing
- Reduce downtime
- Cost Efficiency/ Time efficiency

The Durability Process

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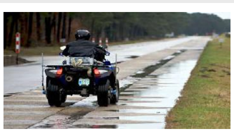
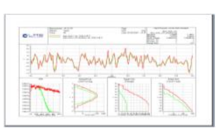
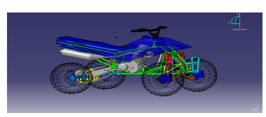
Understanding Operational loads → Target setting & Test Procedures → Design Optimisation Virtual Product Validation → Physical Product Optimisation & Validation → Final Product Test

Acquisition	Analysis	Simulation	Shaker testing	Sign-off
				

Energy Industry
Wind turbine – blade failure / structural failure

"There is a general trend upward in accident numbers over the past 10 years."

Blade failure – 24 accidents per year*

Structural failure – 15 accidents per year*

*=2009

Civil construction
2007 Minneapolis' I-35 Bridge Collapse

Kenneth Russell, professor MIT, suspects metal fatigue could be a contributing factor "The bridge was very near to the fatigue limit and had gone through many cycles," he says.

Turbine Blade Failure

Wall

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Helicopter GVT

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The Ubiquitous…
Tacoma Narrow Bridge

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What is Fatigue?
Versailles rail accident, 1842

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1st French railway accident | **200 lives lost** | **Broken axle**

The start of systematic research into metal fatigue

The birth of fatigue analysis

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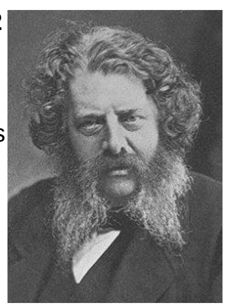
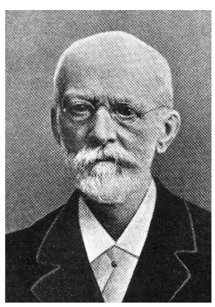
Versailles rail accident, 1842

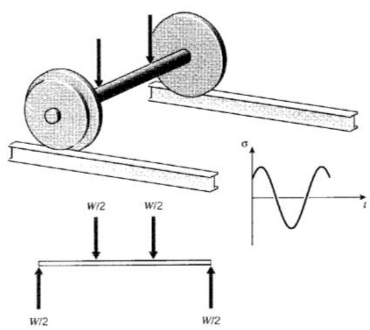
- Examining broken axles by Rankine showed that they had failed by cracking across their diameters, a problem later known as **fatigue**
- Work of Wöhler helped improving testing of axles, and so increasing axle life. He developed the Rotating-Bending Fatigue test and introduced the concept of **fatigue limit**.

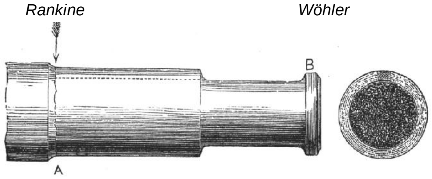


Rankine



Wöhler





Cyclic stress range
Can be more important than peak stress

Famous People In Fatigue

August Wöhler
German
(1819-1914)

Wöhler curves in 1867

Durability Agenda

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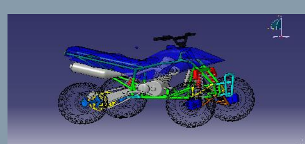

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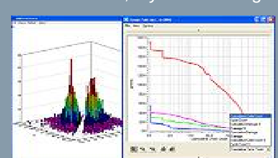

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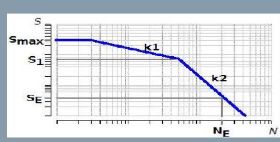
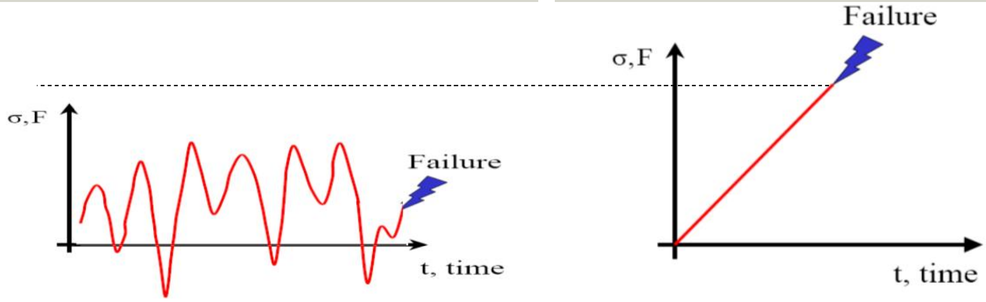


Accelerated Testing & Analysis
RP-Filter, Mission Synthesis

Dynamic versus Static Failures

Cyclic Fatigue	Static Strength
Cyclic Fatigue refers to gradual degradation and eventual failure that occurs under loads which vary with time, and which are lower than the static strength of the metallic specimen, component or structure concerned.	The **static strength** is the load which causes failure in one application.



Static Strength

Aircraft Wing Bending Test

Bend till Break

Dynamic (Cyclic) Loading

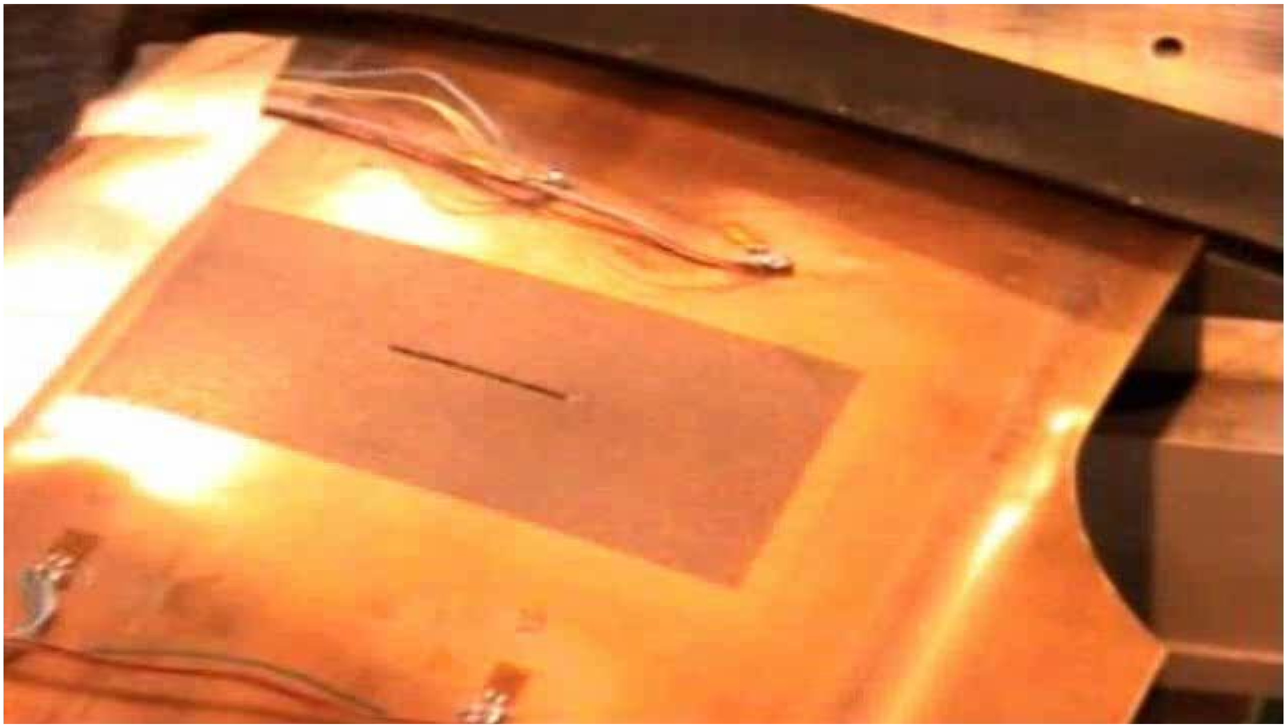
Aircraft Wing Bending Test

Fails, but never bends to static strength

Definitions

Durability is the ability of something to perform its function long-lasting and repeatedly.

Failure is Industry specific. For example: Crack growth versus crack initiation



Fatigue Failures in Real Life – Crack Growth

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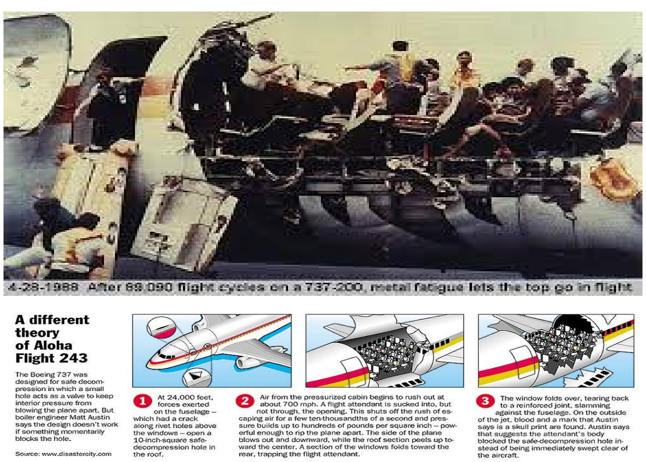

Aloha airlines flight #243
April 28th, 1988
Maui, HI

Fatigue failure occurred due to repeated pressurization of the cabin causing a small crack to rupture in the fuselage, killing a stewardess.

Other Damage Mechanisms exist for Composites
- Delamination shown, decohesion, fibre/matrix breakdown, etc.

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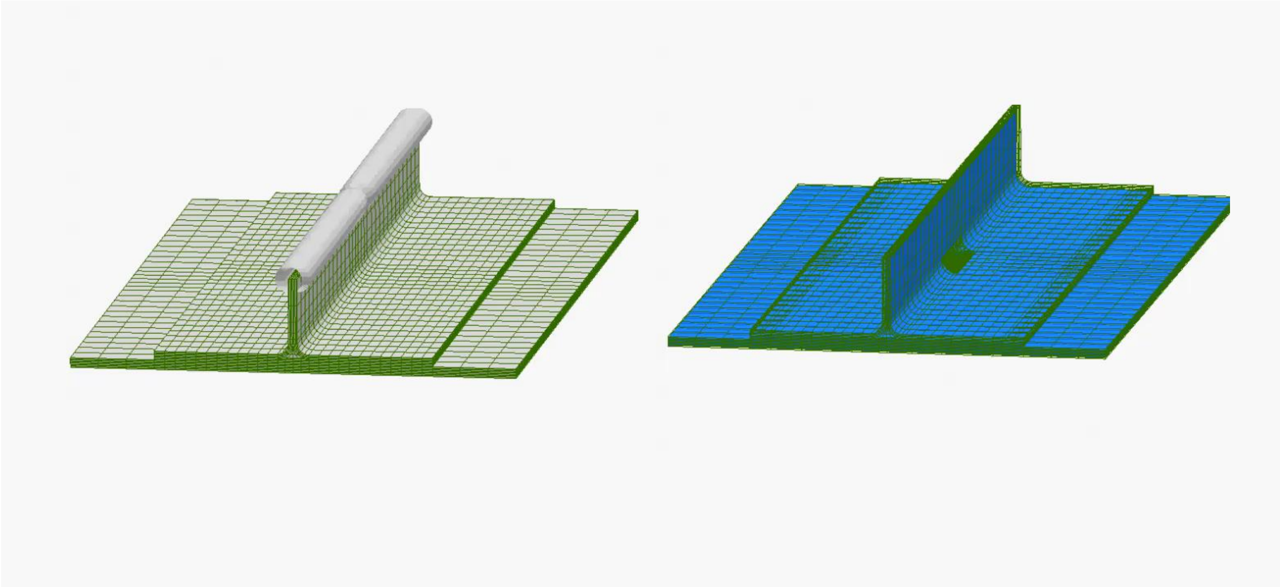
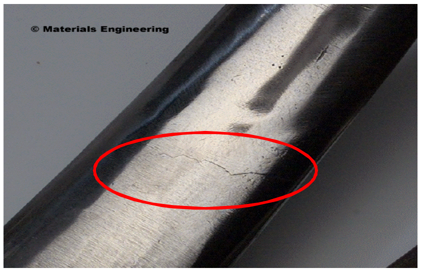
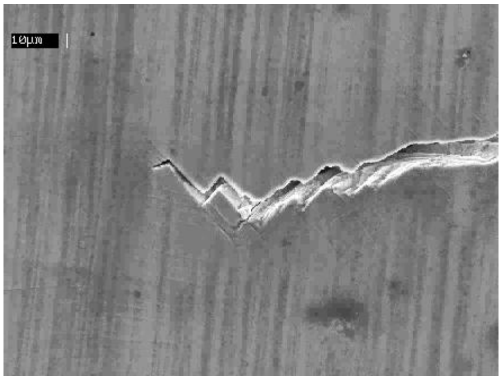


Dynamic Fatigue: Crack initiation





Definitions

Durability is the ability of something to perform its function long-lasting and repeatedly.

Failure is Industry specific. For example: Crack growth versus crack initiation

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Stress and strain are used to calculate fatigue damage.

Damage – Measure of fatigue. When = 1 by Miner's Rule, failure occurs.

Fatigue Life – Inverse of damage (Example: 0.5 damage, is fatigue life of 2)

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What is fatigue?

INTERNATIONAL
Standards Worldwide

The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.

"Standard Definitions of Terms Relating to Fatigue Testing and Statistical Analysis of Data," ASTM Designation E206-72.

Stress

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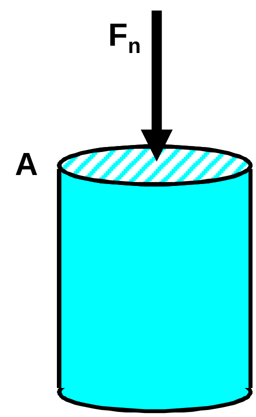
$s = F_n/A$

How to reduce Stress?

Either:

- **Increase Area**
- **Reduce Force**



*** Normal Stress**

Stress

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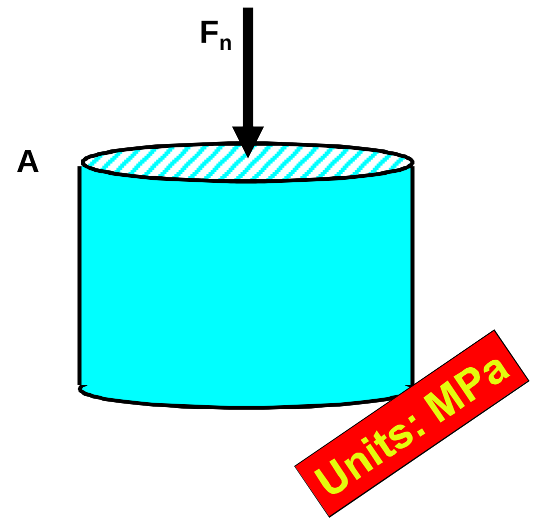

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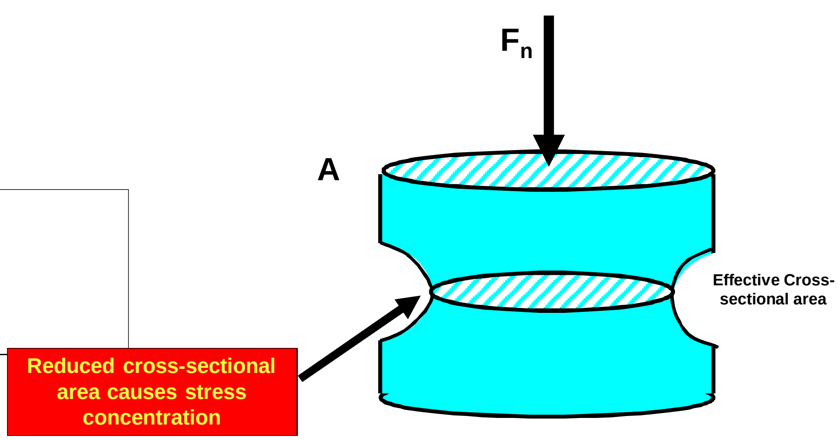

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Strain

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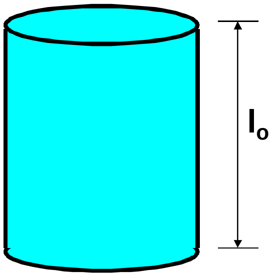

Strain

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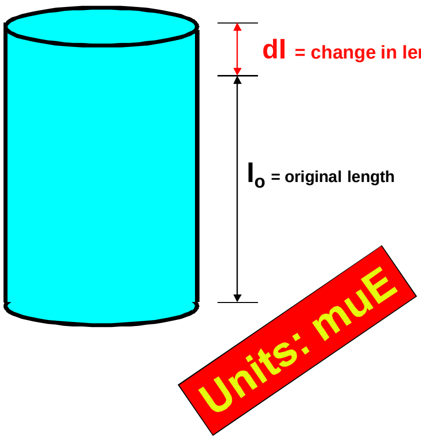
Strain:

$$e = dl / l_o$$



Stress and Strain: Hooke's Law – Young's Modulus

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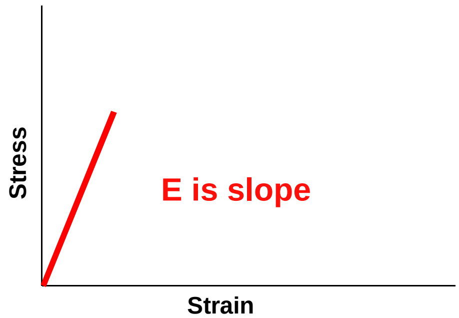
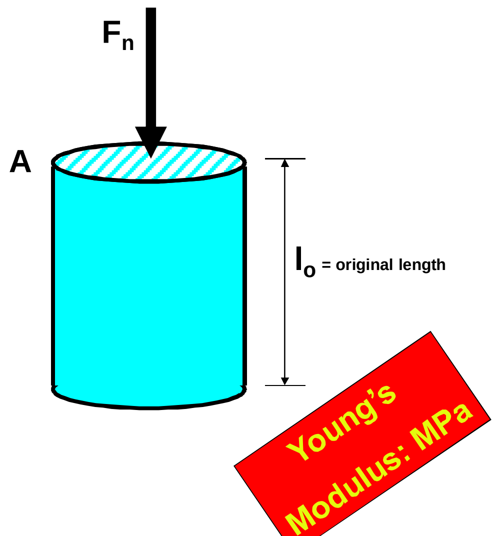
$s = E\ e$

E = Young's Modulus





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Stress and Strain: Hooke's Law – Young's Modulus

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$s = E\,e$

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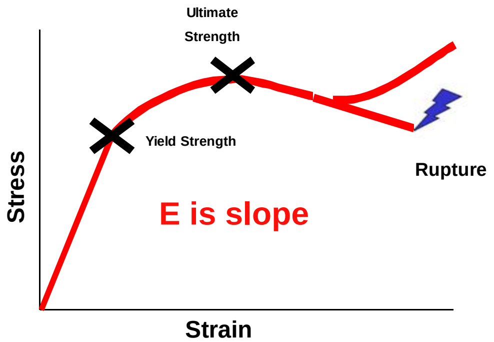

Time Lapsed Video

Static Stress and Strain Relationship

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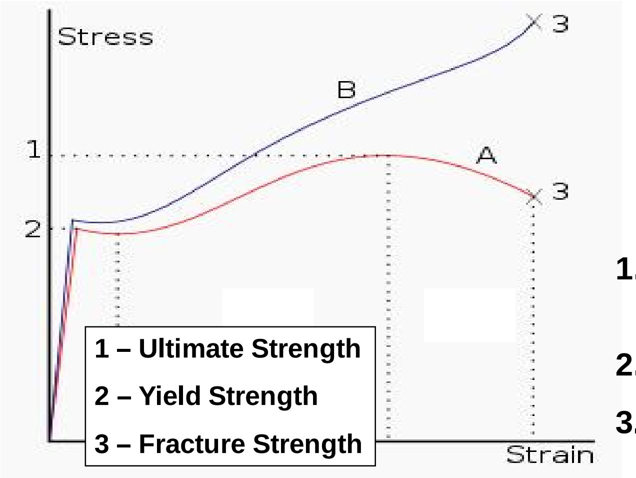

A - Red – Fixed Area

(Engineering Stress)

B - Blue – Changing Area

(True Stress)

1. **Necking occurs, applied load decreases**
2. **Plastic Deformation Begins**
3. **Fracture Occurs**

Materials Terms

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Creep: is a time-dependent deformation of a material while under an applied load that is below its yield strength
•**Hardness**: is the resistance of a material to localized deformation
•**Toughness:** the ability of a metal to deform plastically and to absorb energy in the process before fracture
•**Yield strength or yield point:** of a material is defined in engineering and materials science as the stress at which a material begins to deform plastically.
•**Ductility:** is a solid material's ability to deform under tensile stress

- The following list ranks metals from the greatest ductility to least: gold, silver, platinum, iron, nickel, copper, aluminum, zinc, tin, and lead
- The ductility of steel varies depending on the alloying constituents. Increasing levels of carbon decreases ductility

•**Brittle:** A material when subjected to stress, it breaks without significant deformation (strain)
•**Ultimate tensile strength (UTS), often shortened to tensile strength (TS) or ultimate strength**, is the maximum stress that a material can withstand while being stretched or pulled before *necking.* Point at which load on specimen decreases

Graphical Representation of Material Terms

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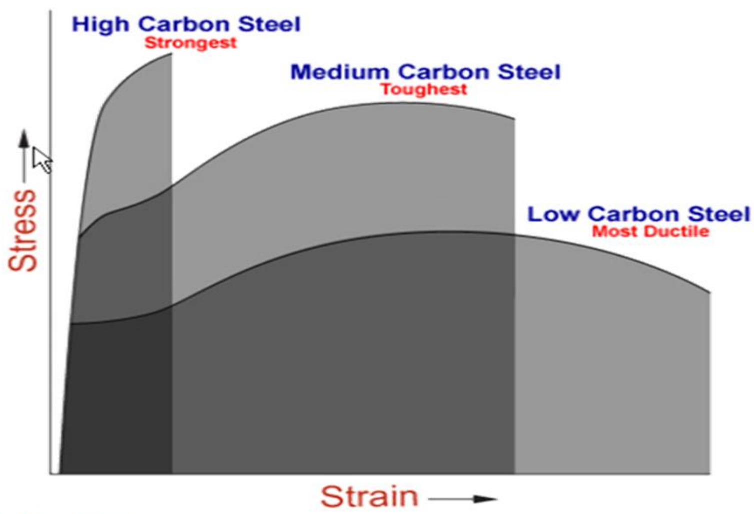

Some Material Properties and Failure Modes

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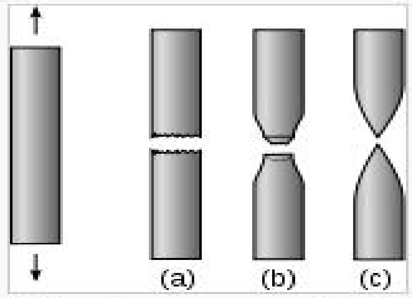
Element	Young's modulus (GPa)	Offset or yield strength (MPa)	Ultimate strength (MPa)
silicon	107		5000–9000
tungsten	411	550	550–620
iron	211	80–100	350
titanium	120	100–225	240–370
copper	130	33	210
tantalum	186	180	200
tin	47	9–14	15–200
zinc (wrought)	105		110–200
nickel	170	14–35	140–195
silver	83		170
gold	79		100
aluminium	70	15–20	40-50
lead	16		12



Schematic appearance of round metal bars after tensile testing.
(a) Brittle fracture
(b) Ductile fracture
(c) Completely ductile fracture

Definition of the Stress Ratio R

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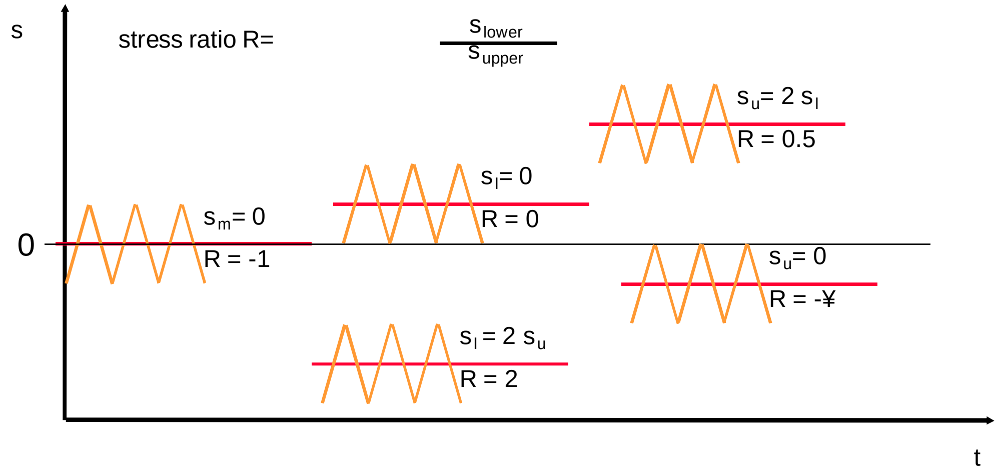

Stress Ratio R Plotted On the Haigh Diagram

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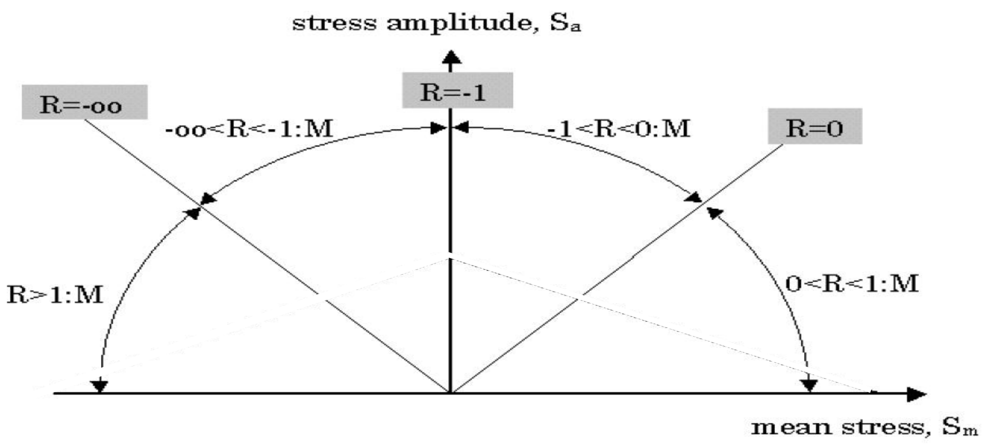

Dynamic Stress/Strain Test

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What influences fatigue?

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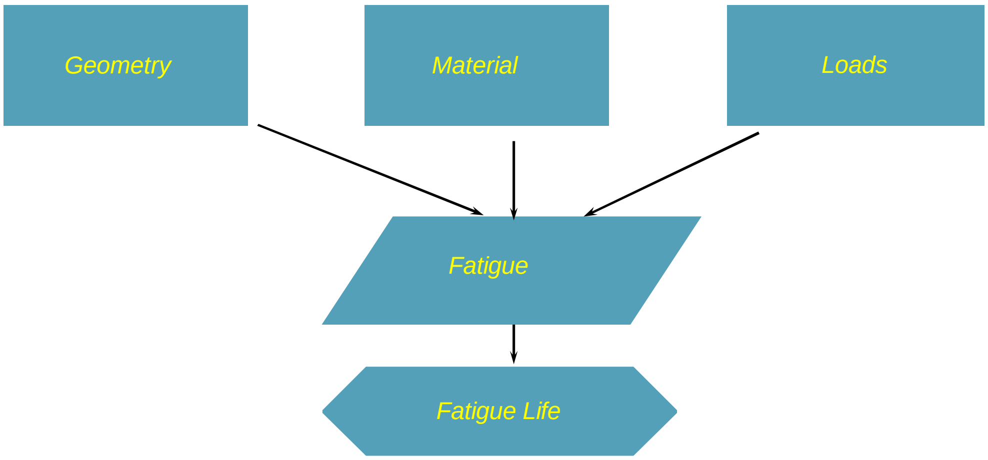

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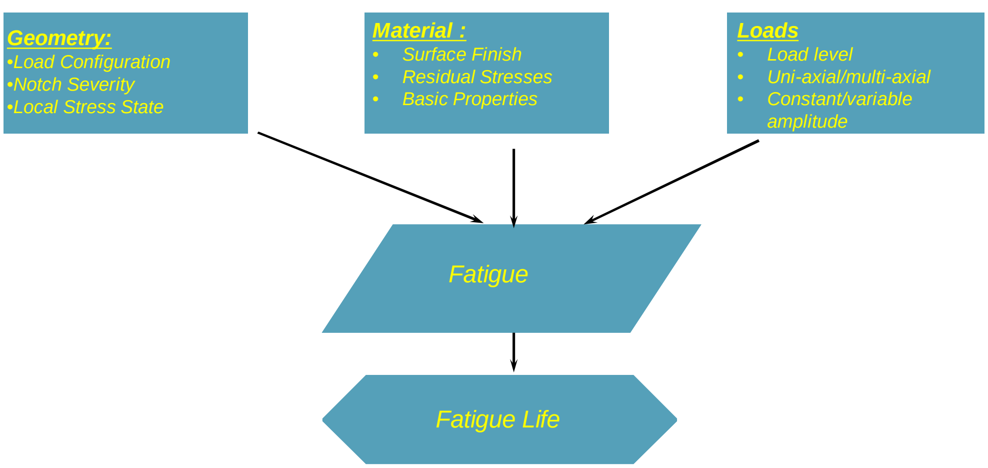

Applied loading vs. structural strength

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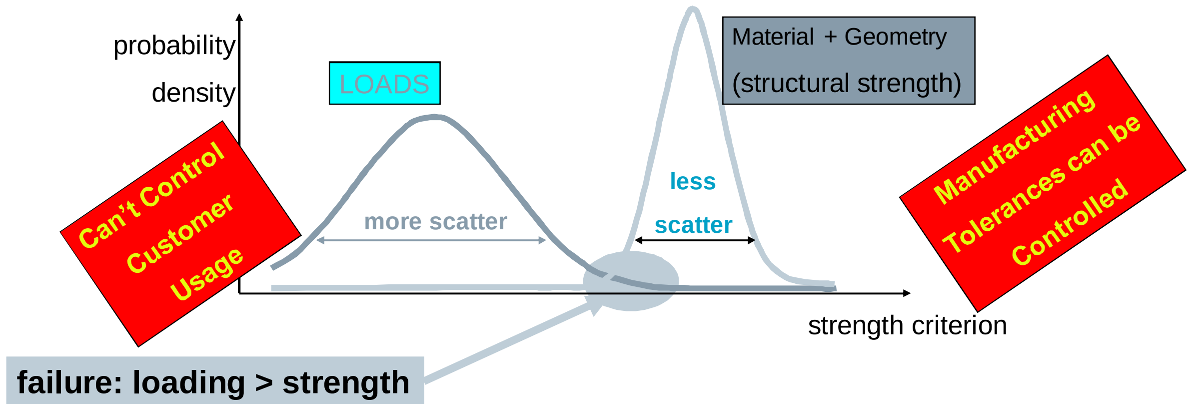
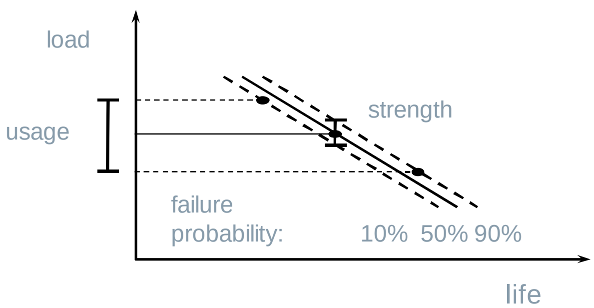
Optimal Design – Minimal Overlap – Affordable Cost



Sources of Fatigue Scattering



typical load ratios of 10% / 90% probability

manufacturing	
geometry	**1.02**
material	
- controlled	**1.15**
- different welds	**1.45**
loads (car)	**2.00**

Today, customer usage is the most important source of fatigue scattering.

When were your durability test schedules established ?
Applied loading vs. structural strength

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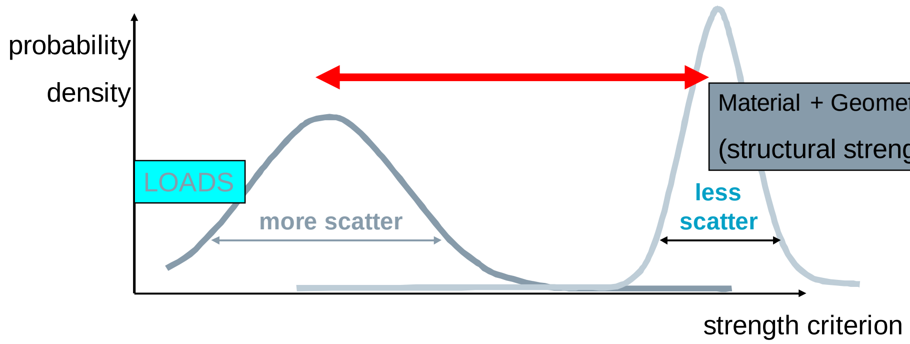
Wider - Over-Design - More expensive



When were your durability test schedules established ?
Applied loading vs. structural strength

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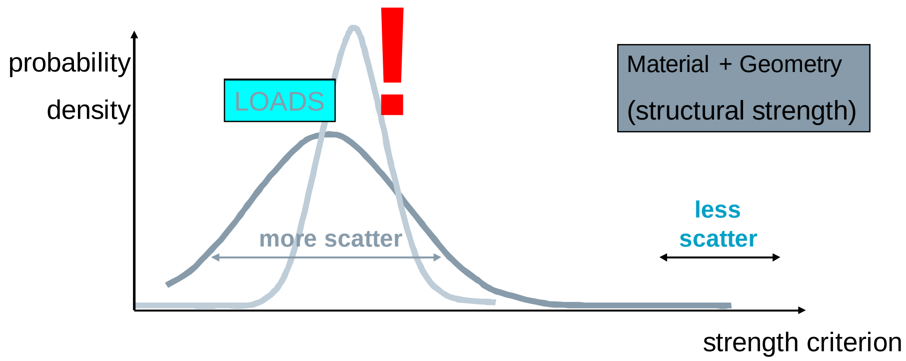
NOT SO GREAT DESIGN



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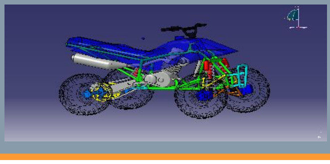

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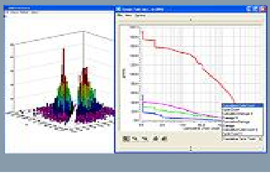

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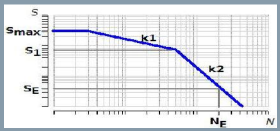

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The Durability Process

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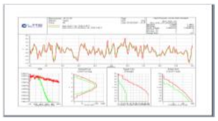
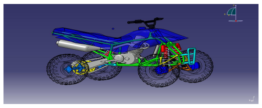
Understanding Operational loads	Target setting & Test Procedures	Design Optimisation Virtual Product Validation	Physical Product Optimisation & Validation	Final Product Test
Acquisition	Analysis	Simulation	Shaker testing	Sign-off
				

Do you know what your customers do with your product ?

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- Where ?
- How hard ?
- How fast ?
- How often ?
- How long ?

How to capture customer usage ?

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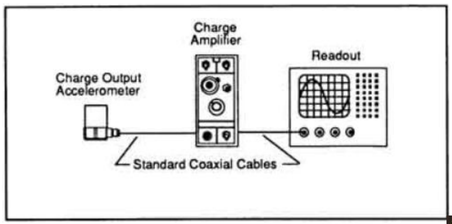
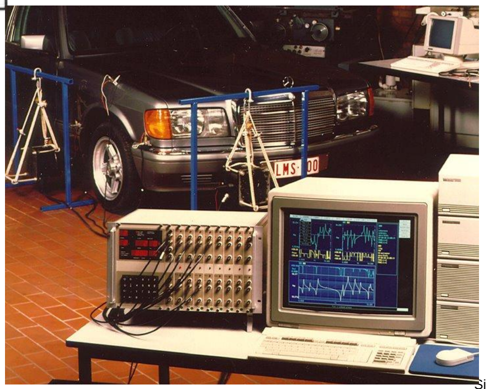
Instrumentation & Setup	Measurement & Validation	Processing & Data sharing
		
		
Pains	Pains	Pains
Test needs to be better prepared.	More information needs to be gathered in limited time available	Data needs to be quickly validated. Faster Delivery to CAE – Rig testing dept.

1992 External Amplifiers





Page 54
Siemens PLM Software

Modern Data Acquisition

- Modern Integrated signal conditioning, digital inputs to include video and universal signal condition cards (IEPE, Strain, Voltage, etc….)
- Capable to record 16 million samples per second

Page 55
Siemens PLM Software

Modern Data Acquisition

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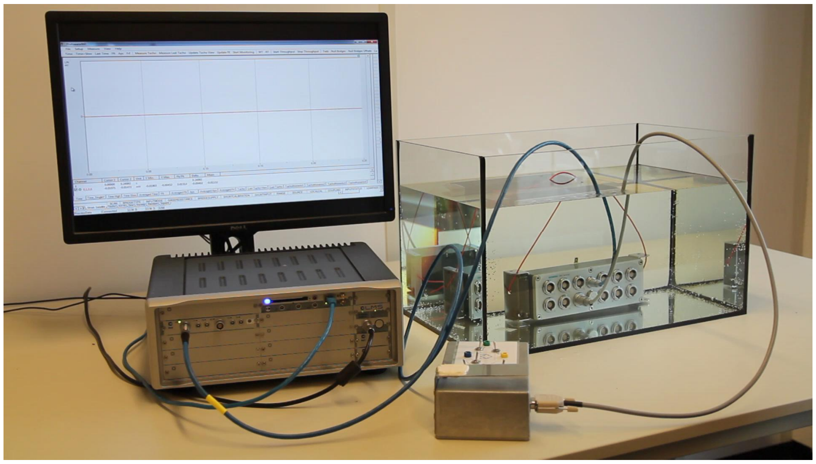

Which sensors to use ?

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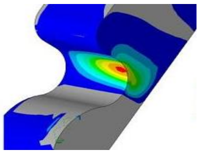
Force

Stress/Strain



Acceleration

Pressure

Moment

Displacement

Temperature

Others

Which sensors to use ?

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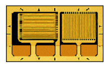
Wheel force

WFT

- Force Fx, Fy, Fz
- Moment Mx, My, Mz
- Angle, speed

Stress/Strain

Strain gauges



- Tension
- Compression
- Torque
- Local stresses

Acceleration

DC-accelerometers

- Body accelerations
- Subsystems

Load/Pressure

Load cells,
Pressure transducer

- Component force
- Brake pressure
- Air pressure - dampers

Moment

Torque Sensors

- Engine torque
- Drive shafts

Displacement

String pots

LVDT

- Absolute displ.
- Relative displ.
- e.g. damper, bushings

Temperature

Thermocouple

- Engine
- Gearbox

Others

- GPS – Global position
- CAN signals

Strain Gauge

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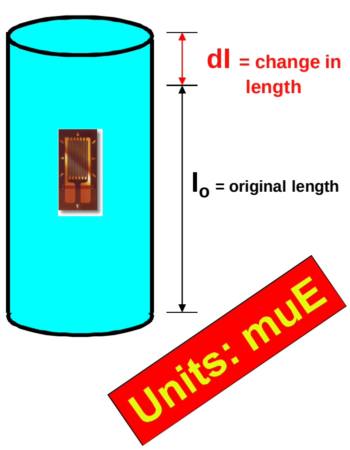
- Strain is defined as the change in length compared to the nominal length
  - $\varepsilon = \Delta L / L$
  - Positive ΔL = “tensile” strain
    Negative ΔL = “compressive” strain
- Strain unit = “microstrain” or με (μE)
  - because of very small relative length changes (1E-6 to 1E-3)



Gauge measures change in resistance

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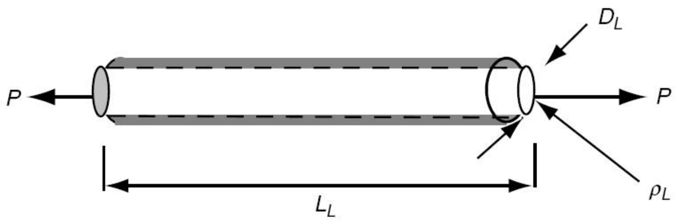

FIGURE 1.2 A resistance wire under mechanical load.

$$\Delta R = \left(\rho_L \times \frac{L_L}{\frac{\pi}{4} D_L^2}\right) - \left(\rho \times \frac{L}{\frac{\pi}{4} D^2}\right)$$

- A strain gauge is one long resistive wire, embedded in a very thin foil
  - Unique property: resistance is proportional to the change in length
  - $\Delta R / R = k \times \varepsilon$

Gauge: Will it measure correctly?

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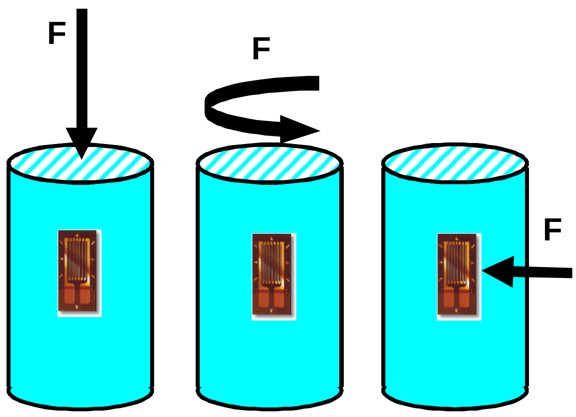

Gauge: Will it measure correctly?

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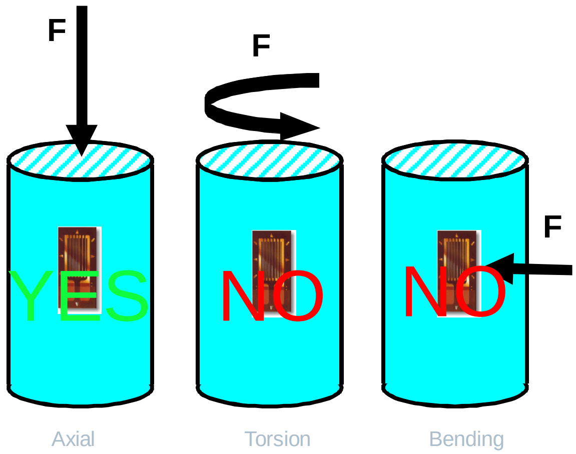

Bridge Types

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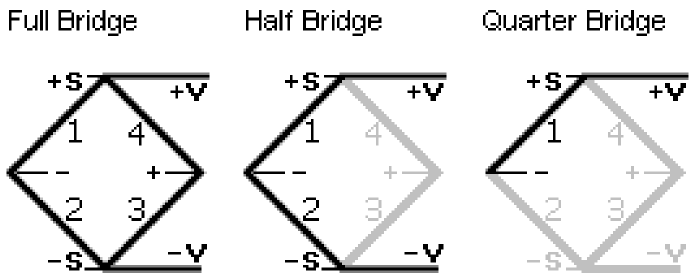

Strain Gauge Formulas – Wheatstone Bridge

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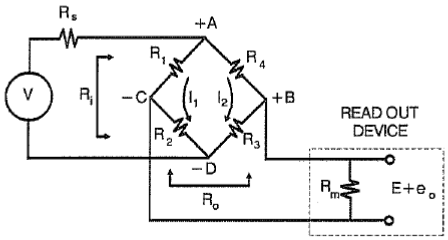

$$V_{BC} = \left(\frac{R_3}{R_4 + R_3} - \frac{R_2}{R_1 + R_2} \right) V = \left(\frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} \right) V$$

$$\frac{e_{OCV}}{E_{ex}} = \left[\frac{N \times GF \times \varepsilon}{4} \right]$$

Formula relates Bridge output voltage to strain

- Typical bridge set-up
  - E.g. Wheatstone bridge
  - Measured voltage dependent on input voltage and strain changes

Signal Conditioning for Strain Gauge

- Excitation Voltage
- Zeroing Capability
- Gain setting
- AC coupling for dynamic strain
- Bridge Completion

Bridge Configurations and Types of Strain

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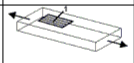
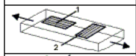
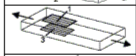
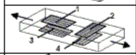
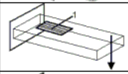
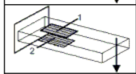
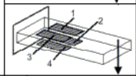
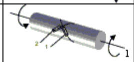
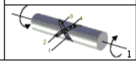
Strain	Gauge Setup	Bridge Type	Sensitivity MV/V @ 1000 uE	Details
Axial		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Also responds to Bending Strain.
		½	0.65	Better: Temperature compensated, but it is sensitive to bending strain.
		½	1.0	Better: Rejects Bending Strain, but not temperature. Must use dummy gauges if compensating for temperature.
		Full	1.3	Best: More sensitive and compensates for both temperature and bending strain.
Bending		¼	0.5	Good: Simplest to implement, but must use a dummy gauge if compensating for Temperature. Responds equally to Axial Strain.
		½	1.0	Better: Rejects axial strain and is temperature compensated
		Full	2.0	Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
Torsional and Shear		½	1.0	Good: Gauges must be mounted at 45 degrees from centerline. Axial and Bending forces produce equal strain and are hence rejected.
		Full	2.0	Best: More sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

Gauges must be oriented in specific directions to measure specific types of strain

- Combinations of several strains
  - To compensate for shear strain
  - To compensate for temperature
  - If loading direction is unknown

Note table taken form NI website

Examples of sensor types
Strain gauge

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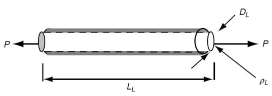
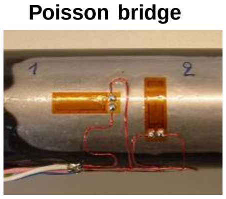


FIGURE 1.2 A resistance wire under mechanical load.

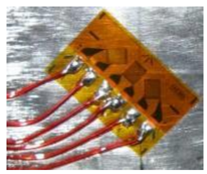
$$\Delta R = \left(\rho_L \times \frac{L_L}{\frac{\pi}{4} D_L^2}\right) - \left(\rho \times \frac{L}{\frac{\pi}{4} D^2}\right)$$

Single strain gauge

Poisson bridge



Strain rosette



- A strain gauge is one long resistive wire, embedded in a very thin foil
  - Unique property: resistance is proportional to the change in length
  - $\Delta R / R = k \times \varepsilon$
- Strain is defined as the change in length compared to the nominal length
  - $\varepsilon = \Delta L / L$
  - Positive ΔL = "tensile" strain
    Negative ΔL = "compressive" strain
- Strain unit = "microstrain" or με (μE)
  - because of very small relative length changes (1E-6 to 1E-3)
- Combinations of several strains
  - To compensate for shear strain
  - To compensate for temperature
  - If loading direction is unknown
- Typical bridge set-up
  - E.g. Wheatstone bridge
  - Measured voltage dependent on input voltage and strain changes

Single Ended Coupling

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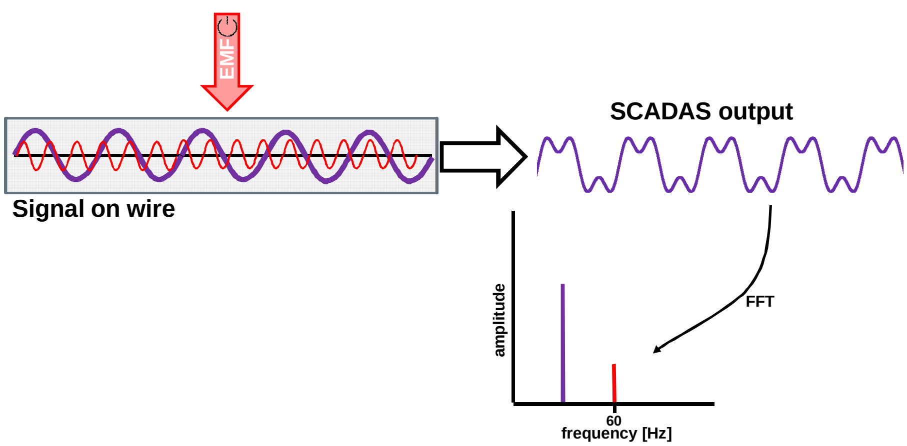

Differential Coupling (common mode rejection)

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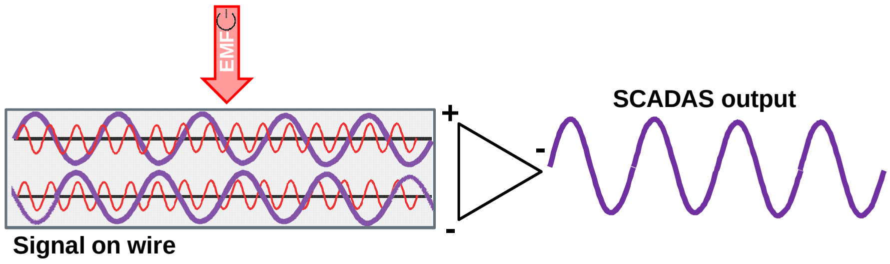

Bridge conditioning – Common Mode Noise Rejection Demo

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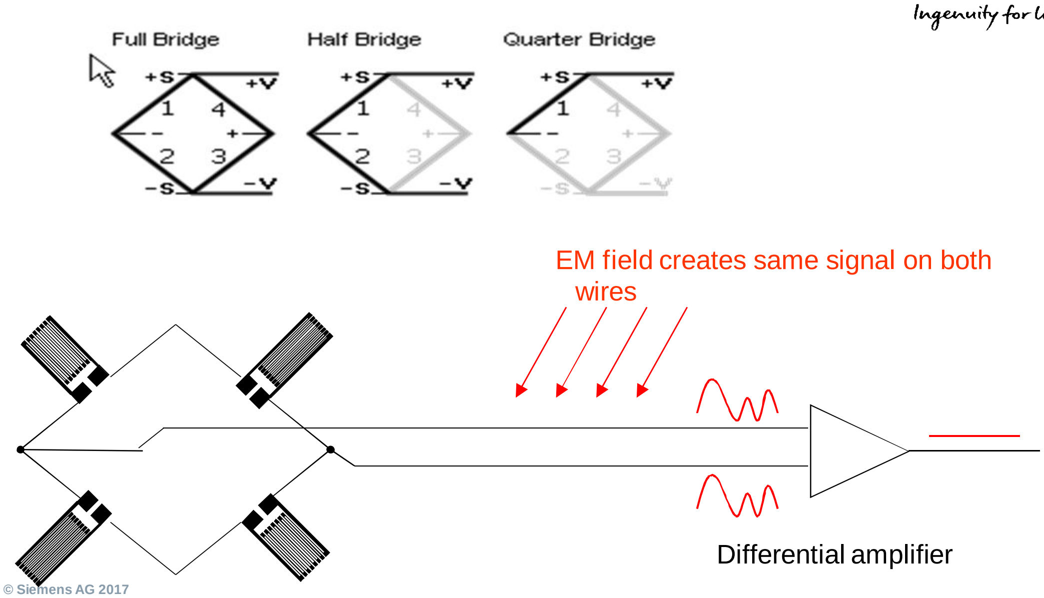

Common Mode Noise rejection Demo

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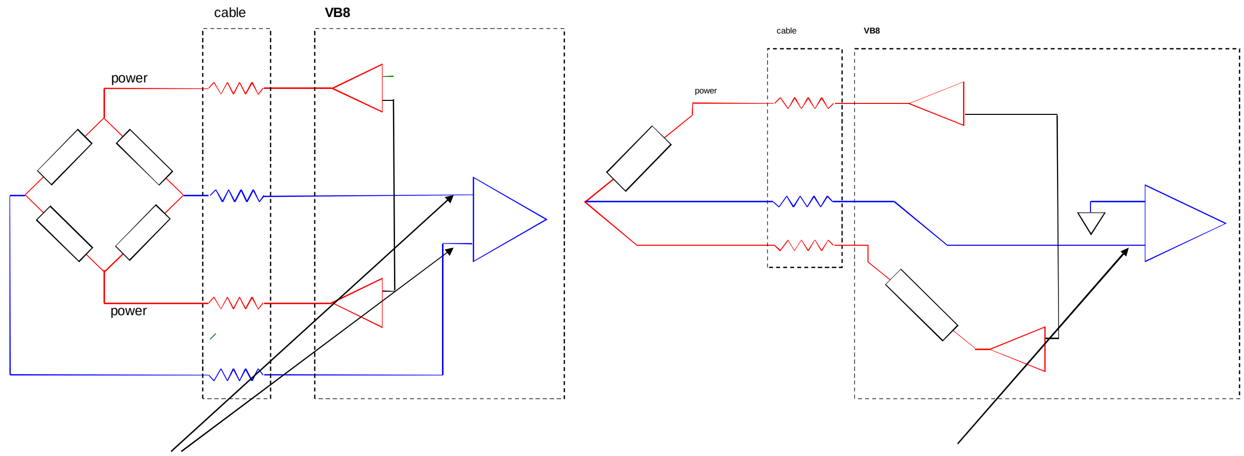

Full Bridge

2 Wire Signal

Quarter Bridge

1 Wire Signal

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GENERAL ACQUISTION DEMO AND COMMON MODE REJECTION SHUNT CHECK DEMO

AC Voltage Excitation

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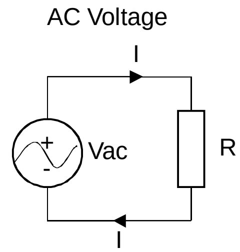
1. Less commonly used for strain gauges
2. Some transducers like LVDT and RVDT require AC excitation
3. Can be used on same circuits as constant voltage source
4. Requires a AC source with carrier frequency in the KHz range
5. Requires a demodulation circuit
6. **Bandwidth limited** due modulation a demodulation process
7. Excellent at rejecting noise



AC Excitation Circuit

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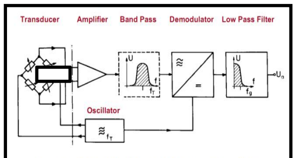

Fig. 3 Principle of Carrier Frequency Amplifier

Note: Diagrams taken from "HIGH-PRECISION MEASURING TECHNIQUE FOR STRAIN GAGE TRANSDUCERS" by Manfred Kreuzer

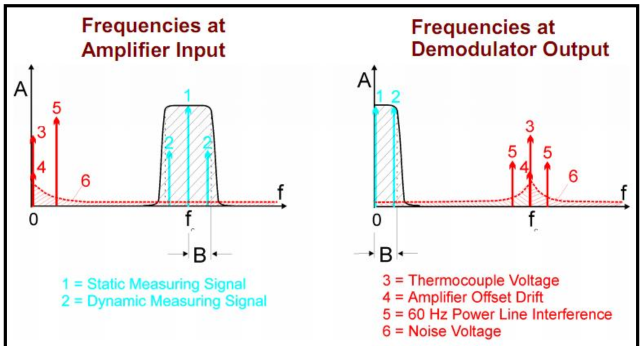

Fig. 4 Frequency Transformation by Carrier Frequency Technique

Dynamic Strain – Constant Current

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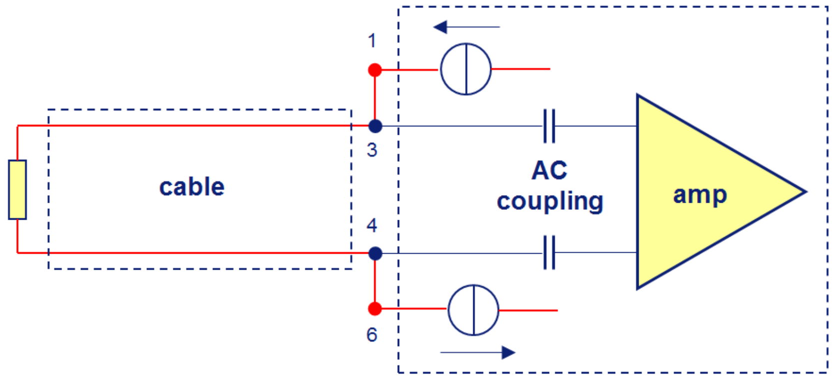

Examples of sensor types
Force transducers

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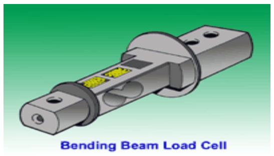
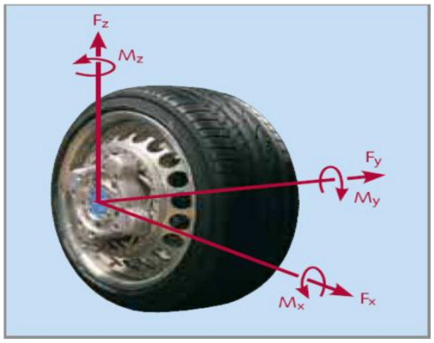
strain-based force cell



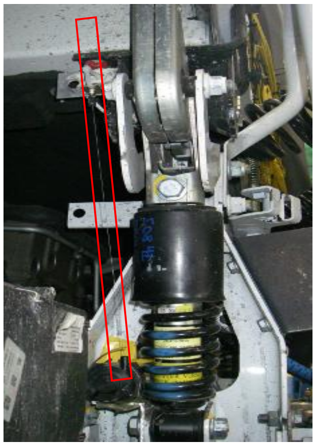
Wheel Force Transducer



Uni-axial Force cells
- Strain gauges measure local strain à can be converted to stress
- Local stress is proportional to load applied to the structure

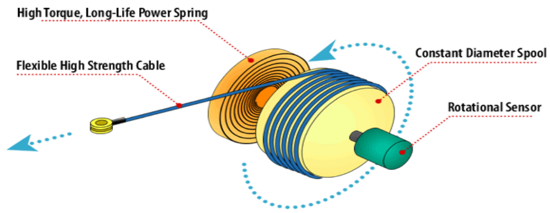
Wheel Force Transducer
- a complete wheel with sensors that measure the forces and the moments in all three directions
- Efficient road load data collection

Examples of sensor types
displacement transducers



String pot sensor

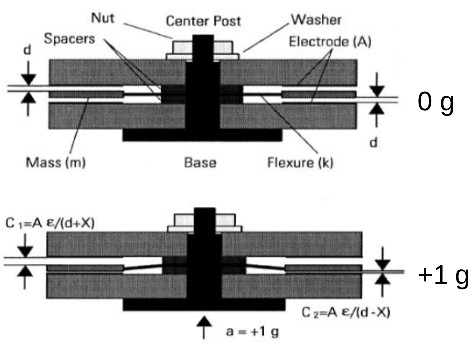
- Measures relative displacement between to components
- Based on high strength wire, rotational spring and rotational sensor



Note: Limited Frequency Response

Examples of sensor types
DC accelerometers

Capacitive accelerometer



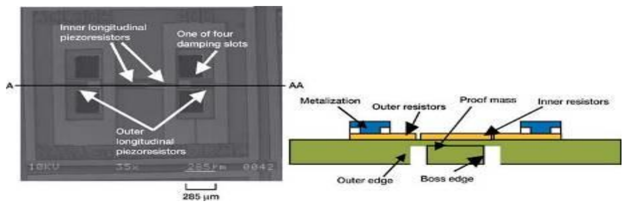
Measure down to 0 Hz

Allow to measure very low frequent accelerations, e.g. curving maneuvers

Types

- Capacitive accelerometers
- 0 Hz acceleration is measured based on distance between mass and electrodes
- MEMS (micro electro-mechanical systems)
- Uses the piezo-resistive effect of silicon

Piezo-resistive accelerometer



INTEGRATION OF ACCEL TO DISPLACEMENT Demo

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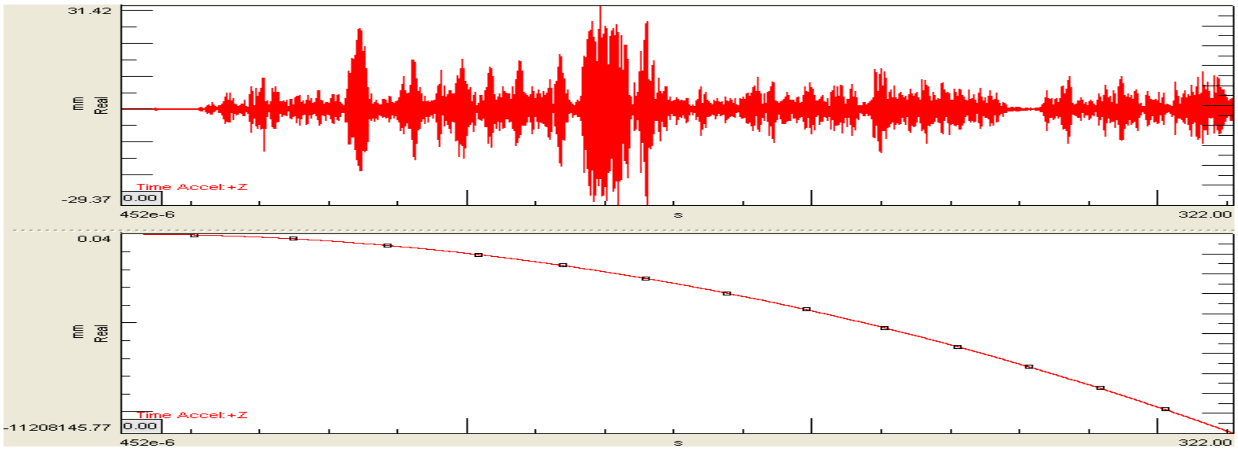

Id	Formula	Point Id
CH136	INTEGRATE(FILTER_HP(INTEGRATE(FILTER_HP(CH1;2;2);2);2;2);2)	Displacement_Filter
CH137	DOUBLEINTEGRATE(CH1;2)	Displacement_No_Filter

CAN Bus History

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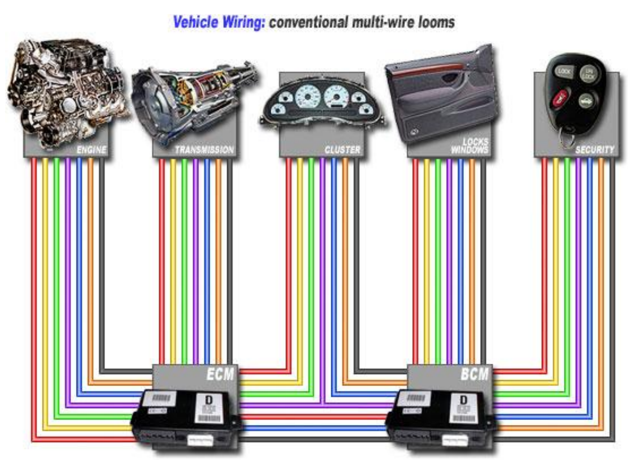

- From 1940 to 1986: Increasing wires to communicate between components
- Wiring harnesses became bigger, heavier

CAN Bus

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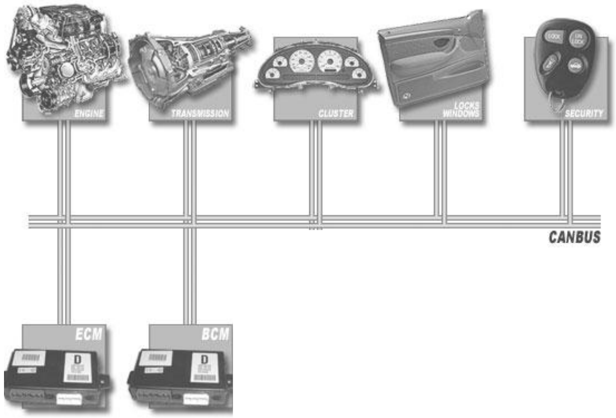

- BMW 850 Coupe in 1986, First car with Canbus
- Wiring harness reduced by 50 kg
- More reliable, single bus
- Canbus is a digital bus where a single wire can carry multiple signals (upto 1 Mps)

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CAN Bus

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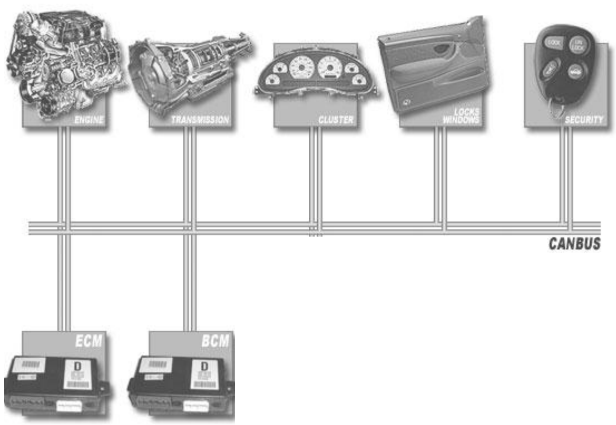

- Modern car components have Electronic Control Units (ECUs)
- ECUs usage is growing.
- CANBus used for messages transmitted between ECUs

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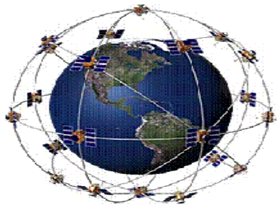
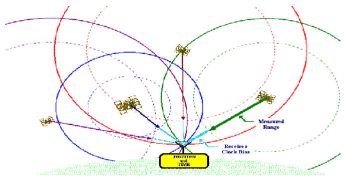
DBC Files – OBD Messages

```
VERSION ""

BS_:

BU_: LMS_OBD2

BO_ 2024 OBD_PIDs: 8 LMS_OBD2
 SG_ C004_Calculated_Load_Value m4 : 31|8@0+ (0.392156862745098,0) [0|100] "%" LMS_OBD2
 SG_ C005_Engine_Coolant_Temperature m5 : 31|8@0+ (1,-40) [-40|215] "°C" LMS_OBD2
 SG_ C00C_Engine_RPM m12 : 31|16@0+ (0.25,0) [0|16383.75] "rpm" LMS_OBD2
 SG_ C00D_Vehicle_Speed m13 : 31|8@0+ (1,0) [0|255] "km/h" LMS_OBD2
 SG_ C00E_Ignition_Timing_Advance m14 : 31|8@0+ (0.5,-64) [-64|63.5] "°" LMS_OBD2
 SG_ C00F_Intake_Air_Temperature m15 : 31|8@0+ (1,-40) [-40|215] "°C" LMS_OBD2
 SG_ C011_Absolute_Throttle_Position m17 : 31|8@0+ (0.392156862745098,0) [0|100] "%" LMS_OBD2
 SG_ C01F_Time_Since_Engine_Start m31 : 31|16@0+ (1,0) [0|65535] "s" LMS_OBD2
 SG_ C033_Barometric_Pressure m51 : 31|8@0+ (1,0) [0|255] "kPa" LMS_OBD2
 SG_ C046_Ambiant_Air_Temperature m70 : 31|8@0+ (1,-40) [-40|215] "°C" LMS_OBD2
 SG_ SignalKind M : 16|8@1+ (1,0) [0|0] "" LMS_OBD2


BA_DEF_ "Baudrate" INT 0 1000000;
BA_DEF_DEF_ "Baudrate" 0;
BA_ "Baudrate" 500000;
```

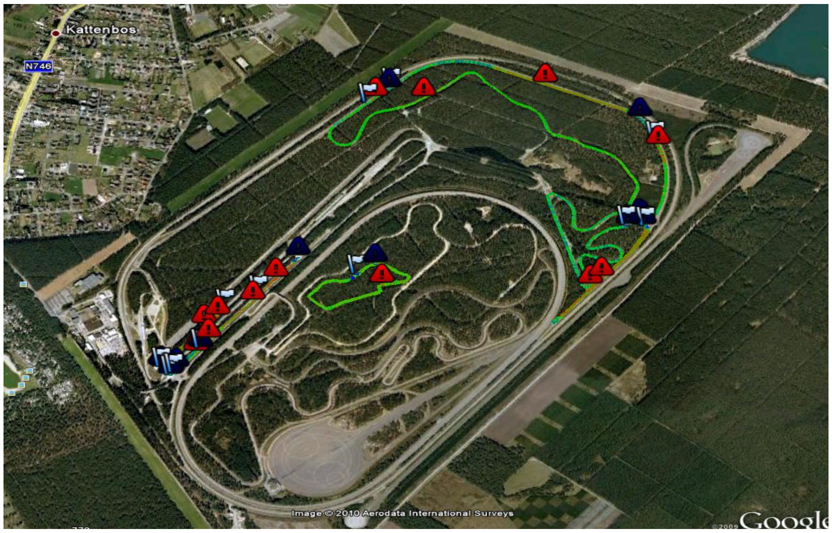
GPS





The Global Positioning System is a constellation of 24 (+3 reserve) satellites for accurate determination of the position of a receiver system on the ground
Based on the signals received by at least 4 satellites (not too close to each other) the receiver on the ground can determine its position.
Enhancements to GPS accuracy can be provided by DIFFERENTIAL GPS, where an extra ‘satellite’ is added by means of a station on the ground broadcasting a GPS signal
The Russian counterpart of the GPS system is called GLONASS
In order to become independent from the USA for global positioning services, the European Space Agency is planning to deploy a proper system called GALILEO. Roll-out of this system is foreseen by the year 2013.

Google Earth



GOOGLE EARTH DEMO

Video Recording During Acquisition

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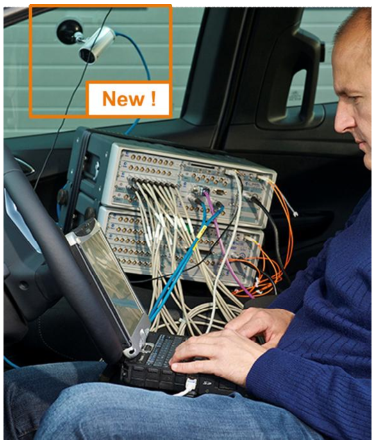

Post Processing Synced with Time Data

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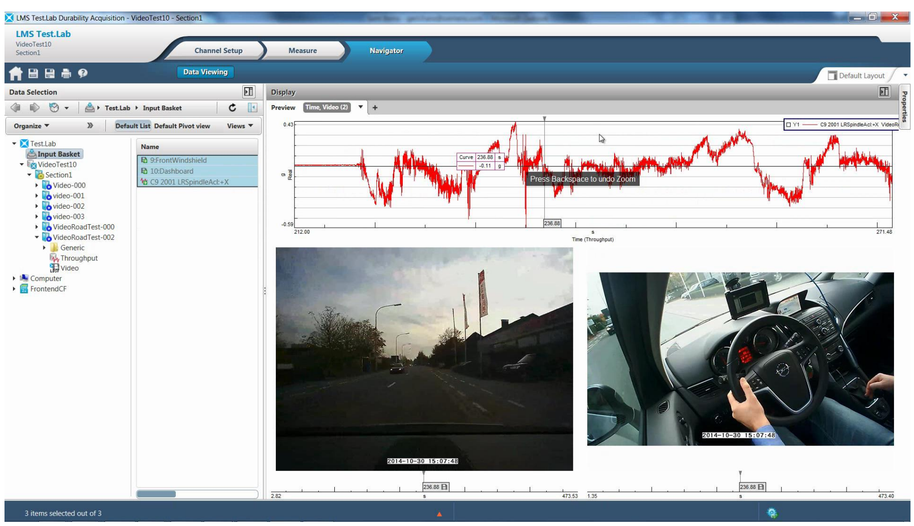
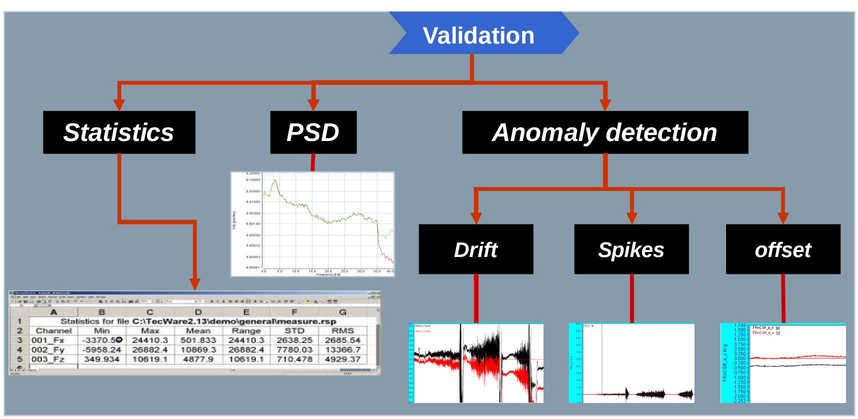


VIDEO DEMO

How to capture customer usage ?
Data validation

Pain

- Durability data = lots of channels, long duration measurements How to validate?



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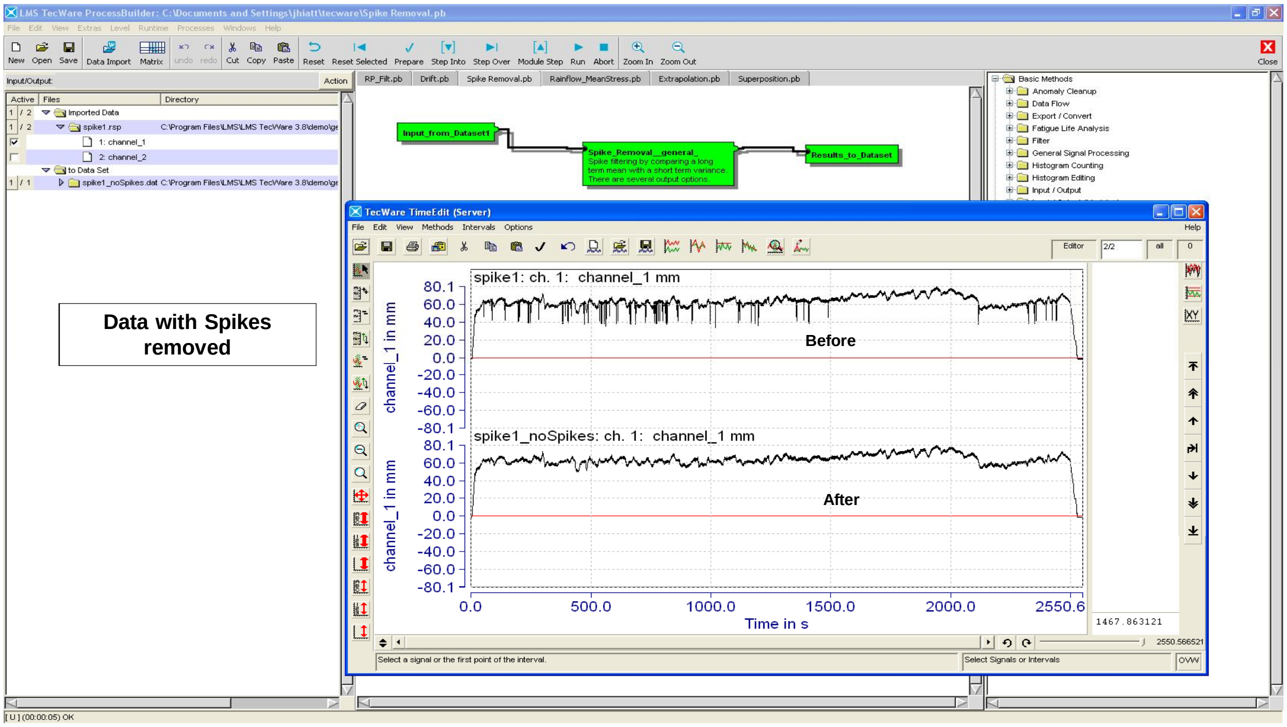
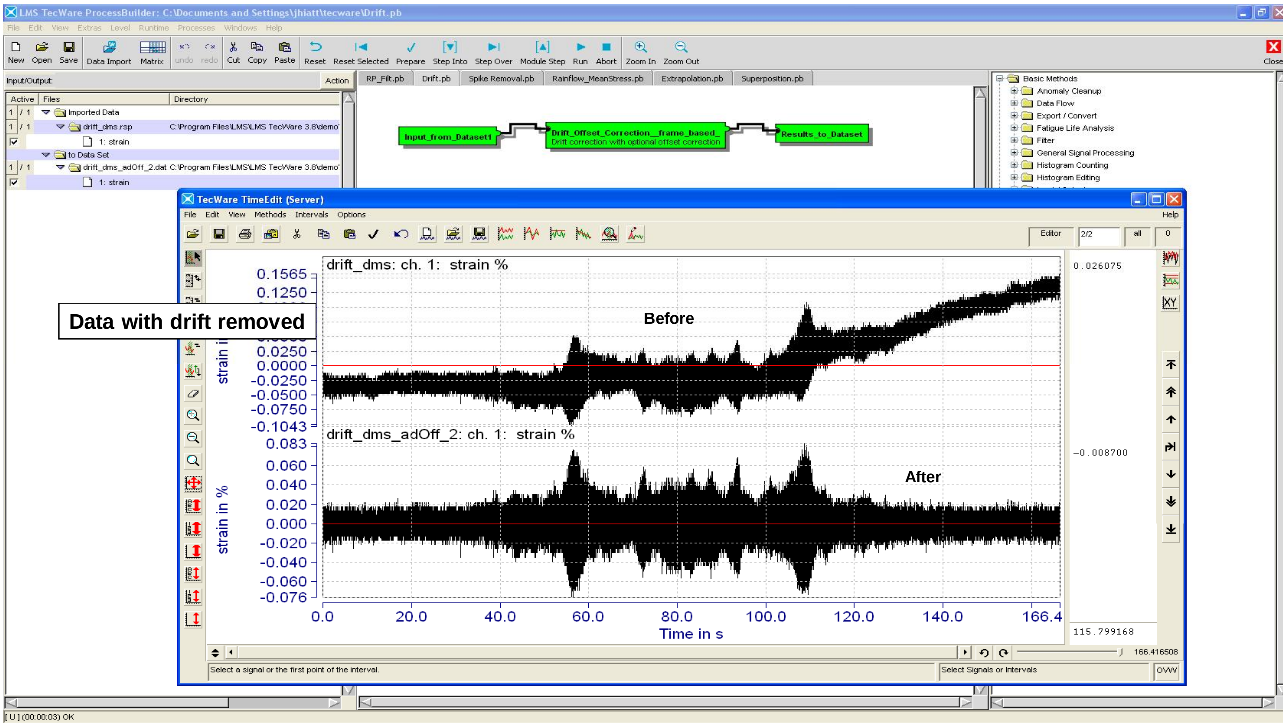
SPIKE AND DRIFT REMOVAL DEMO

TecWare with Drift.rsp and spikes.rsp





Loads: Simulation or Test

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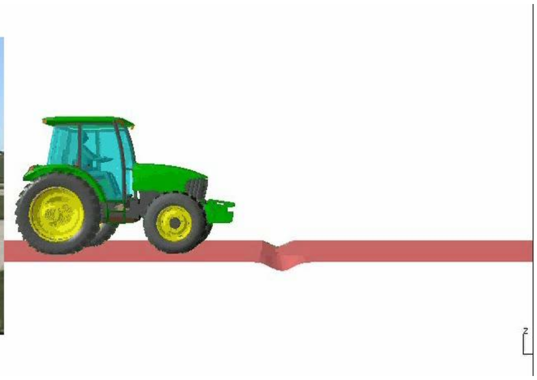
How do we calculate input loads and relate those input loads to stresses at nodes in our model



One reason simulation is useful… variant analysis

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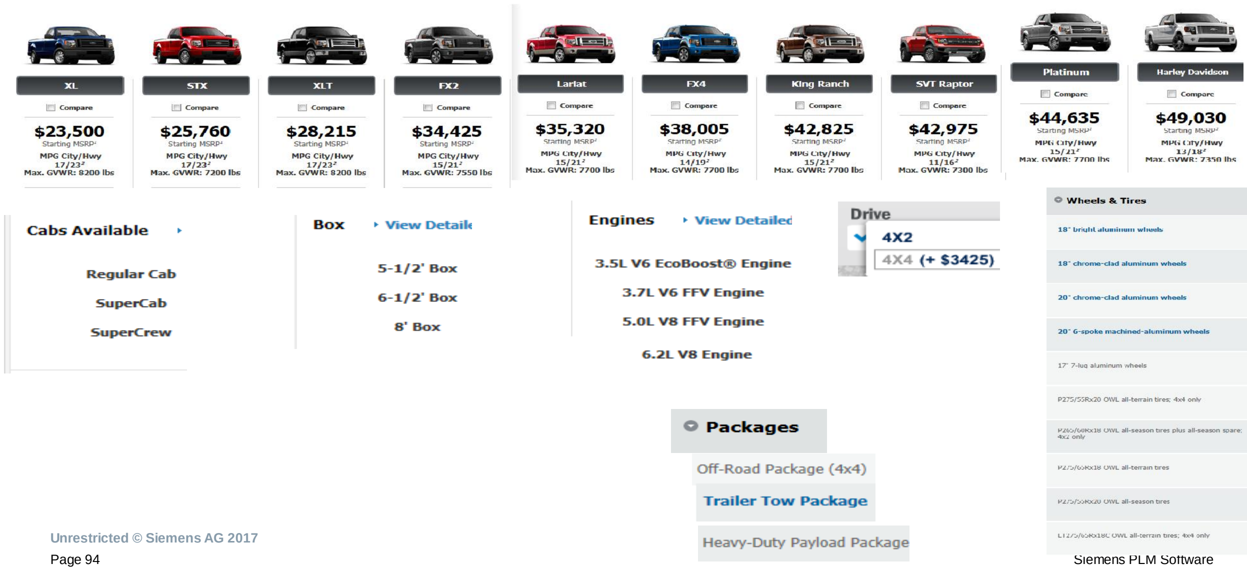

Simulation Fatigue Process

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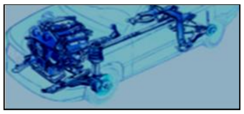
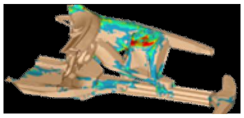
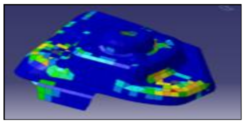


Loading



Mesh + Loading → Stress analysis → Local Stresses



Local Stresses → Fatigue analysis → Damage

1. Get realistic load time histories The fatigue damage is highly influenced by the loads applied to the structure.
2. **Get the local stress/strain tensor histories** Fatigue depends on the complete stress/strain time histories in the structure:
3. Accumulate damage Depending on the fatigue target, the material and loading type fatigue simulation accumulates the damage.

Simulation Fatigue Process

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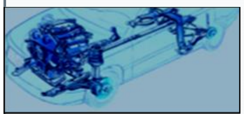
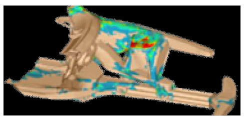


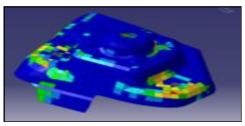
Loading

1. Get realistic load time histories The fatigue damage is highly influenced by the loads applied to the structure.



Mesh + Loading → Stress analysis → Local Stresses

2. **Get the local stress/strain tensor histories** Fatigue depends on the complete stress/strain time histories in the structure:



Local Stresses → Fatigue analysis → Damage

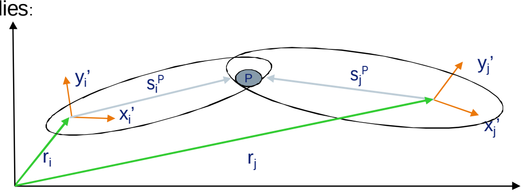
3. Accumulate damage Depending on the fatigue target, the material and loading type fatigue simulation accumulates the damage.

What is Multibody Dynamics for Load Prediction?

Bodies: Maximal Coordinate formulation: 7dof per Body.
Constraints: Idealized versions of real-life joint which remove relative DOF between bodies

Planar example: 2-D revolute joint:

- Point P is constrained to be in the same global location for both bodies:



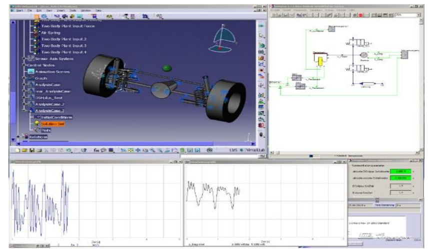
$$\Phi^{r(i,j)} = r_i + \mathbf{A}_i s_i'^P - r_j + \mathbf{A}_j s_j'^P$$

§Where A is the transformation matrix: $A = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_a \\ \gamma \end{bmatrix}$$

Φ_q = Constraint Jacobain
Q_a = Applied Forces (Bushing, tsda's, etc.)
M = mass matrix
λ = LaGrange Multipliers
$\ddot{q}$ = accelerations
γ = Second derivative of acceleration equations

LMS Virtual.Lab Motion
Capturing industry best modeling practices



Mechatronics

Modular assembly

Verticals

Automation

CAD
Create in VL
or Import

Kinematics
Joints
Constraints
Initial Conditions

Dynamics
Forces (Gravity, Friction, Damping, Stiffness, …)

Flexible bodies
CAE / Test modes
Superposition

Solving
Fast
Accurate

Post-processing
2D / 3D
Root cause analysis

VL Durability
VL NVH
VL Acoustics

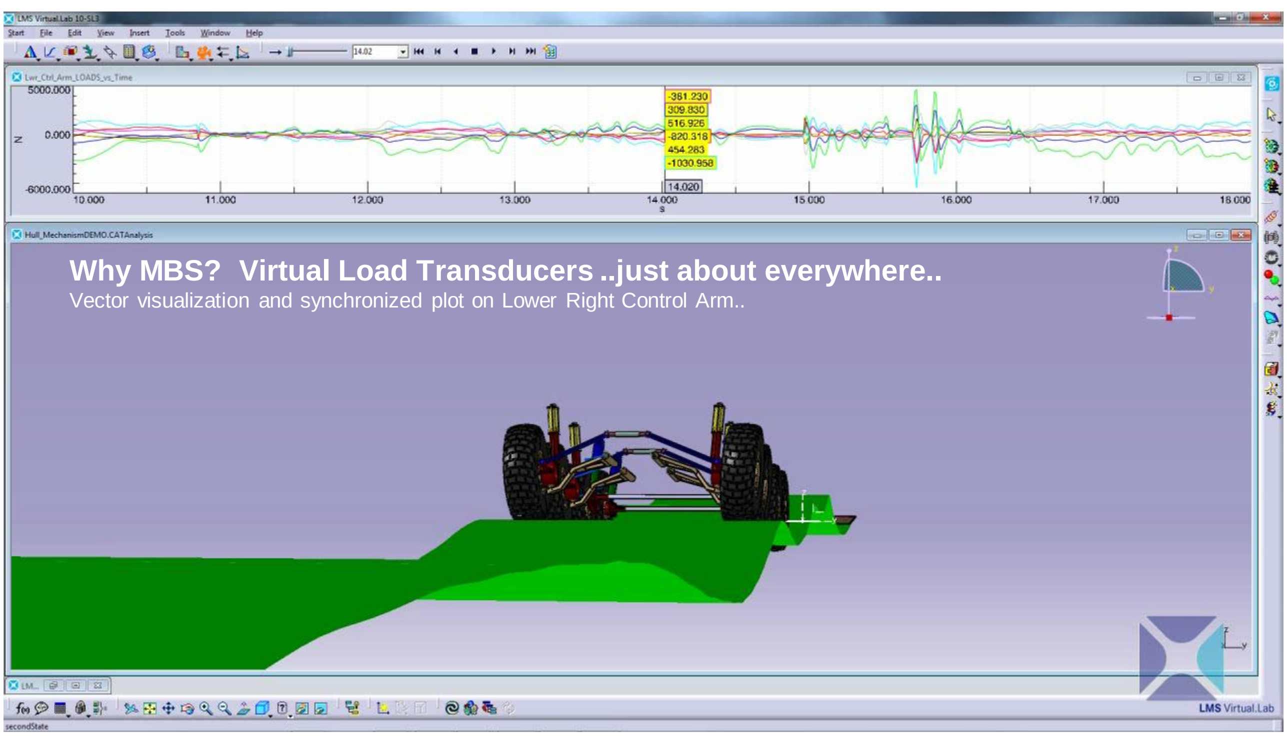
Control system

Electric/ hydraulic model

TEST data

Parameterization
Optimization

Siemens PLM Software



Why use Simulation for Load Prediction?

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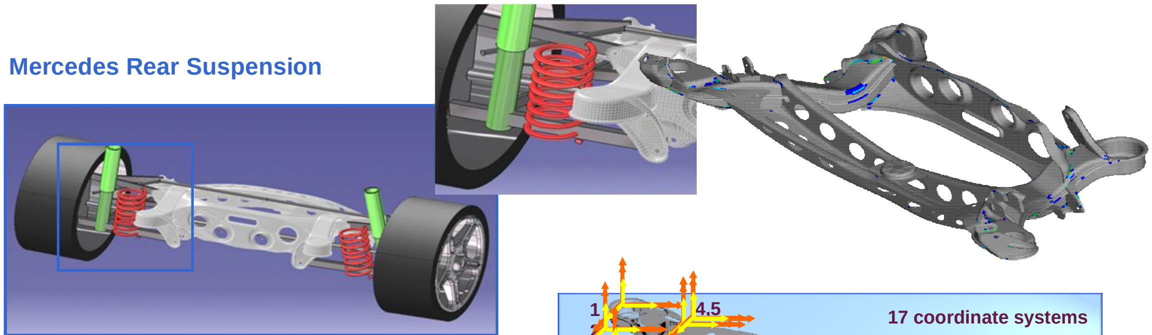
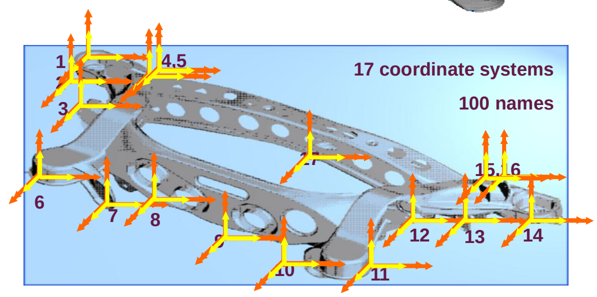
Mercedes Rear Suspension





- "Internal" vs. "External" Loads
- Many load paths involved

Why MBS? Virtual Load Transducers ..just about everywhere..

..For a variety of events and architectural variants..

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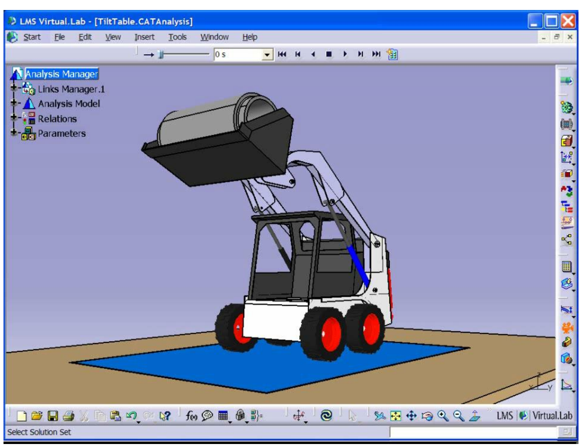

- Reaction Forces anywhere..
- Various Loading/Events/What if Scenarios
- Useful for potentially unsafe setups for physical test, or prohibitively expensive due to scale..

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \end{Bmatrix} = \begin{Bmatrix} Q_a \\ \gamma \end{Bmatrix}$$

Φ_q = Constraint Jacobain
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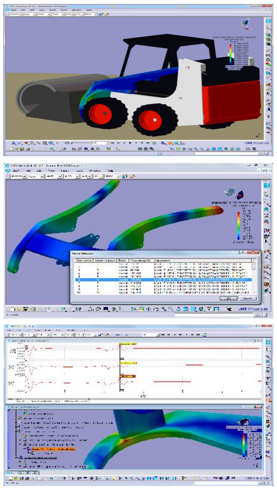
Flexible Bodies

Generating and using Finite Element data



Deformations occur in every mechanism

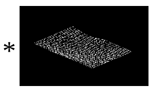
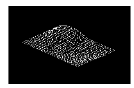
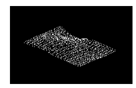
Including flexibility dramatically can improve the fidelity of your simulation

- Deformations and loads are more accurate
- Frequency response of mechanism can be analyzed

Useful for connecting to NVH and Durability analyses

Flexibility uses modal synthesis

- Deformation is a linear combination of mode shapes
- Normal modes: natural vibration of the body
- Static modes: deformation due to localized loading
- Orthogonalized combined mode set: Craig-Bampton modes for accurate AND fast results

Bodies Shape $= a_1$ *  $+ a_2$ *  $+ a_3$ *  …

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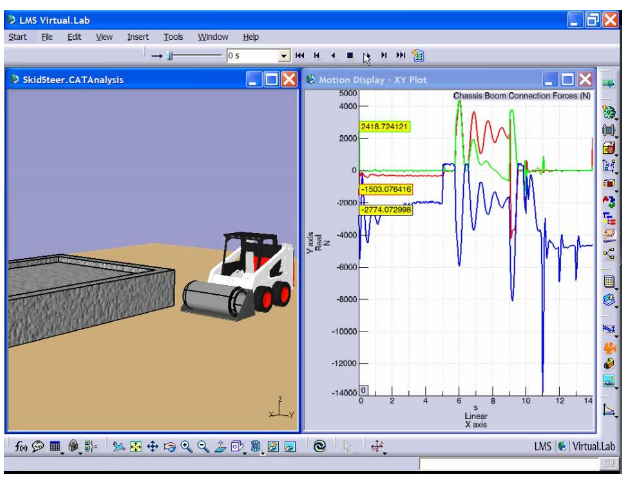

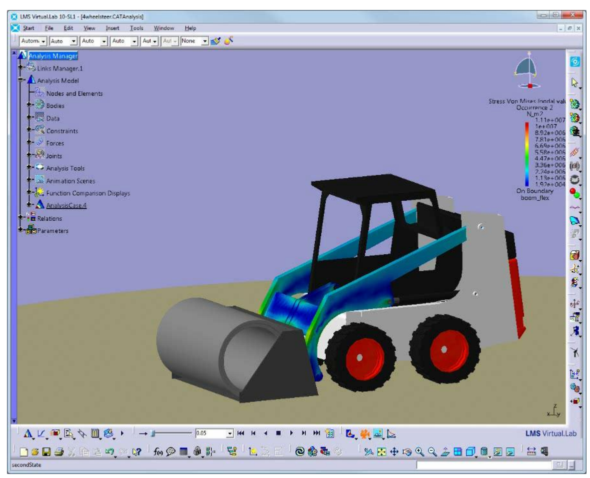

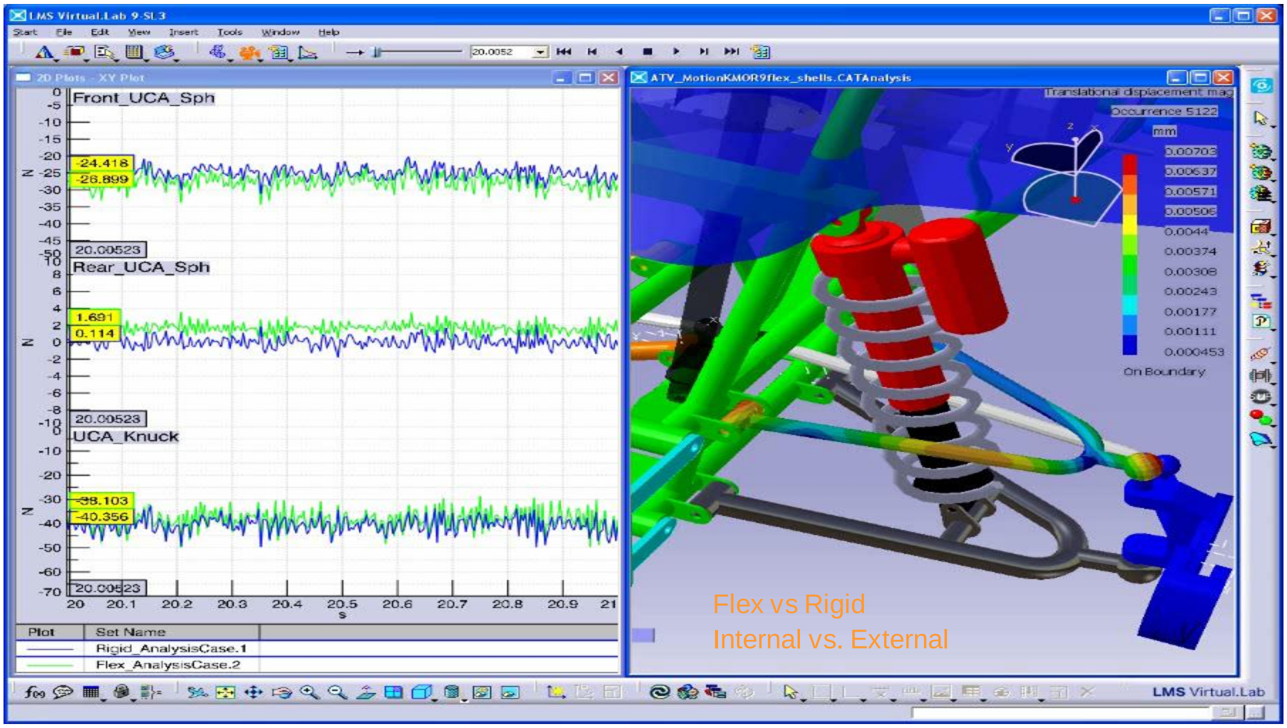

John Deere uses Virtual.Lab Motion to simulate Stress Time-history of Loader Operation

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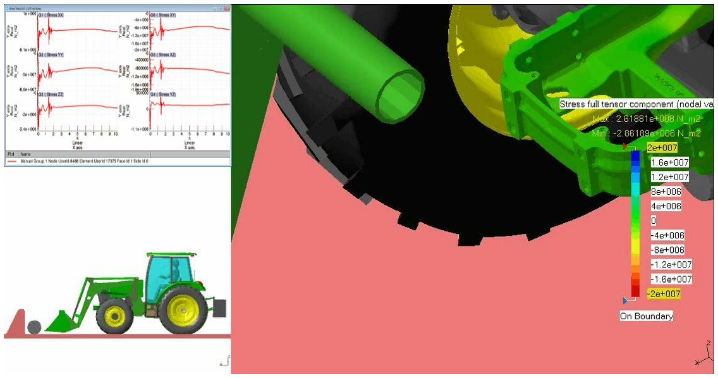
Ingenuity for life

Identify stress levels and hotspots in front cross member during common loader maneuver.



Model courtesy of Deere PEC

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QUARTER CAR FLEX BODY DEMO

How to get Simulated Loads to Match Test ?

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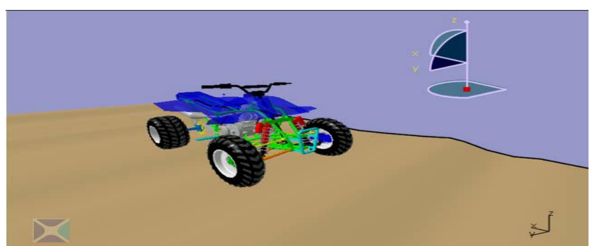

Considerations…

- Is a physical prototype available?
- Only track data from predecessor or similar vehicle is available
- MBS model of the new vehicle is not fully detailed
  - Driver behavior difficult to simulate
  - Soil effects
  - Tire effects

Siemens PLM Software

LMS Virtual.Lab Motion
Multiple Tire Solutions

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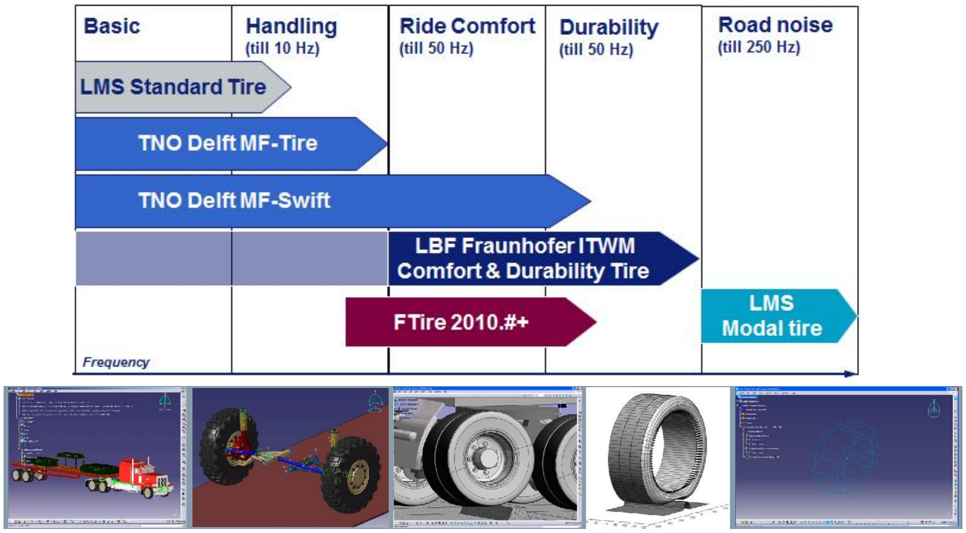

Physical Test-Rig

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..and as if “Regular Tires” weren’t hard enough already..

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Durability Test Rigs tackle a remarkably similar problem

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Ingenuity for life

Goal:
- Have the rig reproduce the same loads as seen on a test track
- More repeatability, controllability, measurability

But there are “errors”
- Tires often removed
- Instrumentation attached
- The rig itself has it’s own dynamics directly coupled

Rig Control Algorithms solve this problem

Time Waveform Replication, a.k.a. “T W R”

Hybrid Road: Unconstrained full vehicle simulation

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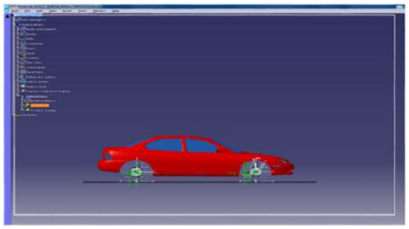
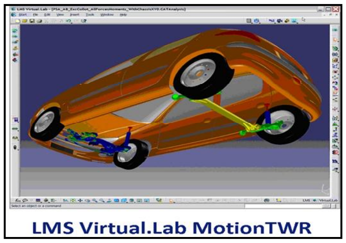
1



Direct application of loads to unconstrained vehicle will cause the vehicle to rotate / roll over after short simulation time è **unacceptable**

2



Vertical loads are used to **back-calculate (Motion TWR)** the equivalent vertical displacement at the tire patch/wheel center.

The other forces moments are applied directly.

?

It’s an **inverse dynamic** problem that a normally a general purpose multi-body code cannot handle

LMS Motion TWR workflow

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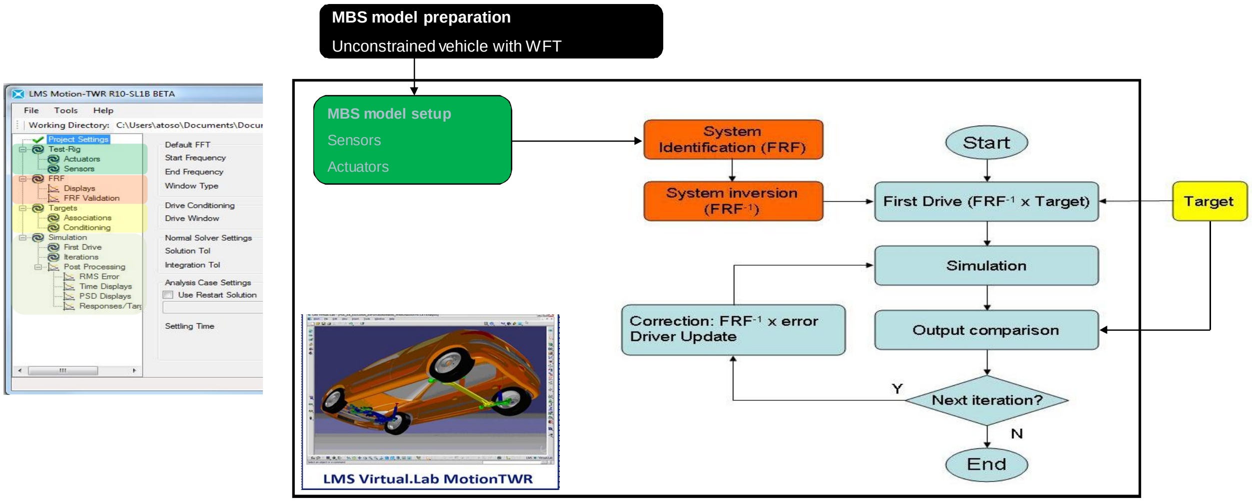

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LIVE TWR DEMO w/MOTION

System Identification (1/2)

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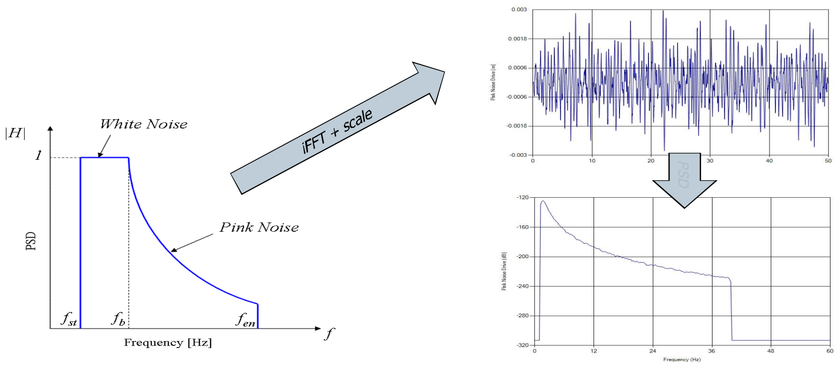
White Pink noise is generated in the frequency band of interest with:
- Standard deviation
- Border frequency
- Power
- Start frequency
- End frequency

$$WPN(f) = \begin{cases} \left(\left(\frac{1}{f_b}\right)\right)^{2\cdot p}, f_{st} \leq f < f_b \\ \left(\frac{1}{f}\right)^{2\cdot p}, f \geq f_b \end{cases}$$



Results – time domain

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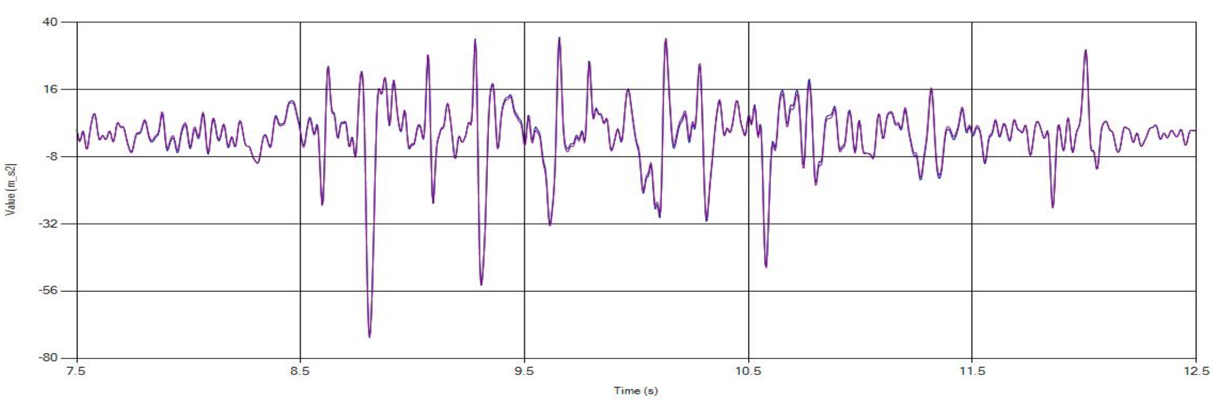
Response vs. Target – Iteration 5



Results – frequency domain and XY plot

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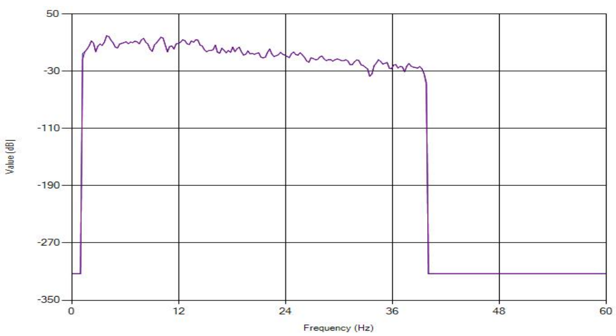
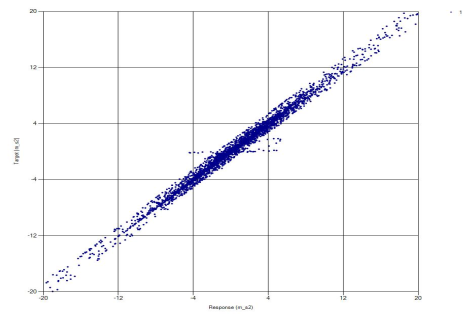
Response vs. Target – Iteration 5





CAE Durability Road Loads Prediction

Current industry practice

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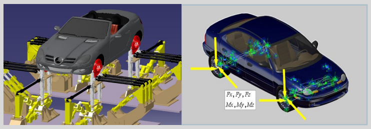
Full Vehicle Loads
Hybrid CAE-TEST



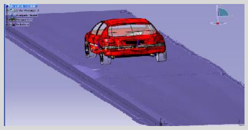
Simulation set-up:
(Predecessor) WFT measurements
Unconstrained MBS model of predecessor & new vehicle

Model excitations:
"Driving function" (usually displacements and loads) which are back-calculated from measurements

- (+) Realistic simulation
- (+) Accurate body loads
- (+) Avoid tire, road, and driver modeling
- (+) More responses available
- (−) Still test data required

LMS Motion-TWR

Full Vehicle Loads
100% CAE: Digital Test Track



Simulation set-up:
MBS vehicle model
MBS durability tire model
3D road surface model
Driver model
Driveline model

Model excitations
3D road profile

- (+) "True" forward prediction.
  (No test or predecessor data required)
- (+) All maneuvers are possible
- (−) Tire, Soil, & Driver parameter identification

Fraunhofer LBF
cosin scientific software
TNO
IPG

Siemens PLM Software

How to get Simulated Loads to Match Test ?

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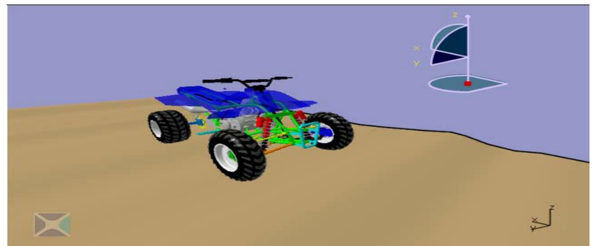

Considerations…

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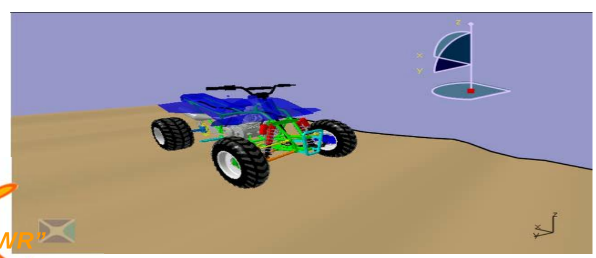
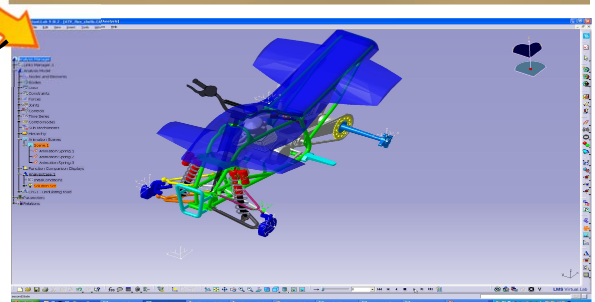
How to get Simulated Loads to Match Test ?





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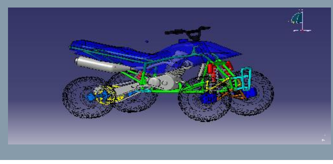
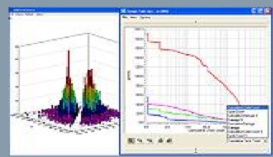
Durability Agenda

Durability Basics
Fatigue, Stress, Strain

Load Determination
Measurements, Multi-Body Simulation

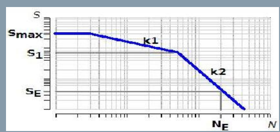


Loads and Damage
S-N Curve, Cycle Counting



Load Characterization
Establishing Durability Targets: Superposition, Extrapolation

Fatigue Life Predictions
Infinite Life, Stress Life, Strain Life



Accelerated Testing & Analysis
RP-Filter, Mission Synthesis

The Durability Process

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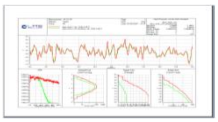
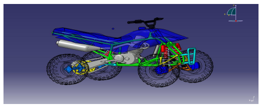
Understanding Operational loads	Target setting & Test Procedures	Design Optimisation Virtual Product Validation	Physical Product Optimisation & Validation	Final Product Test
Acquisition	Analysis	Simulation	Shaker testing	Sign-off





The SN Curve

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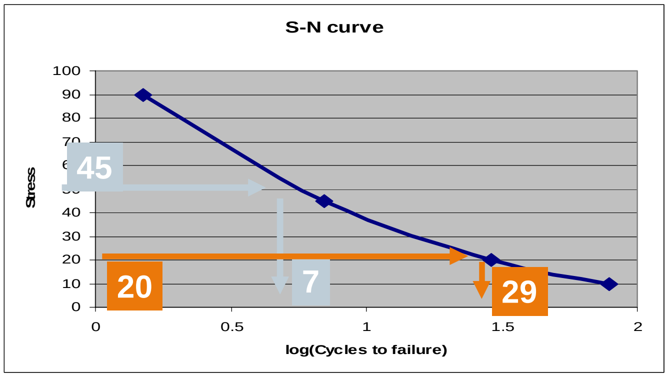

Cycles to Failure from a Constant Amplitude Load test

SN Curve

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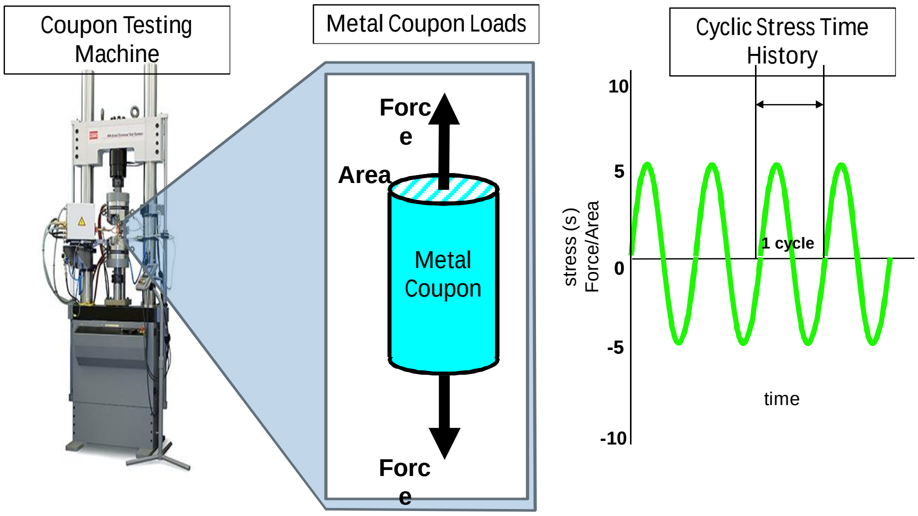
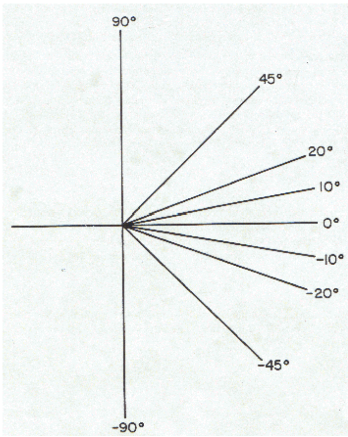


What is an S-N curve ?
The Jumbo Paper Clips experiment



Angle / Load	Cycles to failure
90	1.5
45	7
20	29
10	79

SN-Curve

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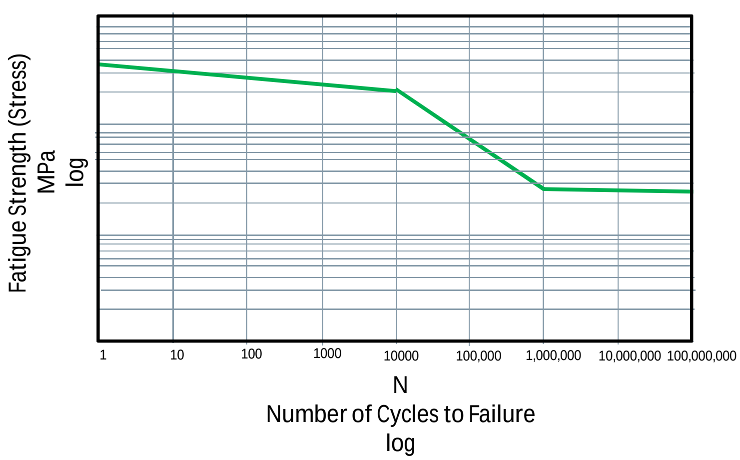

SN Curve

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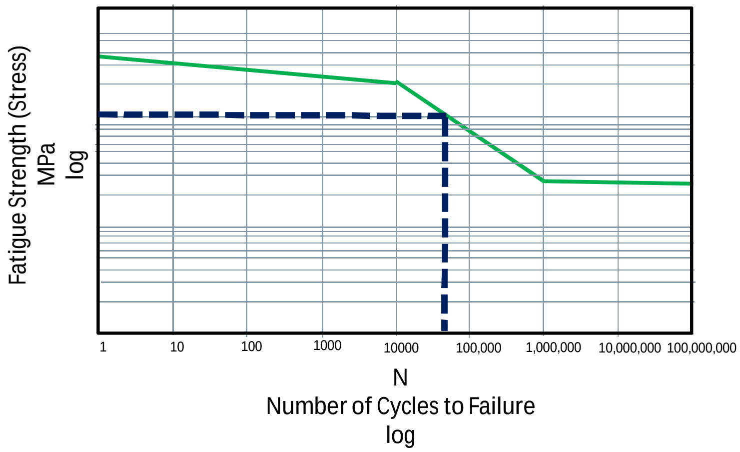
Ingenuity for life



SN Curve

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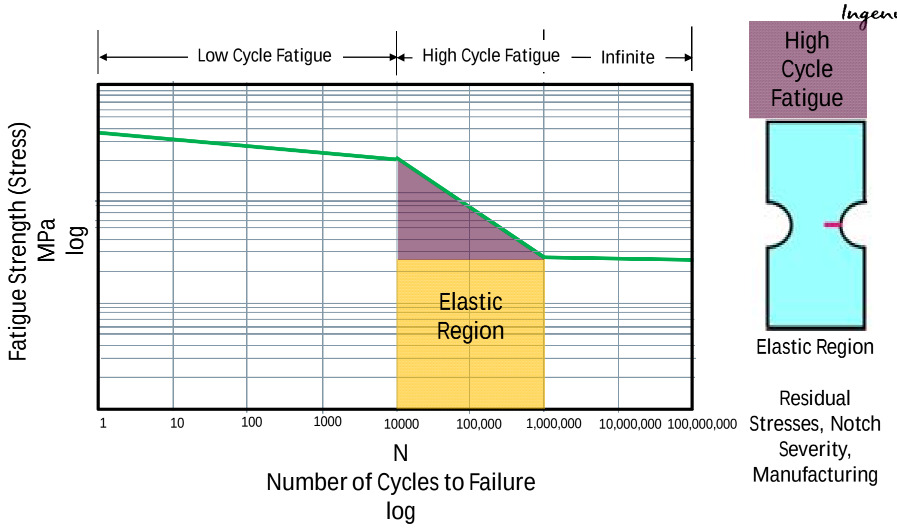

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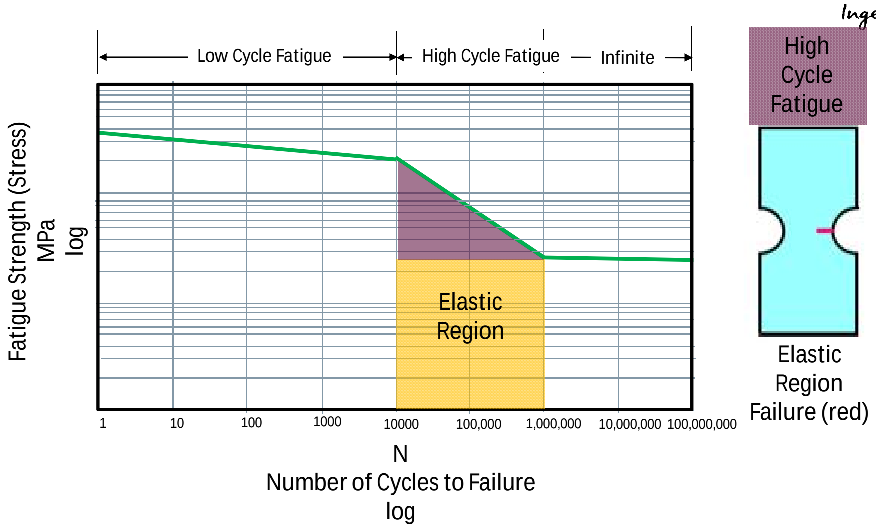

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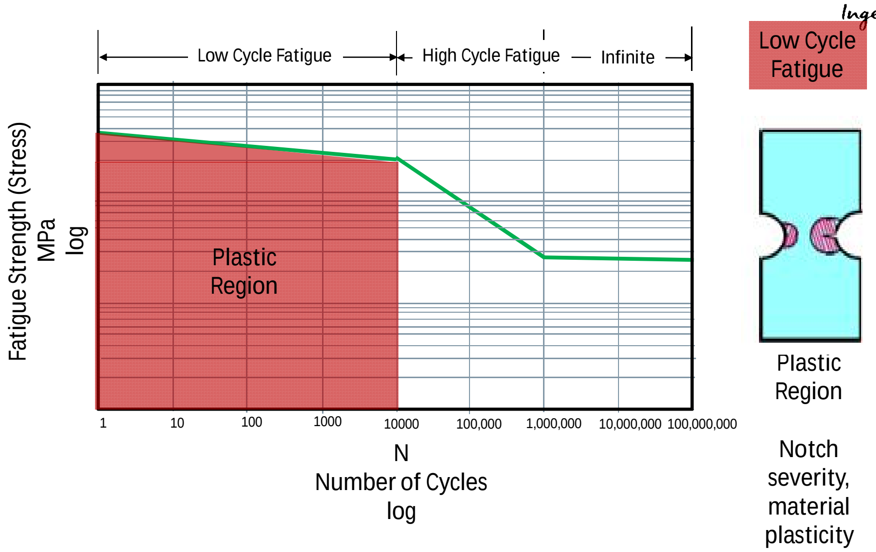
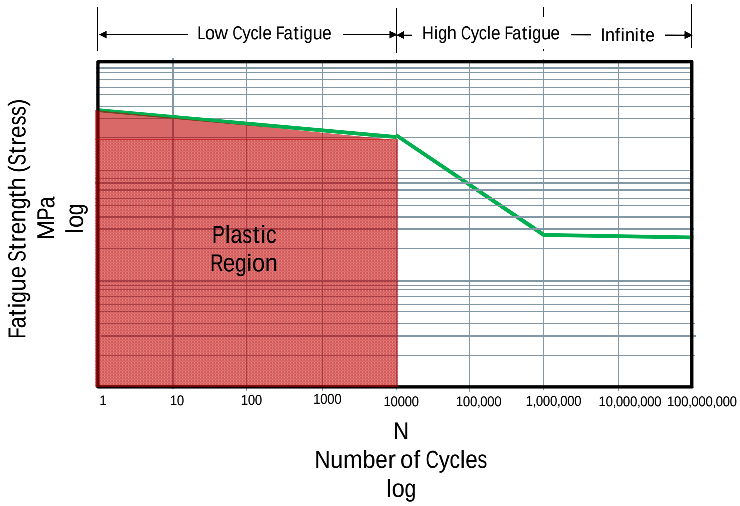
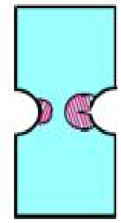


SN Curve

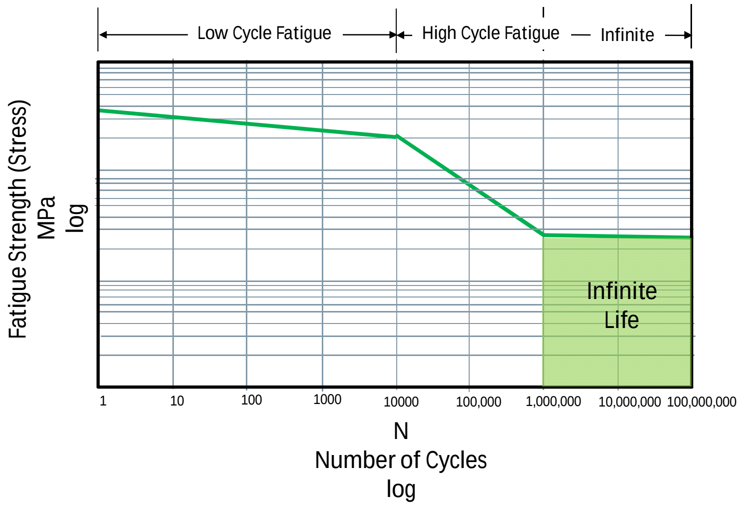


Low Cycle Fatigue

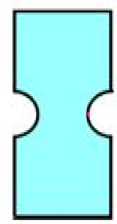


Plastic Region Failure (red)

SN Curve

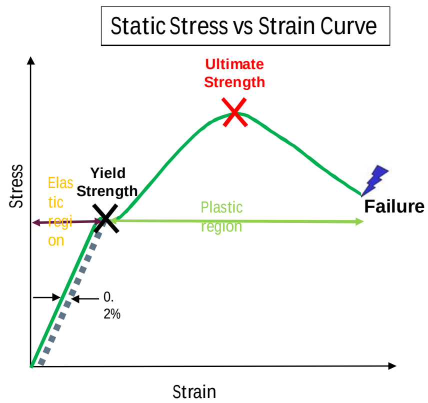


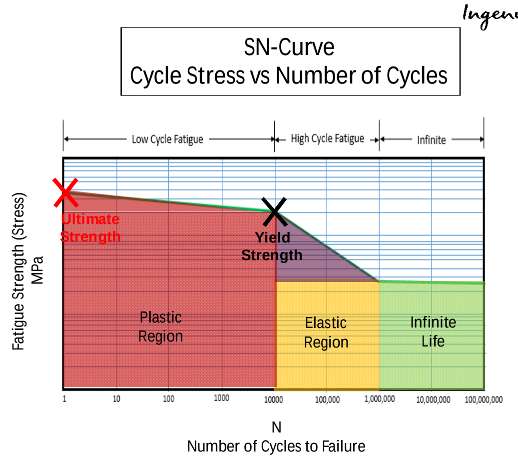
Infinite Life



SN Curve

SIEMENS
Ingenuity for life





SN Curve

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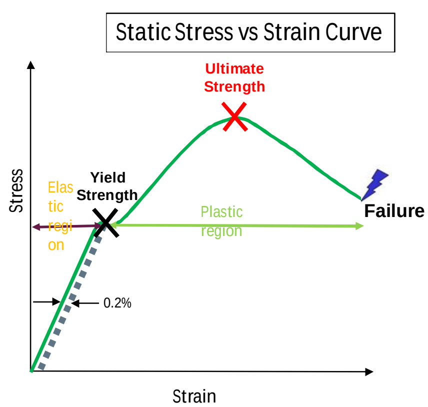

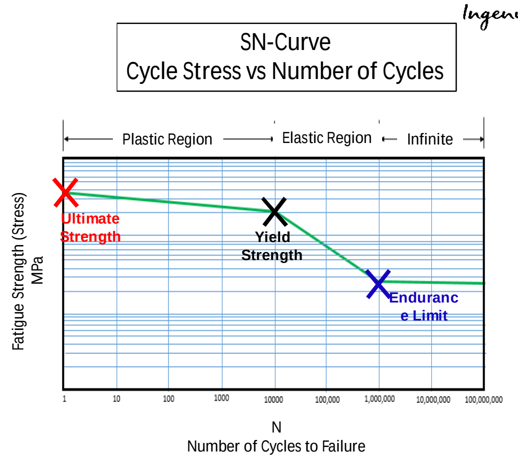

What is an S-N curve ?

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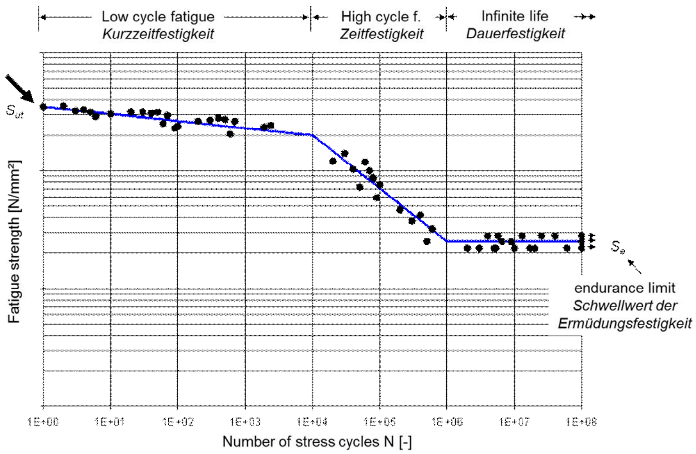

What is an S-N curve ?
Wöhler tests

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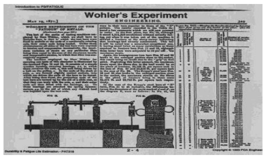
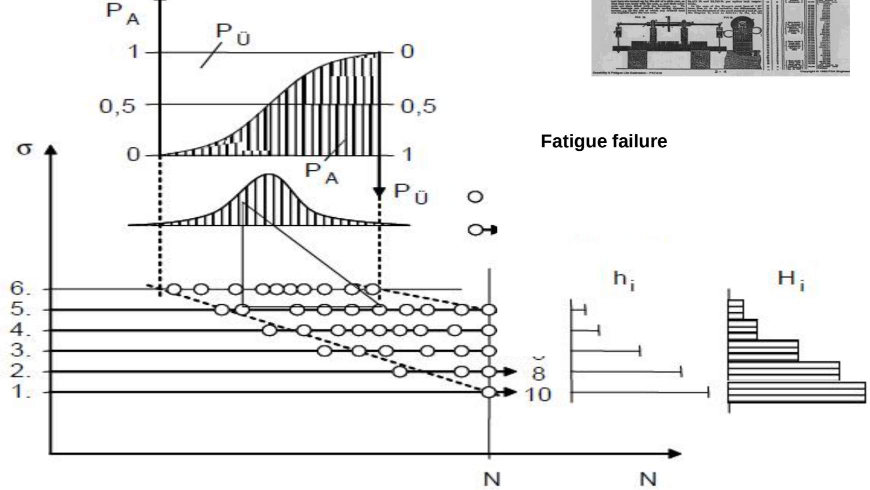


August Wöhler
*1819 U 1914



Fatigue failure

SN Curve

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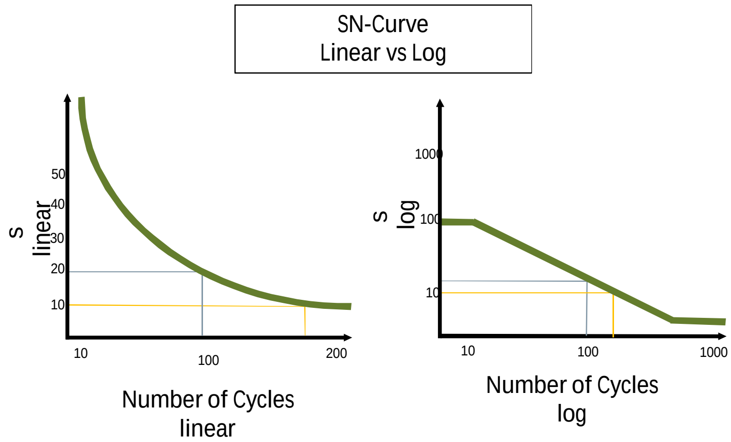

Regions of the SN Curve

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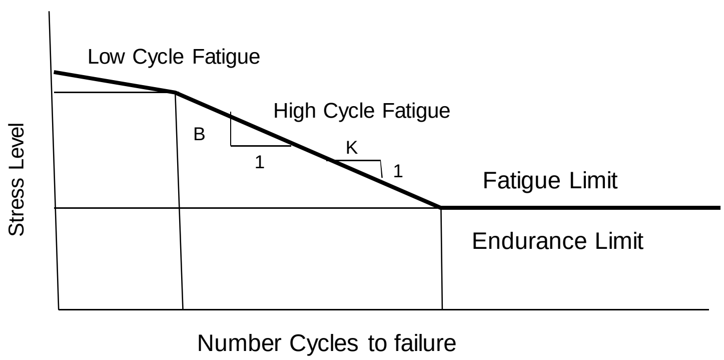

$$k = -\frac{1}{b}$$

$$N_2 = N_1 \left(\frac{S_1}{S_2}\right)^k$$

$$N_2 = N_1 \left(\frac{S_1}{S_2}\right)^{-1/b}$$

- Fatigue limit, endurance limit:
  - Expressions used to describe a property of materials: the amplitude (or range) of cyclic stress that can be applied to the material without causing fatigue failure
  - Ferrous alloys and titanium alloys have a distinct limit, an amplitude below which there appears to be no number of cycles that will cause failure

Uniform Material Law (EN) / Universal Slope Law (SN)

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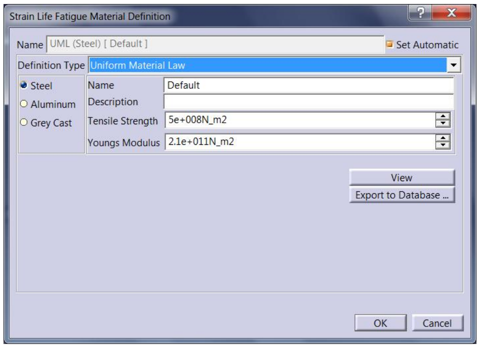
For steel, aluminum and titanium alloys, extensive statistical studies have been conducted that show a correlation between the ultimate tensile strength and the fatigue properties

The UML estimation of these properties requires input of the elastic modulus (E) and tensile strength (Smax) of the



Endurance (Fatigue) limit

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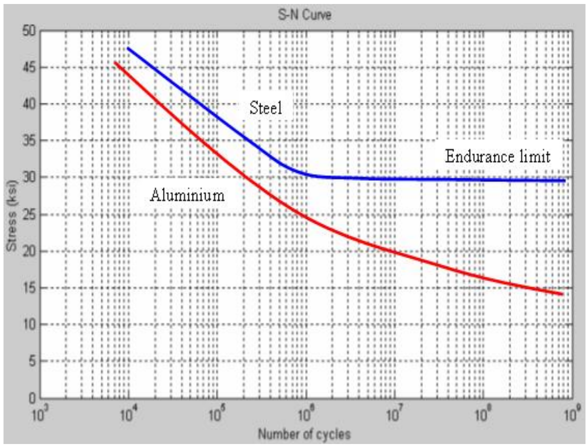
Material	Endurance or Fatigue Limit (maximum)
Steel (typical - 0.5 * UTS)	690 MPa
Iron alloys (0.4 * UTS)	165 MPa
Aluminium alloys (0.4 * UTS)	131 MPa
Copper (0.4 * UTS)	97 MPa



Note : Fatigue ratio = ratio between endurance limit and tensile strength

Load Cycle Terminology

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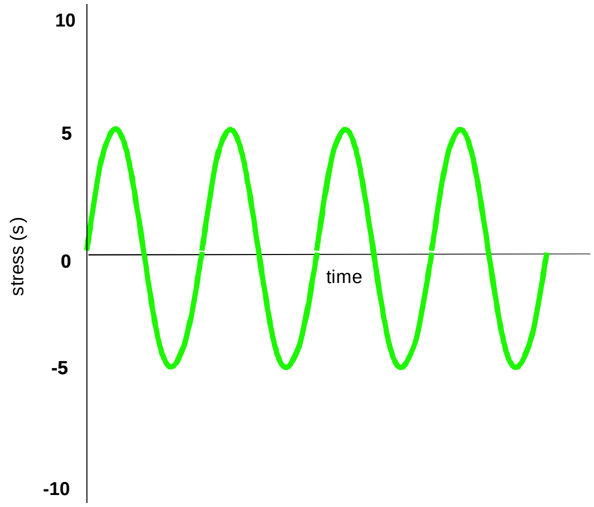

What is one cycle?

Load Cycle Terminology

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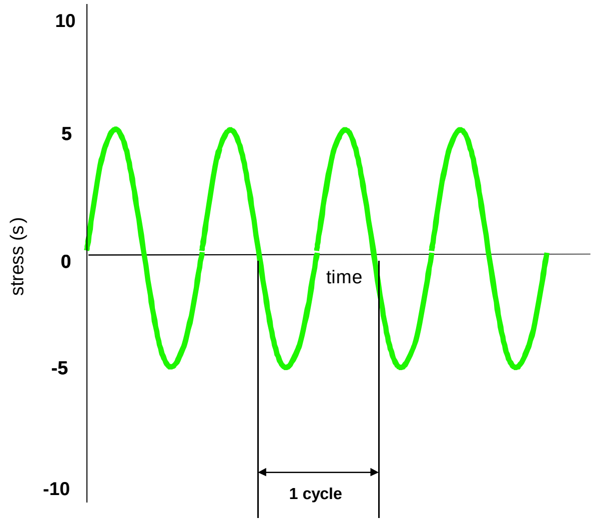

What is one cycle?

Load Cycle Terminology

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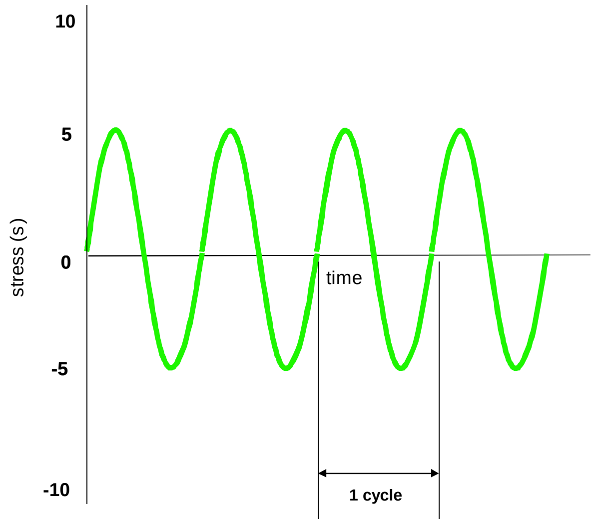

What is one cycle?

Load Cycle Terminology

SIEMENS
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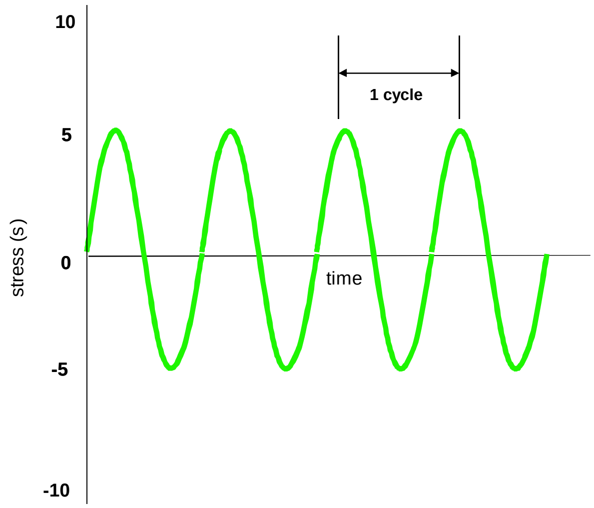

What is one cycle?

Load Cycle Terminology

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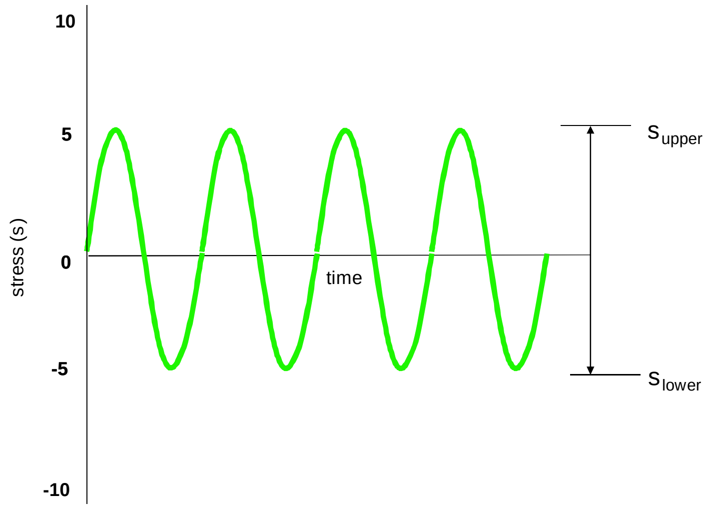

What is amplitude of cycle?

$s_a = (s_u - s_l)/2$

Sometimes called "alternating stress"

$s_a = (5 - (-5))/2$

$s_a = (10)/2$

$s_a = 5$

Load Cycle Terminology

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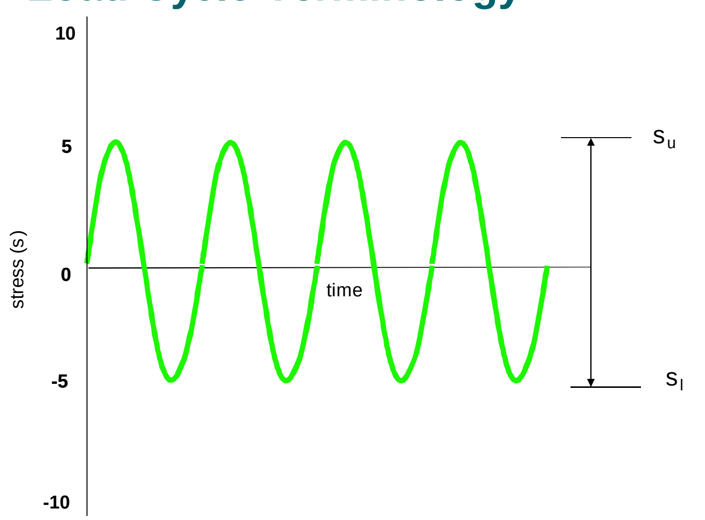
Ingenuity for life



What is range of cycle?

10

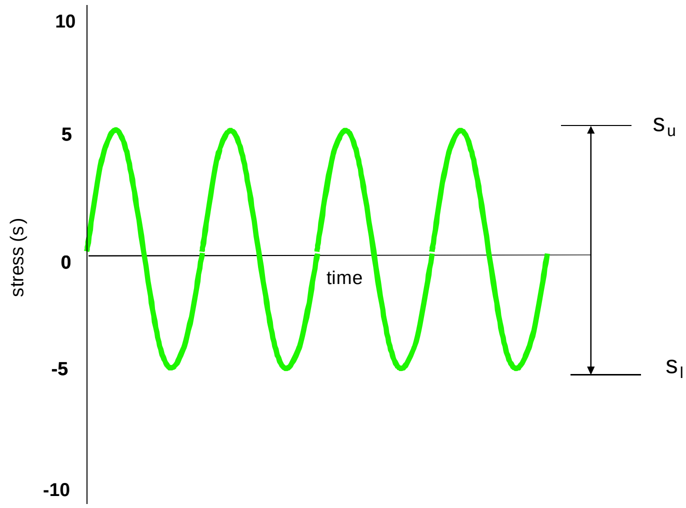
$s_r = s_u - s_l$

$s_r = 5 + 5$

$s_r = 10$

Load Cycle Terminology

SIEMENS
Ingenuity for life



What is average/mean of cycle?

0

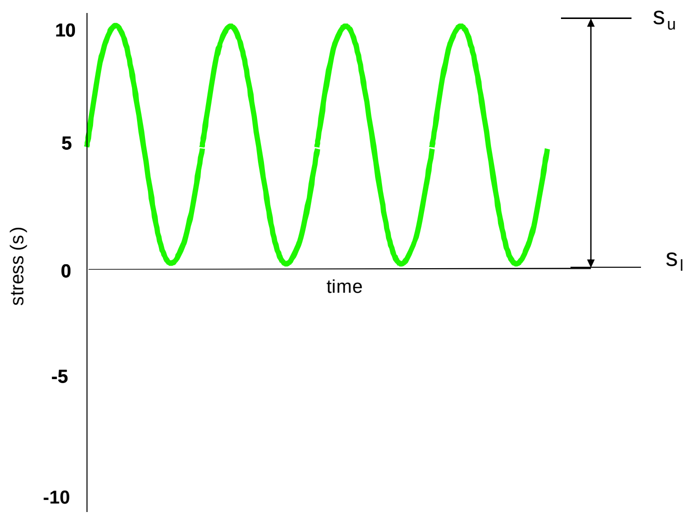
$s_a = (s_u + s_l)/2$

$s_a = (5 - 5)/2$

$s_a = 0$

Load Cycle Terminology

SIEMENS
Ingenuity for life



Has amplitude of cycle changed?

NO

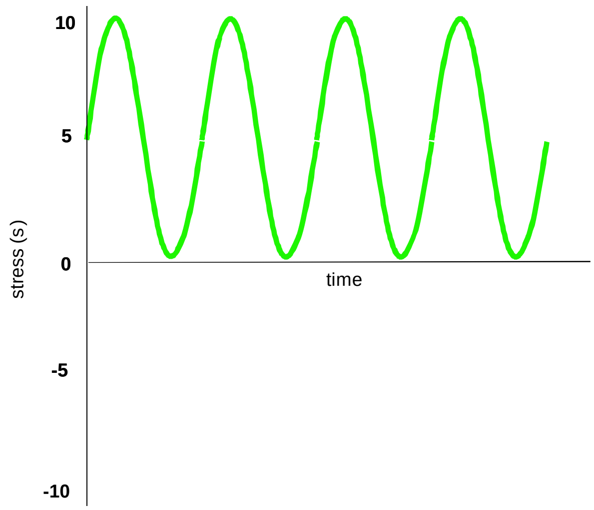
$s_a = (s_u - s_l)/2$

$s_a = (10 - 0)/2$

$s_a = 5$

Load Cycle Terminology

SIEMENS
Ingenuity for life



Has average/mean of cycle changed?

YES

Mean = 5

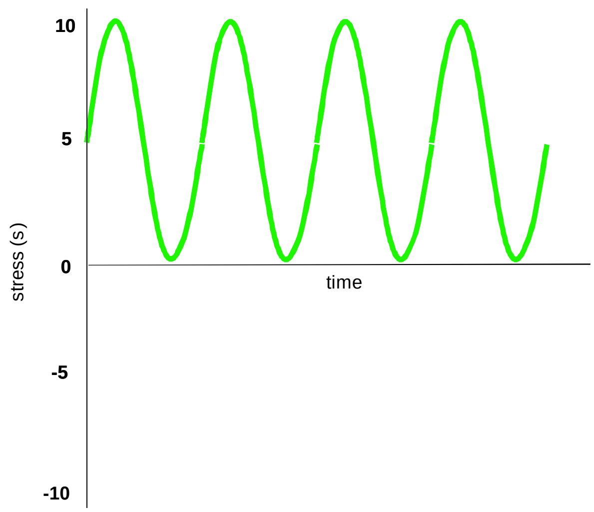
$s_a = (s_u + s_l)/2$

$s_a = (10 + 0)/2$

$s_a = 5$

Load Cycle Terminology

SIEMENS
Ingenuity for life



Has average/mean of cycle changed?

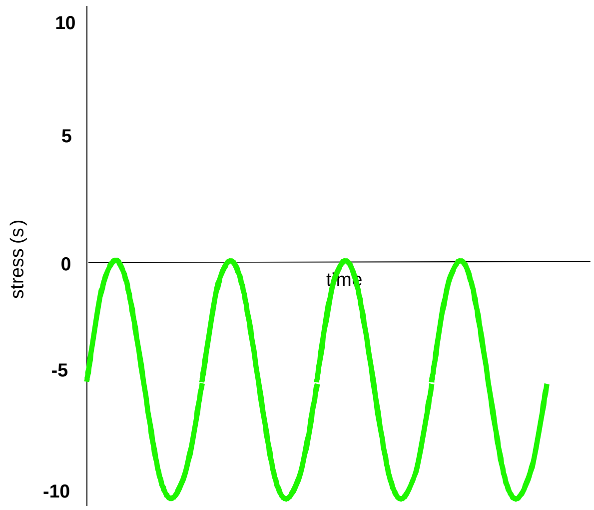
YES

Mean = 5

Tension

Load Cycle Terminology

SIEMENS
Ingenuity for life



Has average/mean of cycle changed?

YES

Mean = -5

Compression

Famous People In Fatigue

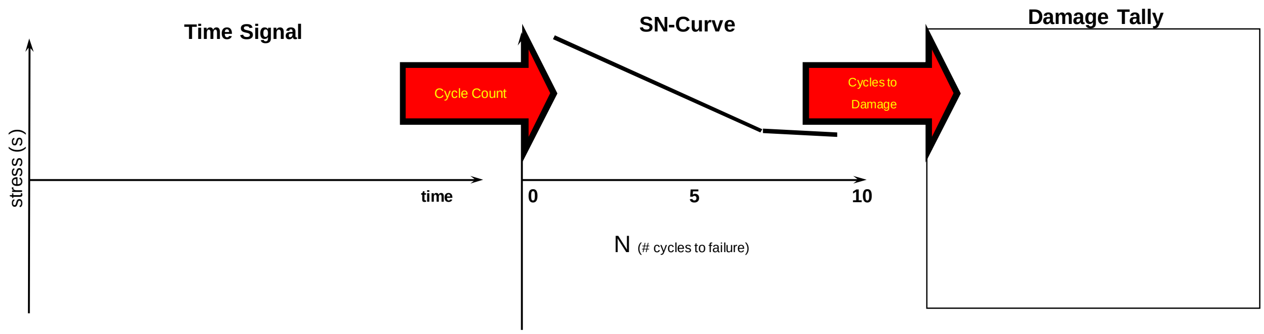
Sir Robert Hooke
British
(1635-1703)

Hooke's Law of Elasticity in 1660

August Wöhler
German
(1819-1914)

Wohler curves in 1867

SN Curve – Miner’s Rule



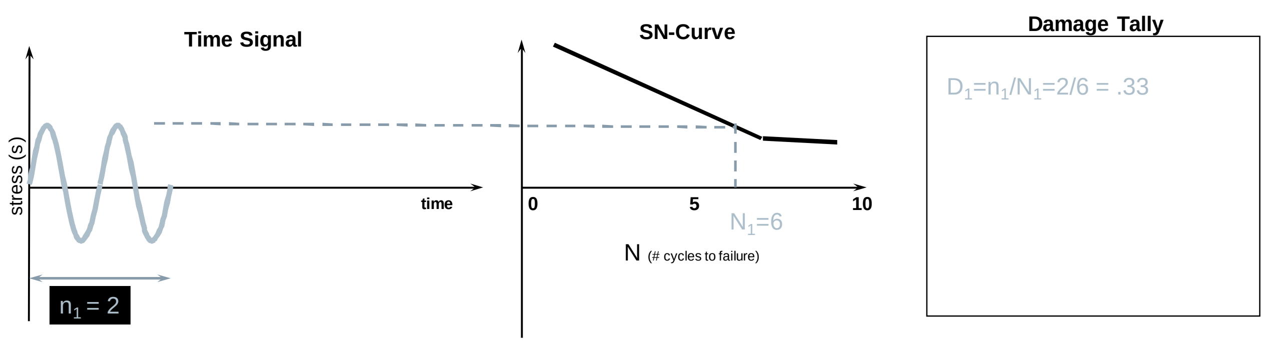
Key:

D_{tot} = Total Damage (when D=1, failure occurs)

N = # of Cycles to failure from SN Curve

n = # of Cycles in load signal

SN Curve – Miner’s Rule



Key:

D_{tot} = Total Damage (when D=1, failure occurs)

N = # of Cycles to failure from SN Curve

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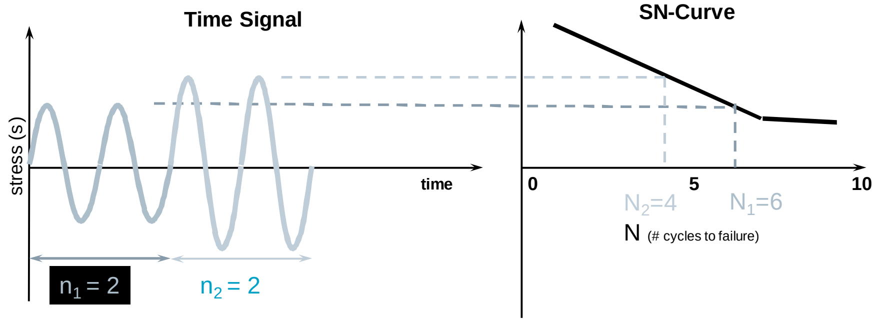
SN Curve – Miner's Rule

SIEMENS
Ingenuity for life



Damage Tally

$D_1 = n_1/N_1 = 2/6 = .33$

$D_2 = n_2/N_2 = 2/4 = .5$

$D_{tot} = D_1 + D_2$

$D_{tot} = .33 + .5 = .83$

Key:

D_{tot} = Total Damage (when D=1, failure occurs)

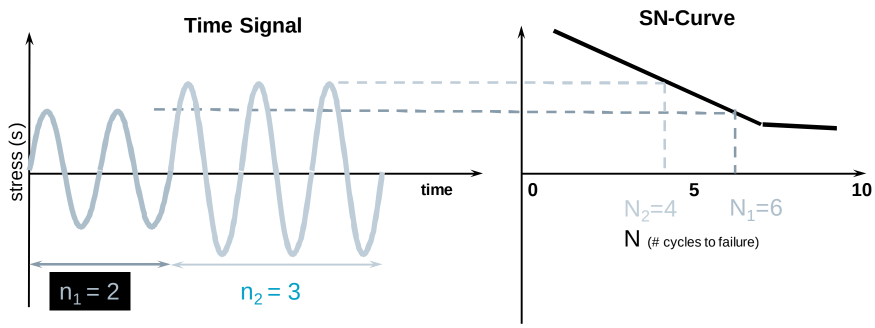
N = # of Cycles to failure from SN Curve

n = # of Cycles in load signal

No Failure!

SN Curve – Miner's Rule

SIEMENS
Ingenuity for life



Damage Tally

$D_1 = n_1/N_1 = 2/6 = .33$

$D_2 = n_2/N_2 = 3/4 = .75$

$D_{tot} = D_1 + D_2$

$D_{tot} = .33 + .75 = 1.08$

Key:

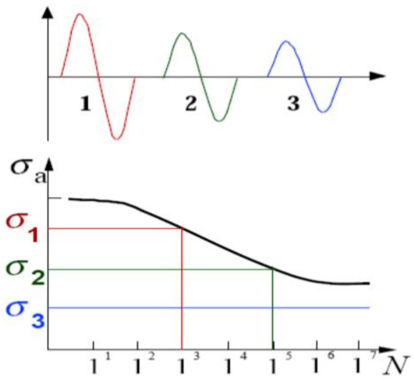
D_{tot} = Total Damage (when D=1, failure occurs)

N = # of Cycles to failure from SN Curve

n = # of Cycles in load signal

Failure!

How to understand fatigue content of loads ?
Palmgren (1924)-Miner (1945). Damage accumulation rule



$$\sum_{i=1}^{I}\frac{n_i}{N_i} = \boxed{\frac{500}{10^3}} + \boxed{\frac{10^3}{10^5}} + \boxed{\frac{10^4}{\infty}} = 0.51 < 1$$

Assume that, during the service life, we have 500 loadings of type **1** (defined by mid-value and magnitude), 1000 loadings of type **2** and **10000 loadings of type 3,** the **Palmgren – Miner** rule states that **failure** occurs when

$$\sum_{i=1}^{I}\frac{n_i}{N_i} = 1$$

where n_i is the number of applied load cycles of type i, and N_i is the pertinent fatigue life

SINE COUNTING DEMO

Tec.Ware with sines.ldsf

SINE CHANGE AMPLITUDE DEMO

Tec.Ware with sines.ldsf

Life very sensitive to changes in load

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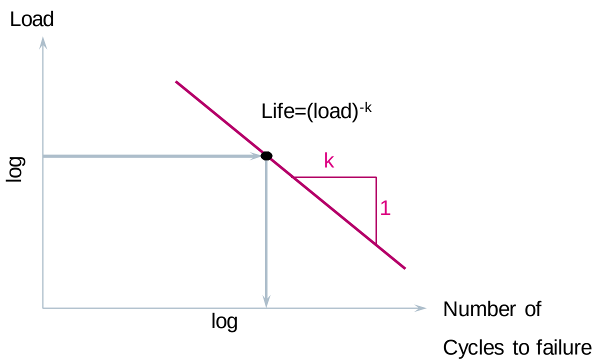
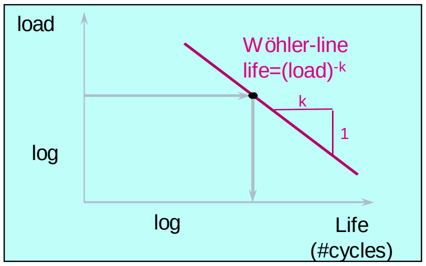


Reducing the cyclic load applied to an optimally shaped steel component with 13% doubles life

Number of cycles to failure
is a function of Load and k factor

Load \ k	5
1	1
1.15	0.5
0.87	2

Logarithmic nature of fatigue



load	k=3 life	k=5 life	k=7 life
1	1	1	1
1.1	0.75	0.62	0.51
1.2	0.58	0.40	0.27
1.3	0.45	0.27	0.16

As k increases, small changes in load cause big change in life

What about Simulation?

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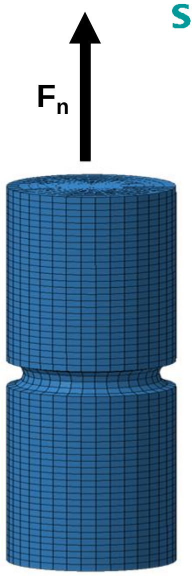
Finite Element Models are used

- **When Fn=1: referred to as a "Static Unit Load Case"**
- **Stress is calculated at each element – as opposed to a predetermined location**
- **because real geometry is more complex than this . . .**



*** Normal Stress**

VIRTUAL LAB DEMO

Double amplitude damage

S-N Curve Adjustments

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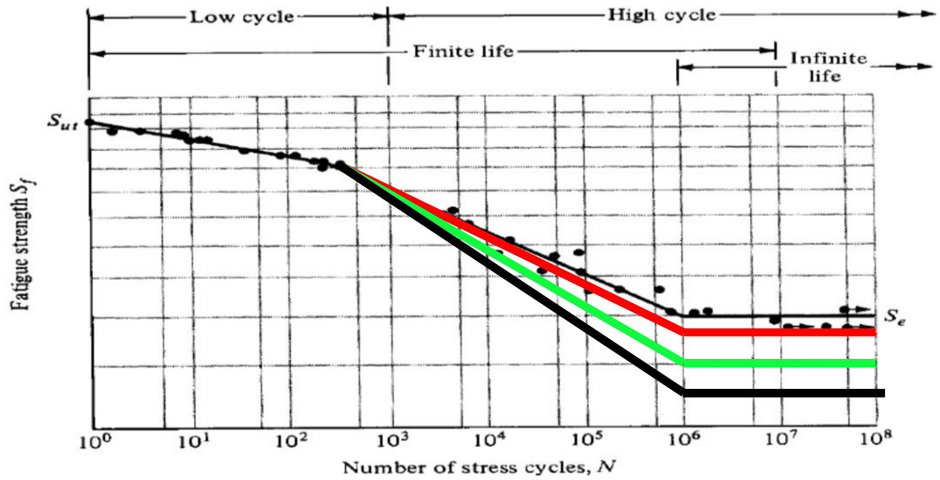
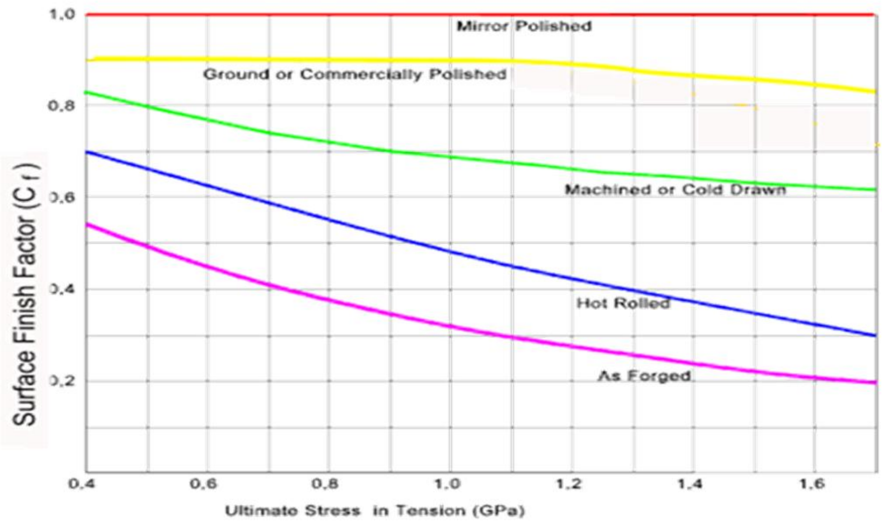


Completely reversed cyclic stress, UNS G41200 steel

SN Curve Adjustments: Surface Finish

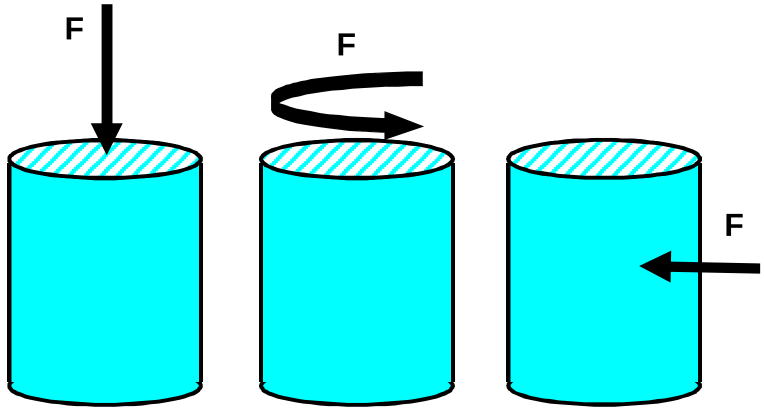


Rougher surface more chance of crack

http://www.roymech.co.uk/Useful_Tables/Fatigue/FAT_Mod_factors.html

SN Curve Adjustments: Loading

Rotating Beam Fatigue Tester



Axial Torsion Bending

SN Curve Adjustments: Loading

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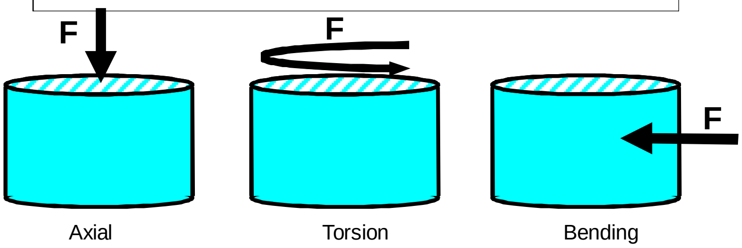
"Fatigue Testing and Analysis" Lee, Pan, Hathaway

TABLE 4.11 Load Factors, C_L

Type of Loading	C_L	Comments
Pure axial loading	0.9	
Axial loading (with slight bending)	0.7	
Bending	1.0	
Torsional	0.58	For steels
Torsional	0.8	For cast iron



SN Curve Adjustments: Size

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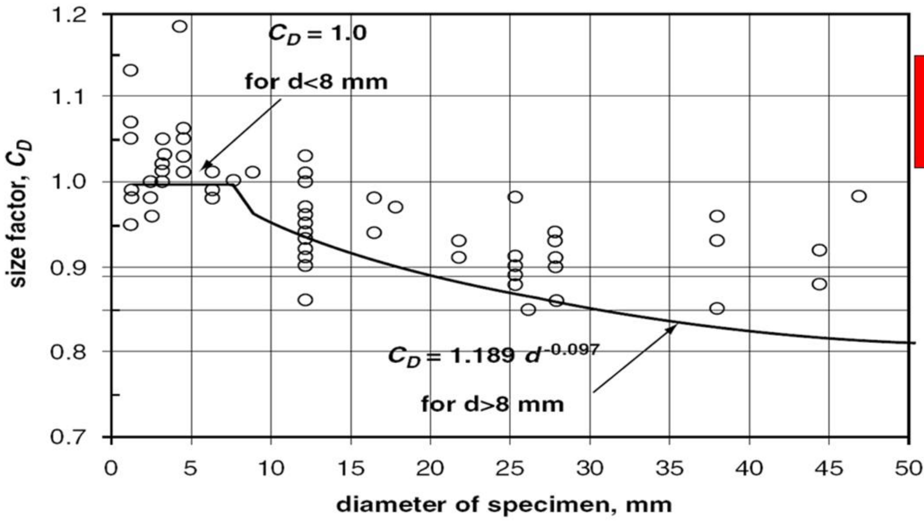

Bigger = BAD
(For same stress!)

Kuegel 1961

"Fatigue Testing and Analysis" Lee, Pan, Hathaway

SN Curve Adjustments: Size

SIEMENS
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Bigger = BAD
(For same stress!)

$$C_s = \begin{cases} 1.0 & D \le 10mm \\ 0.9 & 10 \le D \le 50mm \\ 1 - \dfrac{D - 0.76}{380} & 50 \le D \le 230mm \end{cases}$$

http://www.efunda.com/formulae/solid_mechanics/fatigue/fatigue_factor.cfm

Notch Factors

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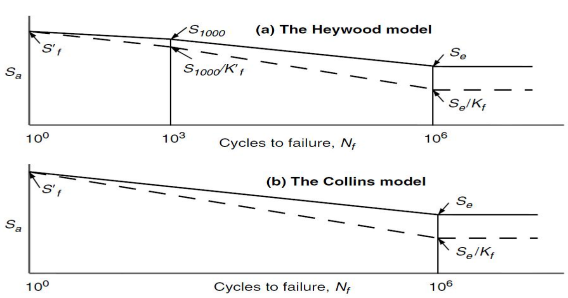

"Fatigue Testing and Analysis" Lee, Pan, Hathaway

Endurance Limit is divided by the fatigue notch factor

$$\boxed{S_e^{'} = \frac{S_e}{K_f}}$$

Theoretical Stress Concentration Factor

(Function of Geometry)

$$K_T = \frac{S_{\max}}{S}$$

Max Local Stress

Nominal Stress

Notch Sensitivity Factor q

$$q = \frac{1}{1 + \sqrt{\frac{\rho}{r}}}$$

r = root radius

ρ = material Property

$$q = \frac{K_f - 1}{K_T - 1}$$

Fatigue Notch Factor

(Function of Geometry and material)

$$K_f = \frac{S_e(unnotched)}{S_e(notched)} \qquad 1 \le K_f \le K_T$$

SN Curve Adjustments: Mean Stress

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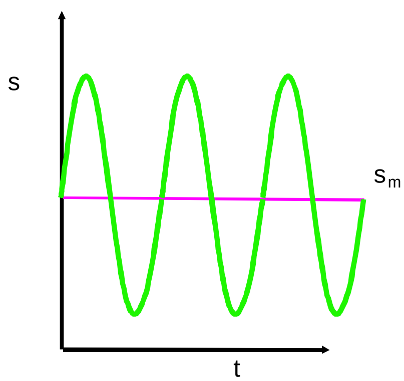
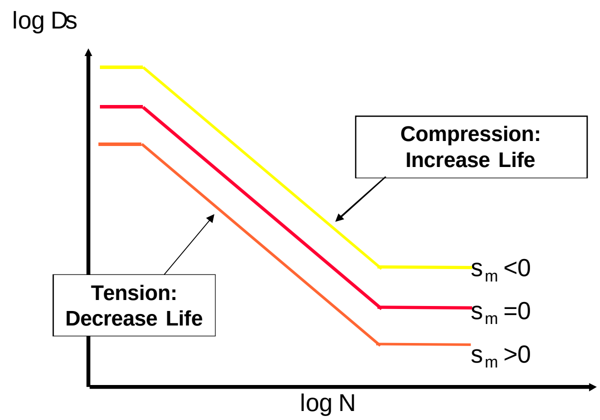
load history



s_m: mean stress

constant amplitude life curves



And More

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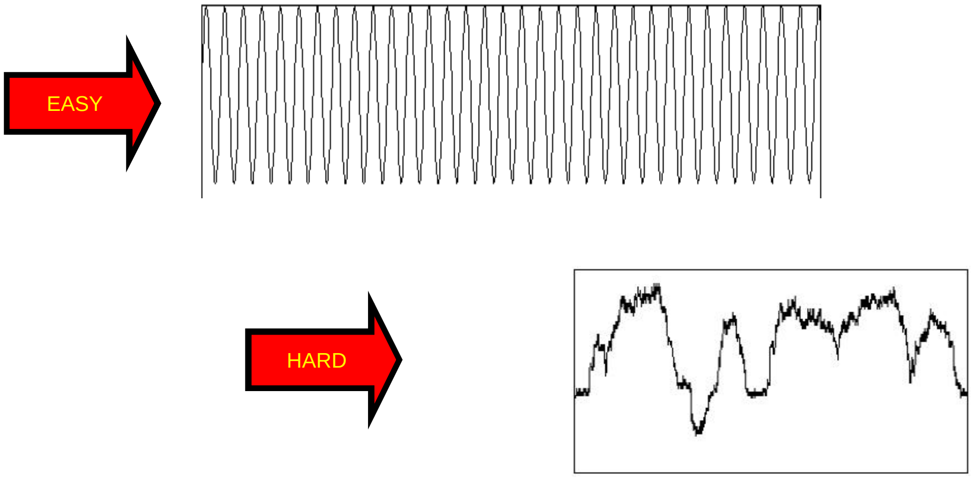
NOT
EVERYTHING IS
A SINE WAVE!

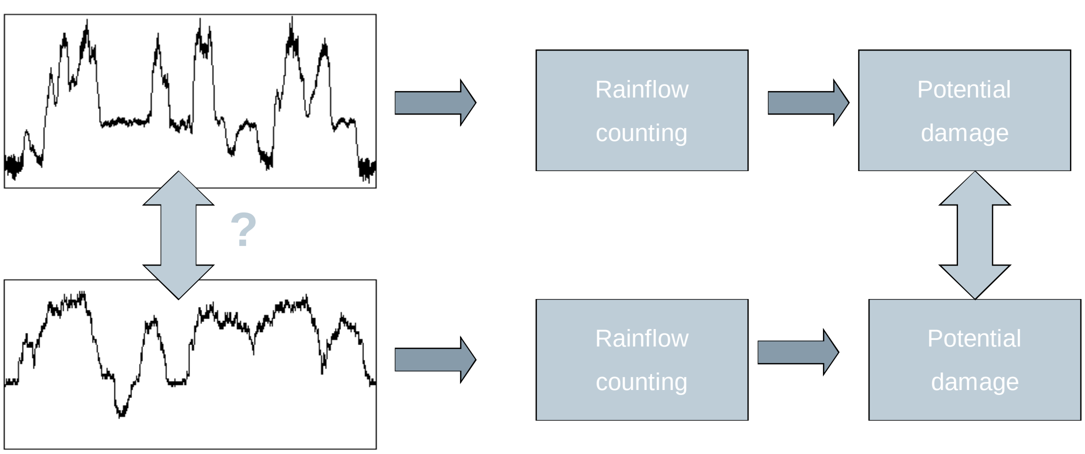
SINE SUM
DEMO

Tec.Ware with sines.ldsf

Cycle Counting



Comparison of 2 measurements



Durability load data processing
Rainflow counting - methods

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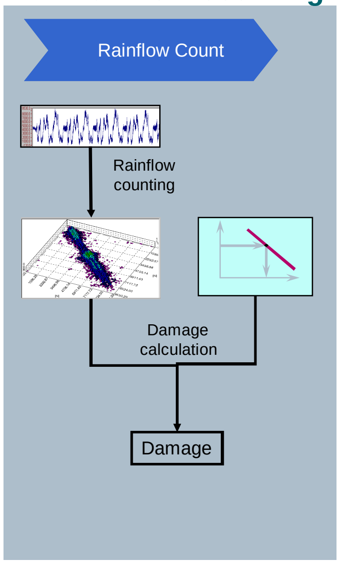
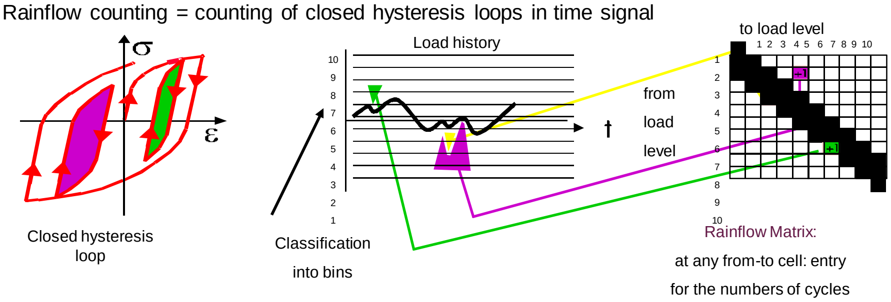
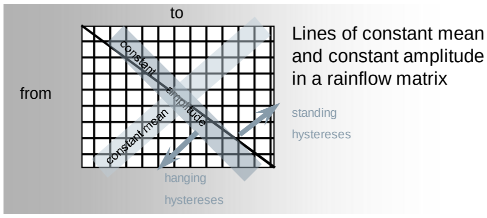


- **Basic damage event : closed hysteresis loop**
- Rainflow counting = counting of closed hysteresis loops in time signal





Counting methods in fatigue analysis
Rainflow variations

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Endo 1967	First definition
De Jonge 1968	Range-pair-range
Clormann/Seeger 1986	Counting all hysteresis cycles in stress-strain path
	Standard
ASTM 1986	Most effective and general on-line method
4-point counting	Two-dimensional distribution (dimension independent)
	Mathematical aspect (hysteresis operator, independent of dimension)
Oscillation counting	
Memory counting	

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Siemens PLM Software

Rainflow Counting
Pre-Processing steps

Steps	Motivation, justification
• Hysteresis filtering	reduces number of samples, endurance limit
• Peak/valley-filtering	reduces number of samples, does not affect hysteresis cycles
• Discretization	necessary for counting

4 Point Cycle Counting Technique

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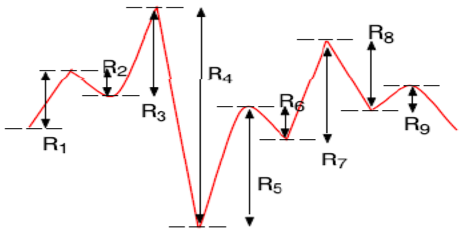
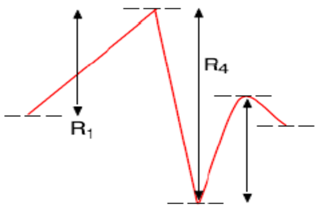
1. Chose four Consecutive stress points S1, S2, S3, S4
2. Define Inner Stress |S2 -S3|
3. Define Outer Stress |S1 -S4|
4. If inner stress range <= to outer stress range and the points comprising the inner stress range are bounded by the outer.





Famous People In Fatigue

Sir Robert Hooke
British
(1635-1703)

Hooke's Law of Elasticity in 1660

MA Miner
English
(1915 - 1978)

Miner's Rule in 1945

August Wöhler
German
(1819-1914)

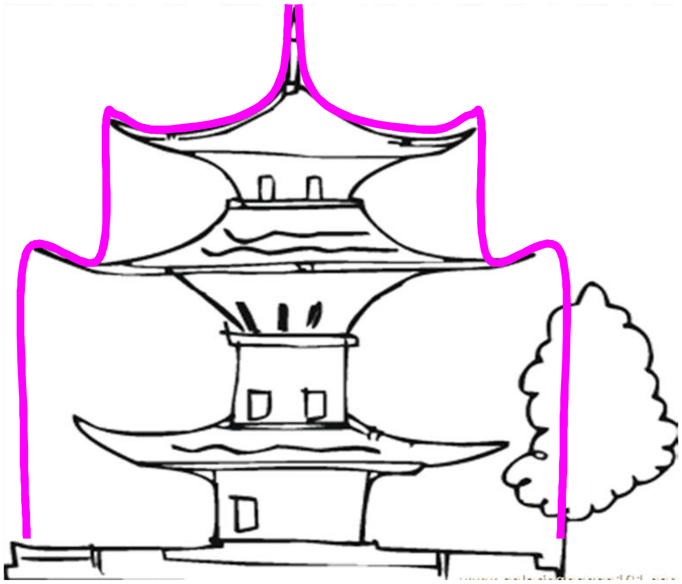
Wöhler curves in 1867

Tatsuo Endo
Japan
(1925 - 1989)

Rainflow Counting in 1968

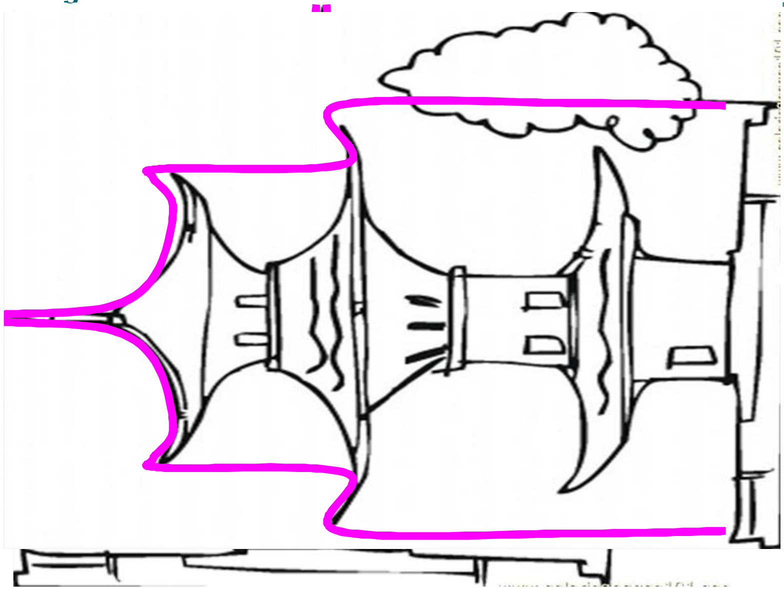
Rainflow Counting

SIEMENS
Ingenuity for life



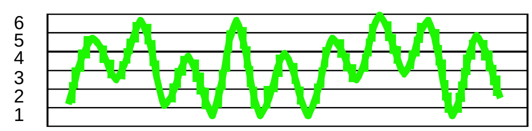
Rainflow Counting

SIEMENS
Ingenuity for life



Four Point Rainflow Counting

SIEMENS
Ingenuity for life

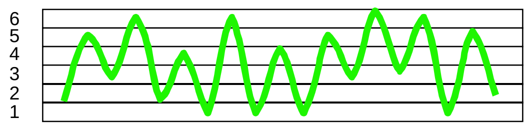


Unrestricted © Siemens AG 2017

Siemens PLM Software

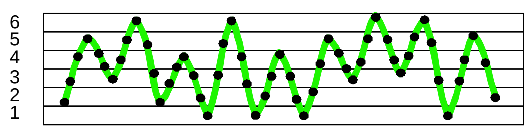
Four Point Rainflow Counting

SIEMENS
Ingenuity for life

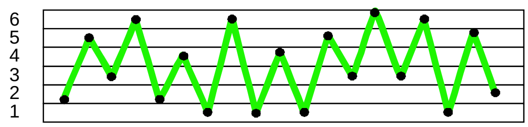


Peak Valley

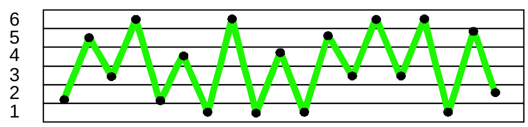
SIEMENS
Ingenuity for life



Peak-Valley After



Binning Before



Binning After

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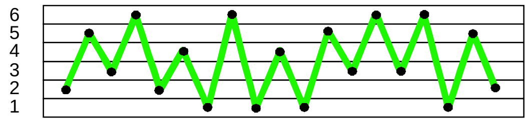
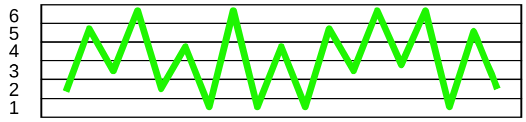
Ingenuity for life



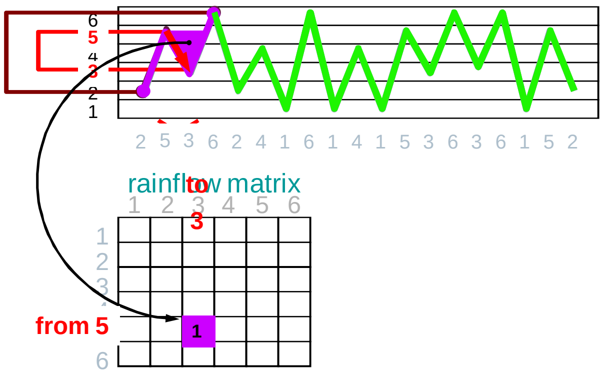
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



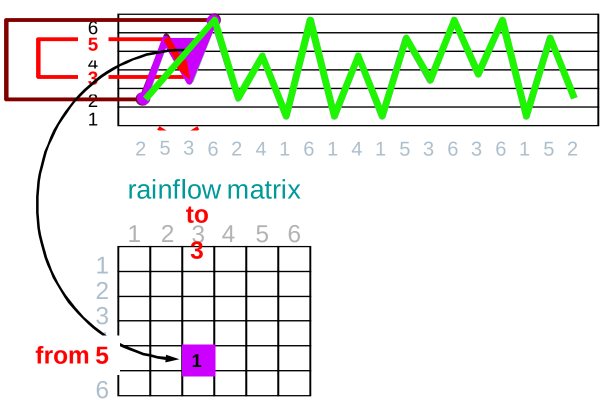
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



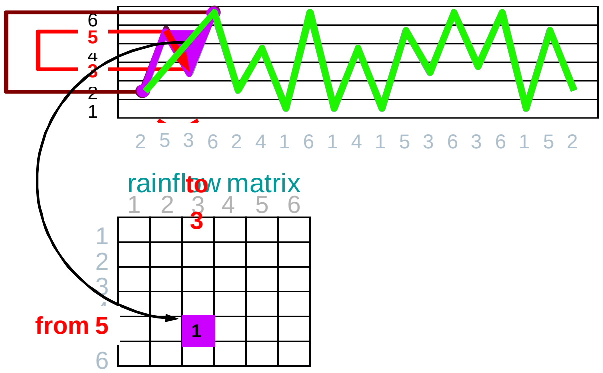
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



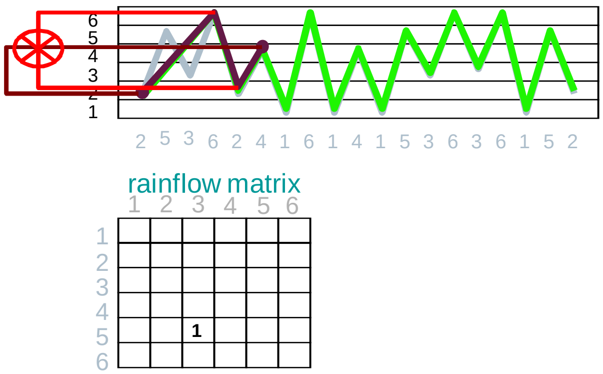
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



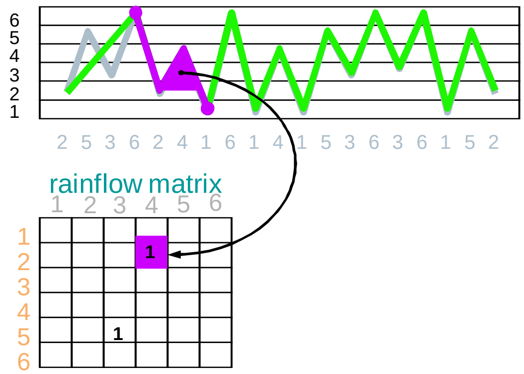
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



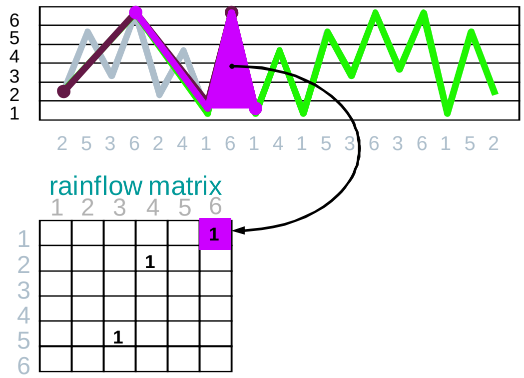
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



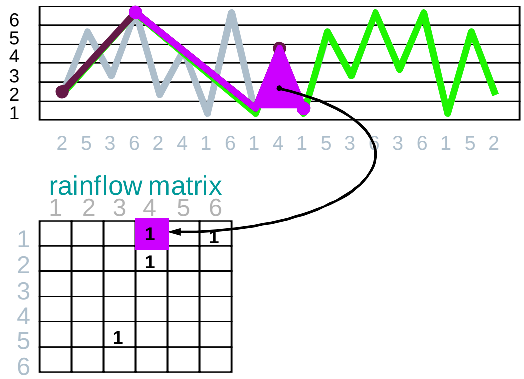
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



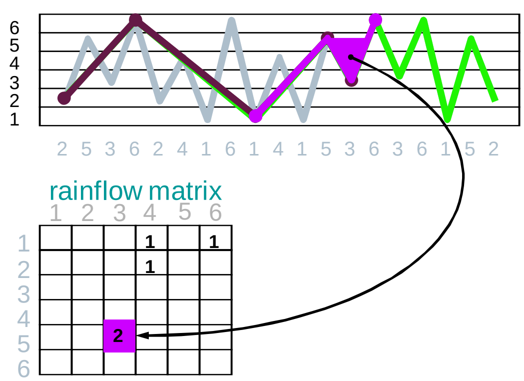
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



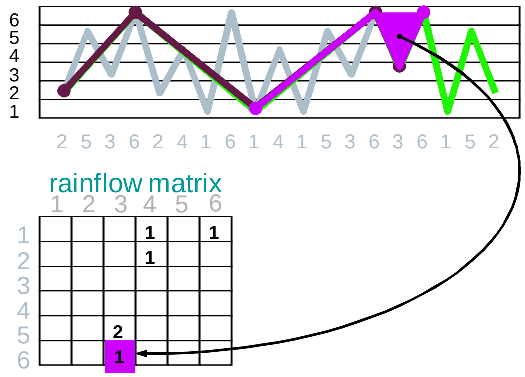
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



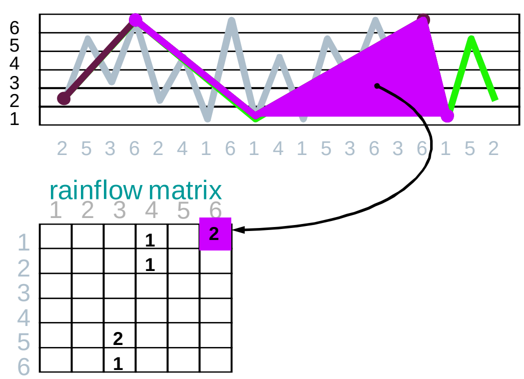
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



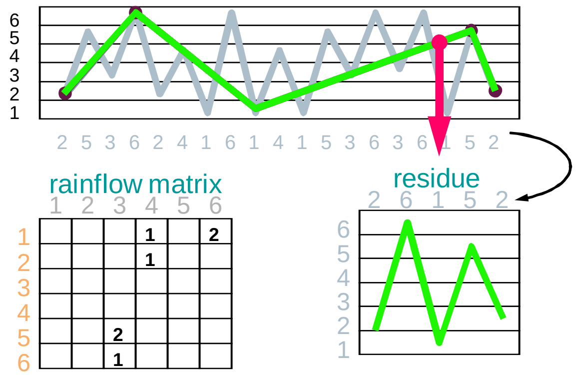
Four Point Rainflow Counting

SIEMENS
Ingenuity for life



Four Point Rainflow Counting

SIEMENS
Ingenuity for life



Example – Residue Repeated Block

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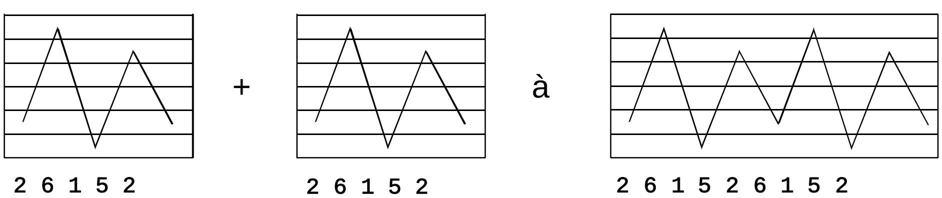
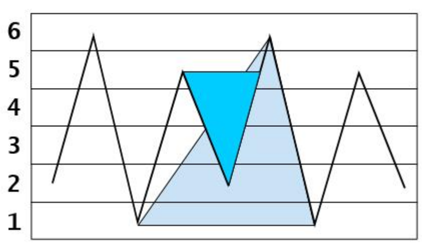
Residue cycles for a repeated block:

Count the sequence (RES,RES) with the 4-point algorithm





Additional residue cycles are displayed in the matrix (*) and are taken into account for the damage accumulation.

Residue

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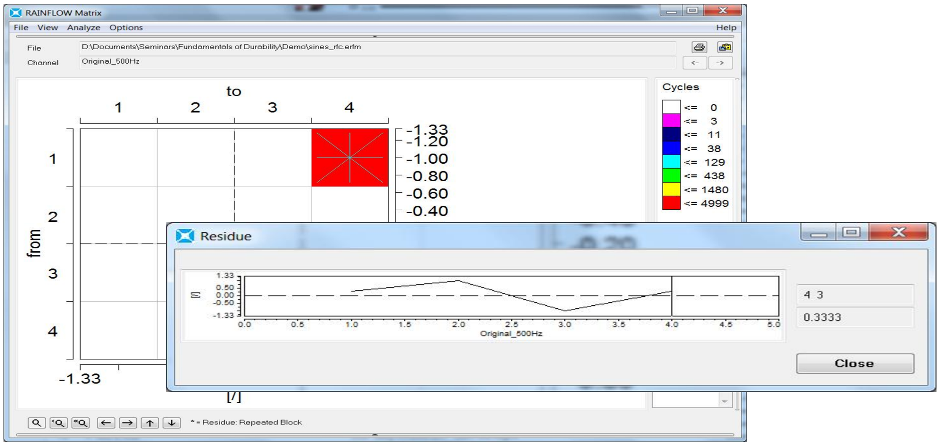

How to understand fatigue content of loads ?
Rainflow -> RangePair -> Damage distribution

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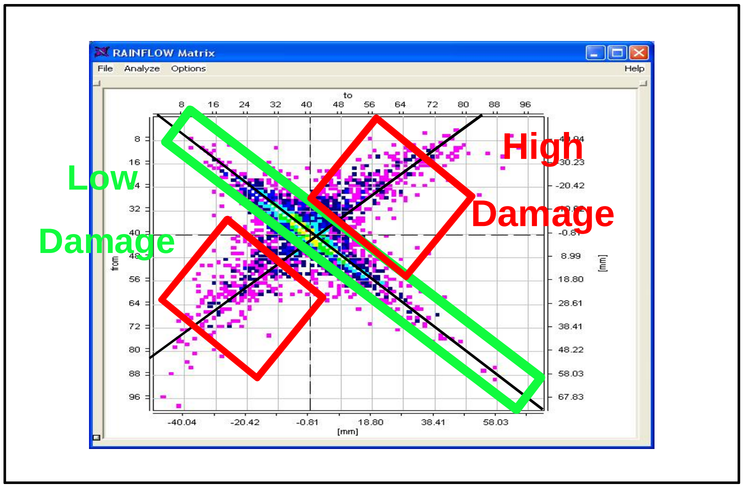
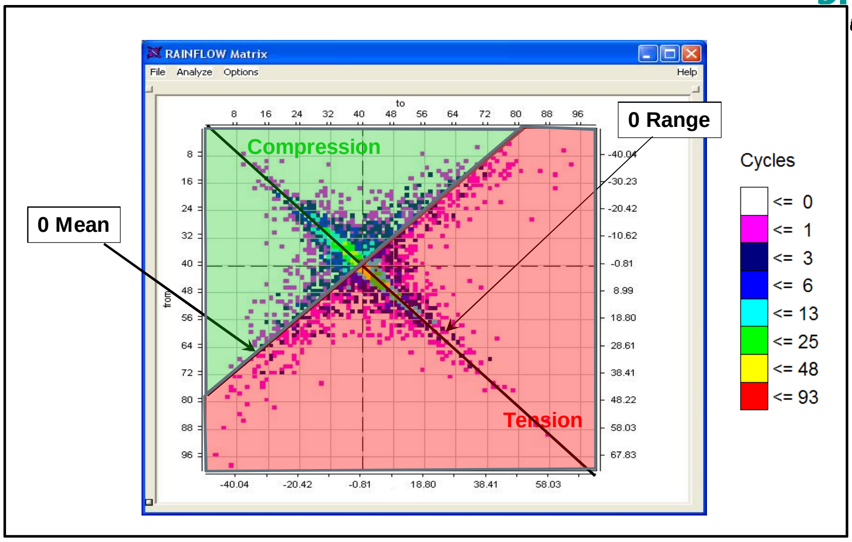
Ingenuity for life



SIEMENS
Ingenuity for life



How to understand fatigue content of loads ?
Rainflow -> RangePair -> Damage distribution

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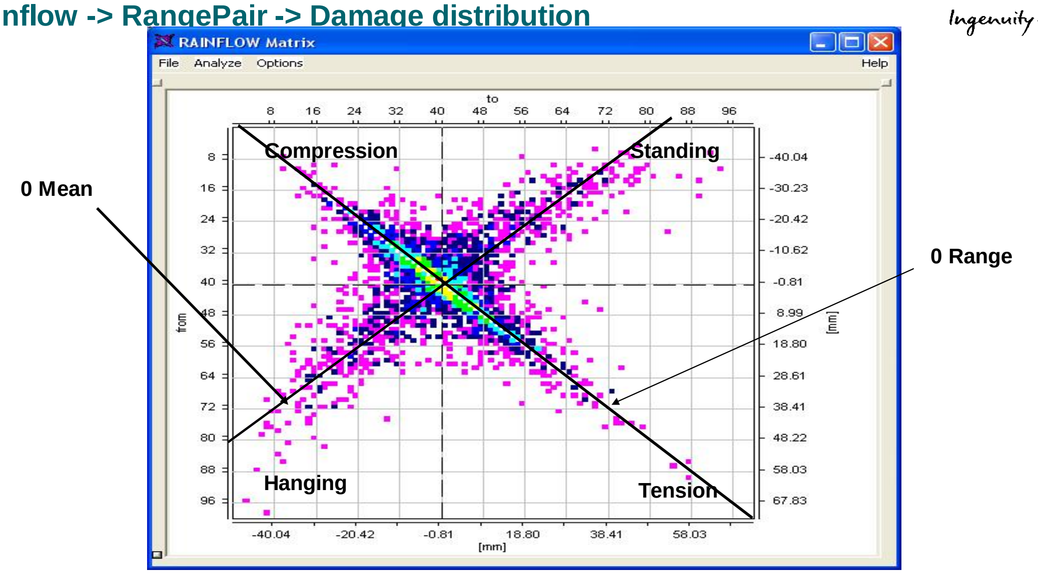

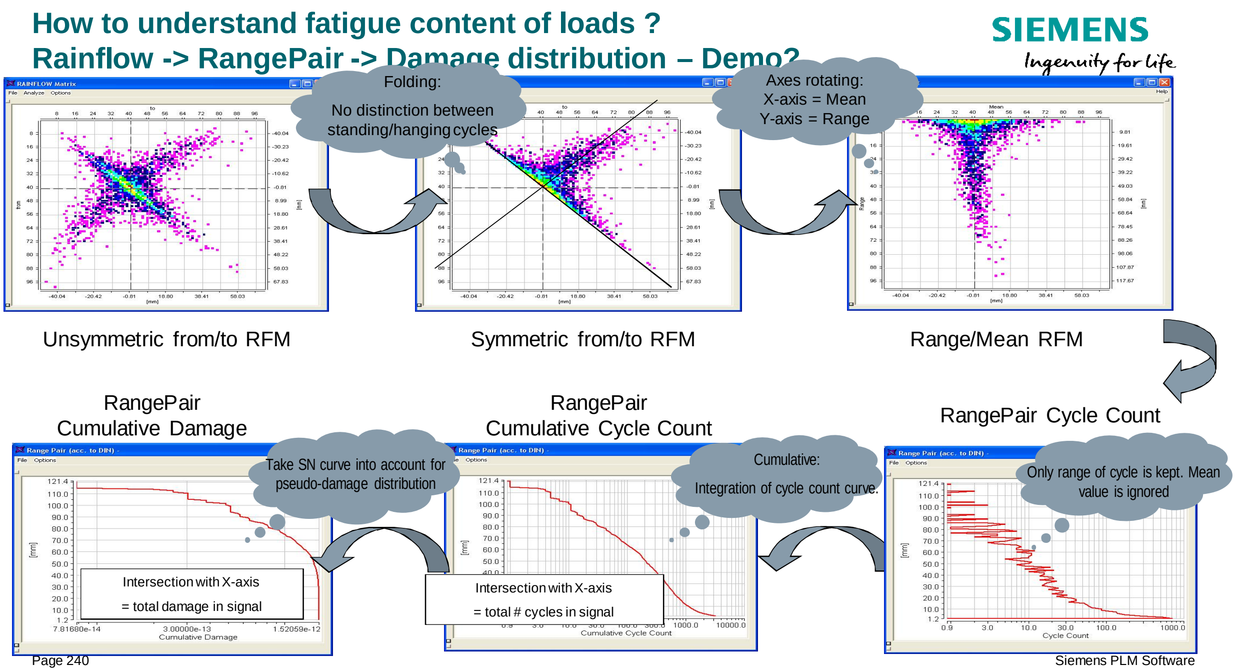

REAL DATA RAINFLOW Demo

Level Crossing versus Rainflow Counting

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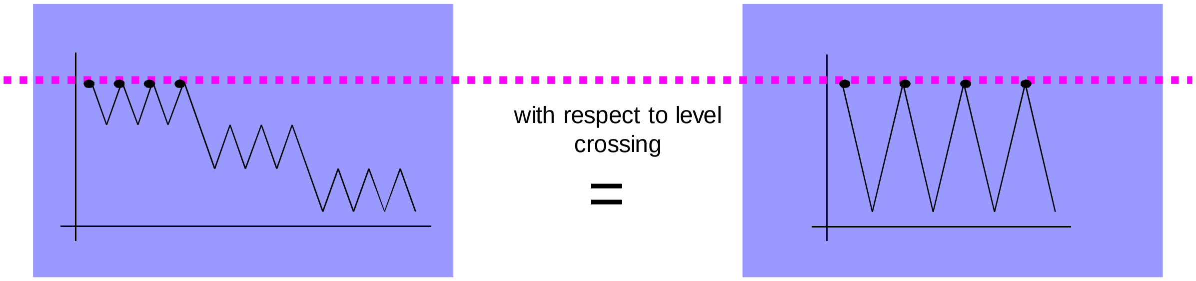

Problem:

The amplitude values of the cycles are lost with the level crossing technique

What if the Part is Rotating – Like Gear Teeth

Traditional Method - Rotating Moment Histogram

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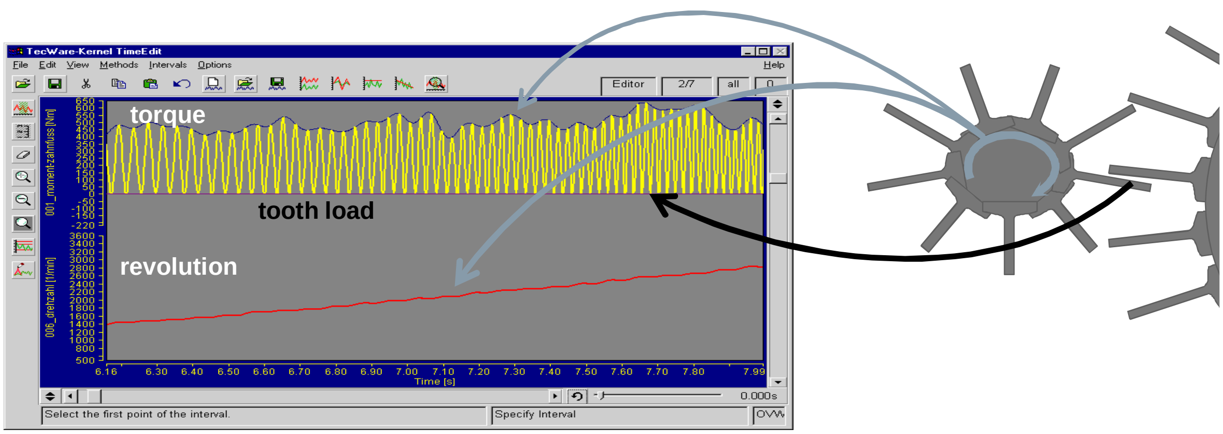

Input => Load and Shaft RPM

Tooth Loading Model

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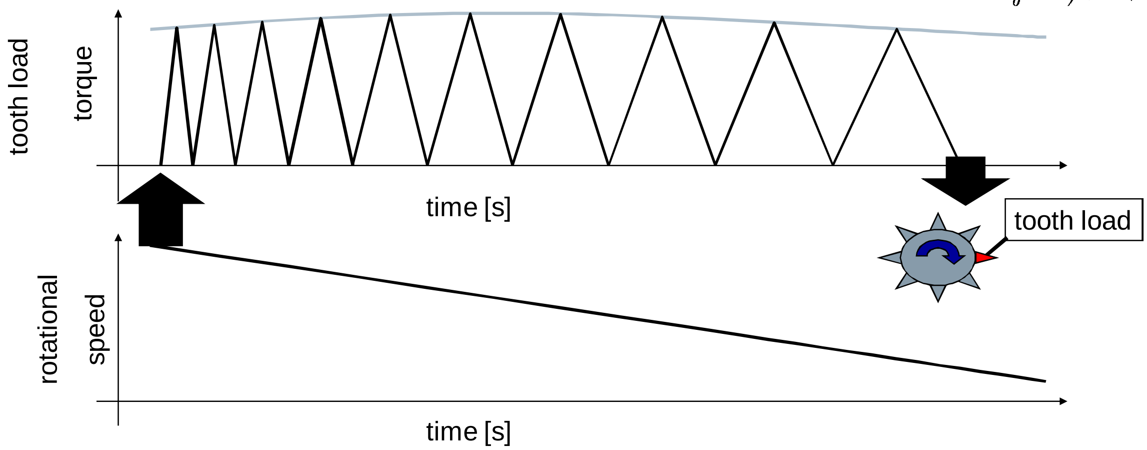

In each completed revolution the reference tooth touches its counterpart once. Only then it experiences the applied torque.

What if the Part is Rotating – Like Gear Teeth

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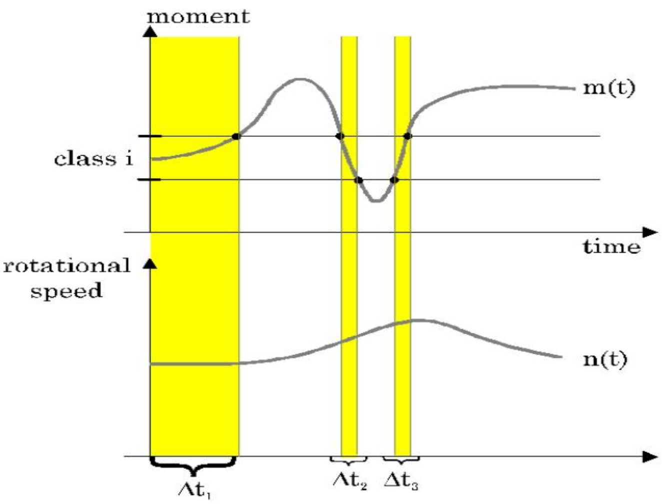
Traditional Method - Rotating Moment Histogram



$$\tau_i = \int_{\Delta t_1} n(t)dt + \int_{\Delta t_2} n(t)dt + \int_{\Delta t_3} n(t)dt$$

- Gear Tooth is loaded once per revolution
- Each bin represents fixed load level
- Integrate Rotational Speed to get revolutions in bin (loading Cycles)
- Sum over all load bins

Rotating Moment Histogram - Output

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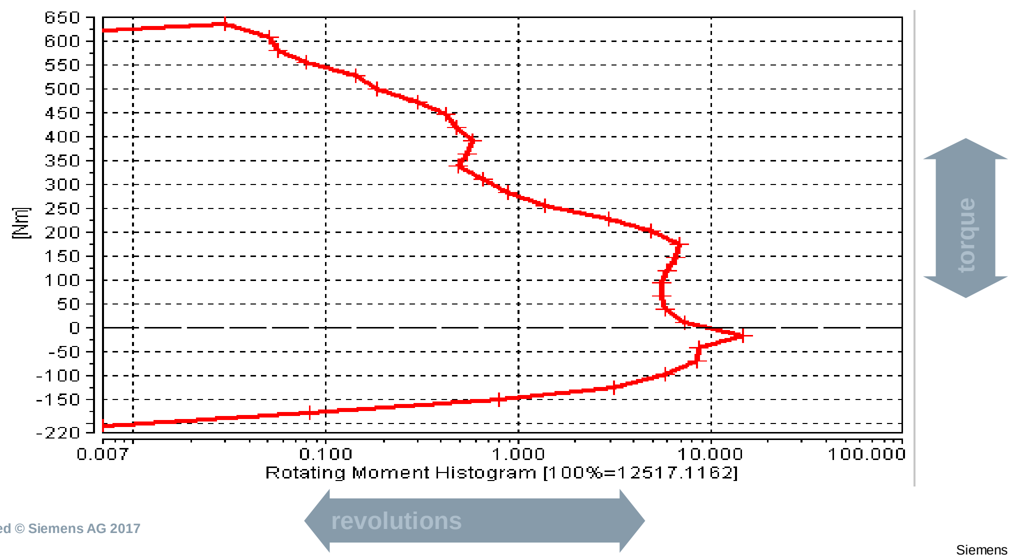
Number of revolutions at a given load level



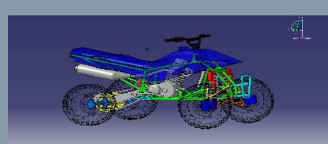
Durability Agenda

Durability Basics

Fatigue, Stress, Strain

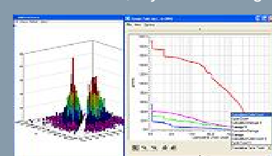
Load Determination

Measurements, Multi-Body Simulation



Loads and Damage

S-N Curve, Cycle Counting

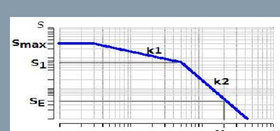


Load Characterization

Establishing Durability Targets: Superposition, Extrapolation

Fatigue Life Predictions

Infinite Life, Stress Life, Strain Life



Accelerated Testing & Analysis

RP-Filter

The Durability Process

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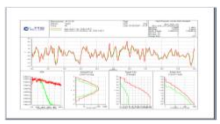
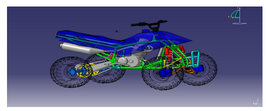
Understanding Operational loads	Target setting & Test Procedures	Design Optimisation Virtual Product Validation	Physical Product Optimisation & Validation	Final Product Test
Acquisition	Analysis	Simulation	Shaker testing	Sign-off
				

When were your durability test schedules established ?
Applied loading vs. structural strength

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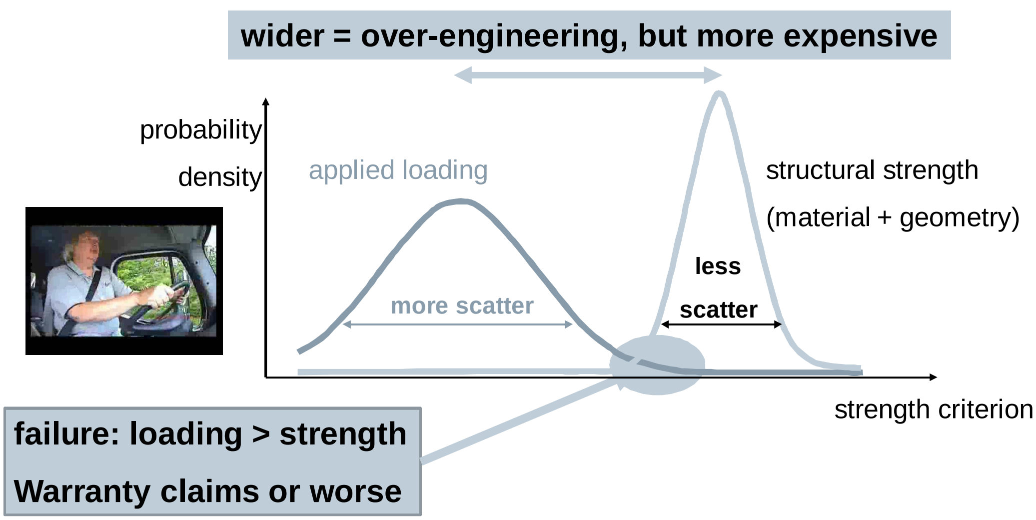

How to design realistic test schedule ?

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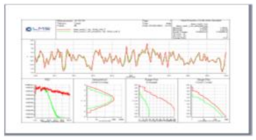
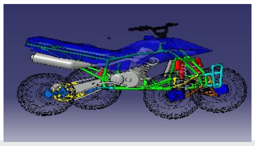
Understanding Operational loads → Target setting & Test Procedures → Design Optimisation Virtual Product Validation → Physical Product Optimisation & Validation → Final Product Test


Mobile data acquisition

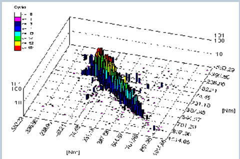



Simulation


Laboratory testing


Extensive field testing

Measurement of loads in different markets → Derivation of market correlated requirements → Building of accelerated Test procedure



Simulation

Laboratory testing

Application case
Driving 1.2 million kilometers in 8 weeks

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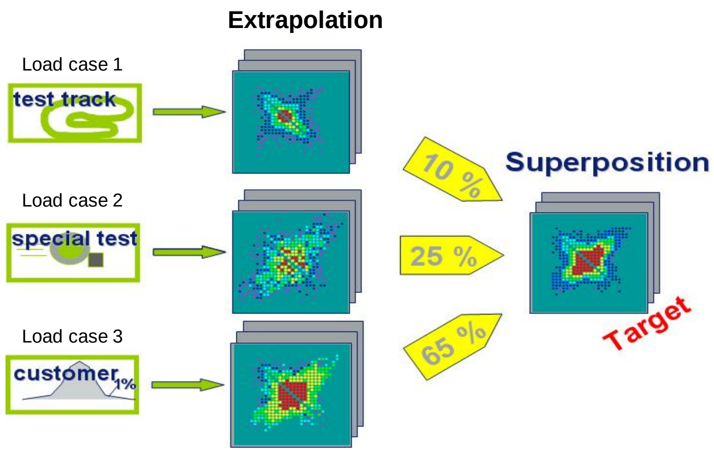
Accelerated durability testing cycles

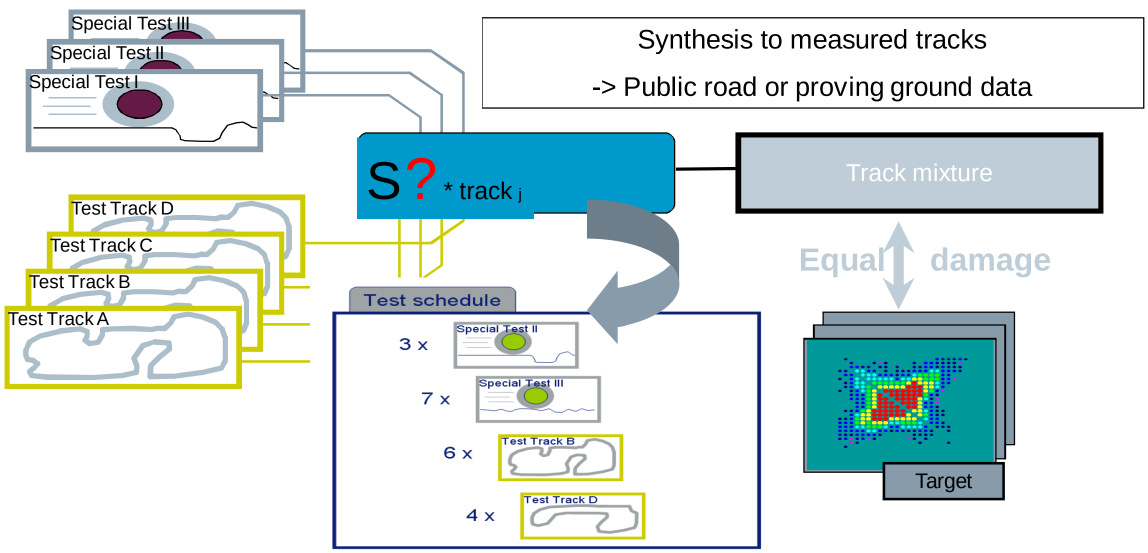
- Meeting 1.2 million km durability requirement
- Real tests would take 3 years
- Large-scale customer data collection
  - 5000 km Turkish public road data
  - Ford Lommel proving ground
- Development of accelerated rig test
  - Target setting
  - Test schedule definition
- Resulting test schedule 8 weeks
- Test acceleration of factor 100

LMS engineers performed dedicated data collection, applied extensive load data processing techniques and developed a 6- to 8-week test track sequence and 4-week accelerated rig test scenario that matched the fatigue damage generated by 1.2 million km of road driving.

Setting Target



Equivalent Test to match Target



Extrapolation

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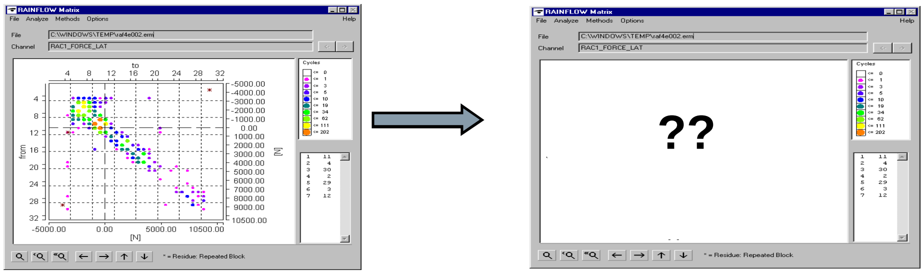
Test schedule definition

Extrapolation

How does one go from 1 hour to 100 hours?

Multiply by 100?

New matrix = x times original
(longer time duration)



1 HOUR

100 HOURS

Extrapolation to longer duration
Solution : kernel shape

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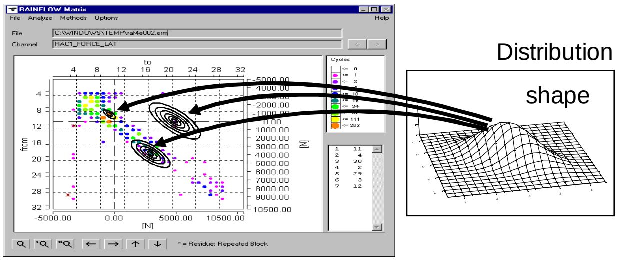
Test schedule definition

Extrapolation

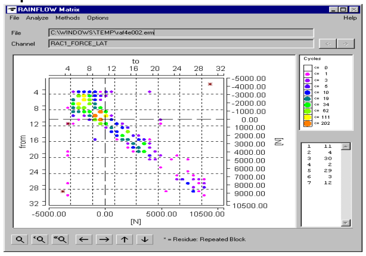
Solution:
2-D-normal-density kernel :



Distribution

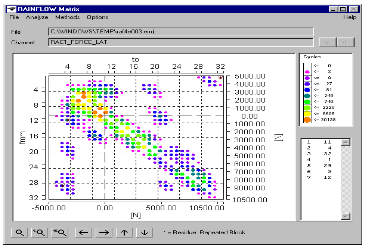
shape

Result:
Original and extrapolated matrix



original matrix

extrapolated matrix



Extrapolation to longer duration

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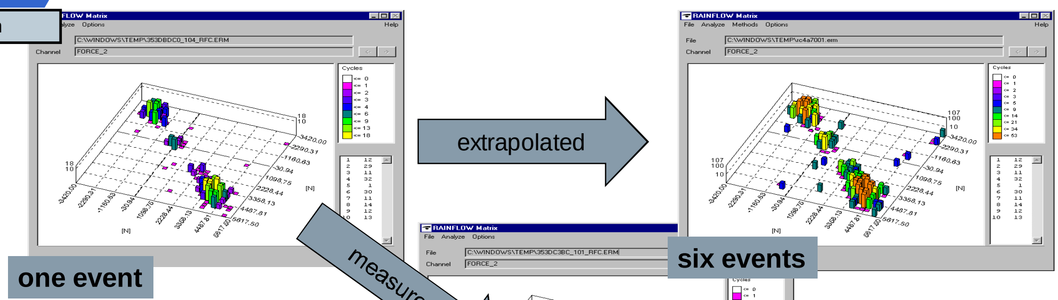
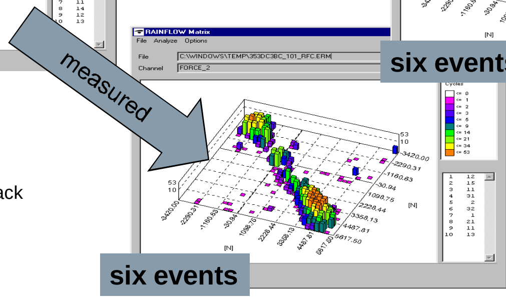
Test schedule definition
Extrapolation





- lateral wheel force
- Example:
  - 6 laps of the same test track
  - OR
  - 6 landings, etc

Target synthesis

Quantile Extrapolation - Extrapolation to 'Worst' Operator

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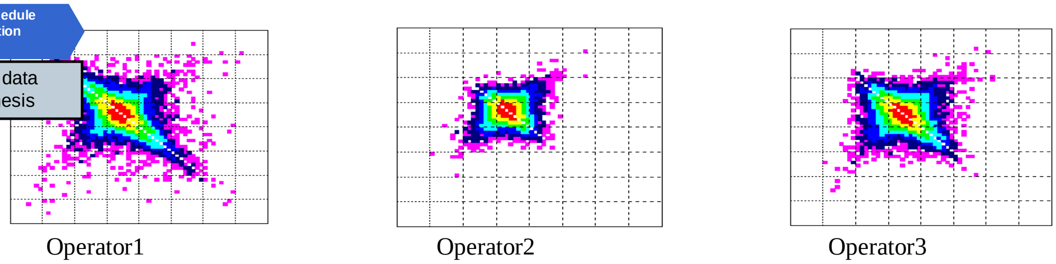
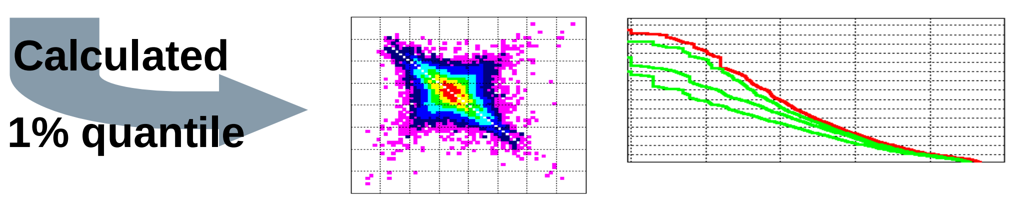
Test schedule definition
Load data synthesis

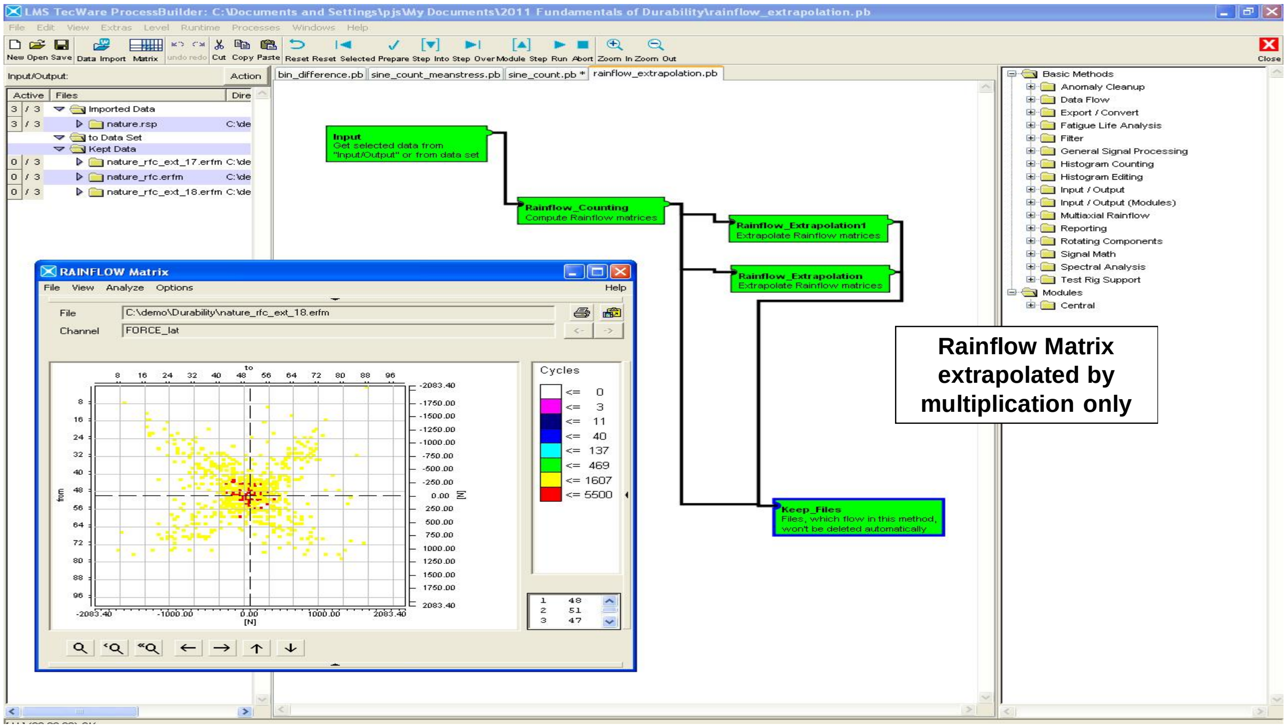


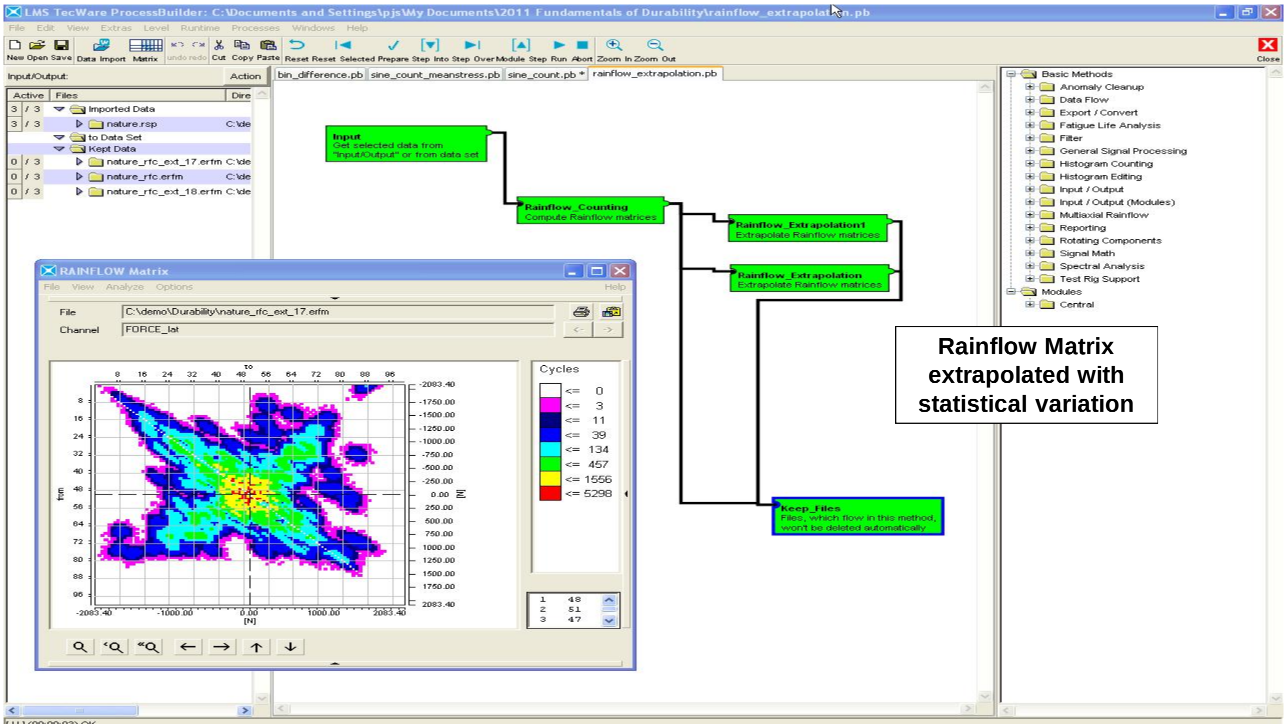
Calculate, what the x% (e.g. 1%) driver would produce !

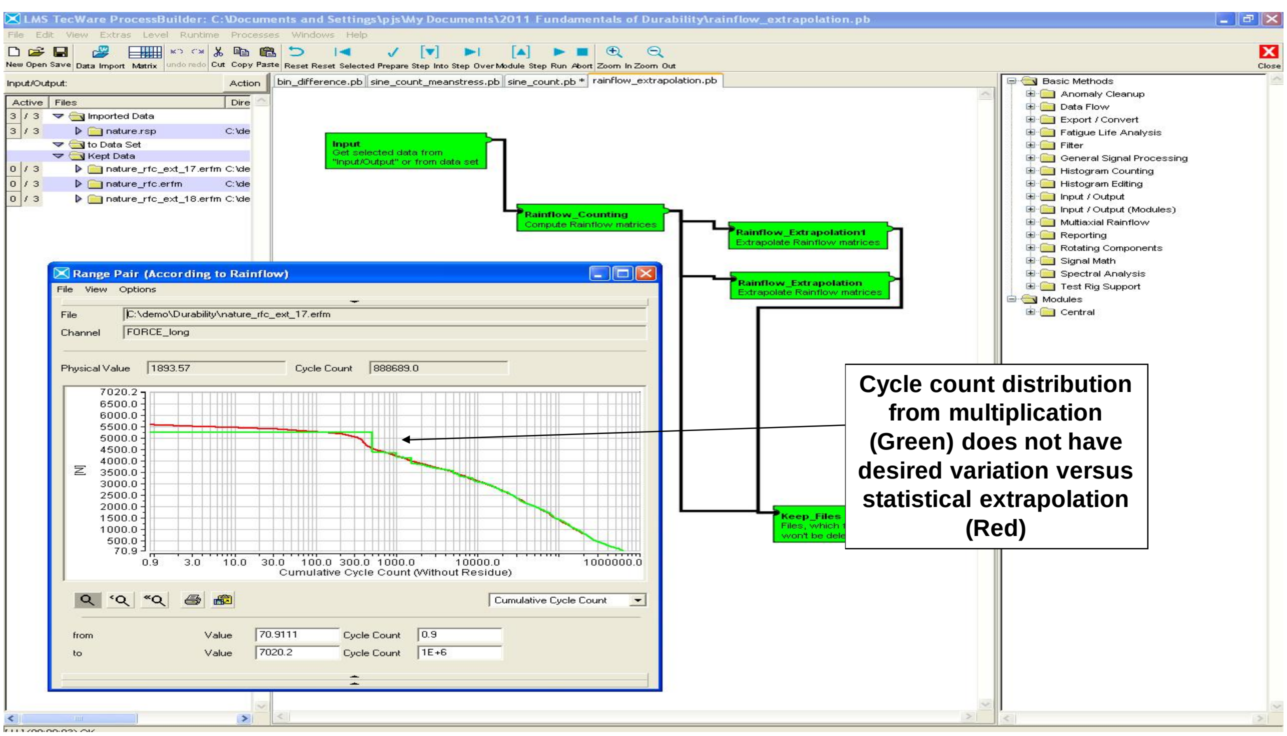


EXTRAPOLATION DEMO

TecWare




LMS TecWare ProcessBuilder: C:\Documents and Settings\pjs\My Documents\2011 Fundamentals of Durability\rainflow_extrapolation.pb
RAINFLOW Matrix
Rainflow Matrix extrapolated with statistical variation


LMS TecWare ProcessBuilder: C:\Documents and Settings\pjs\My Documents\2011 Fundamentals of Durability\rainflow_extrapolation.pb
Range Pair (According to Rainflow)
Cycle count distribution from multiplication (Green) does not have desired variation versus statistical extrapolation (Red)

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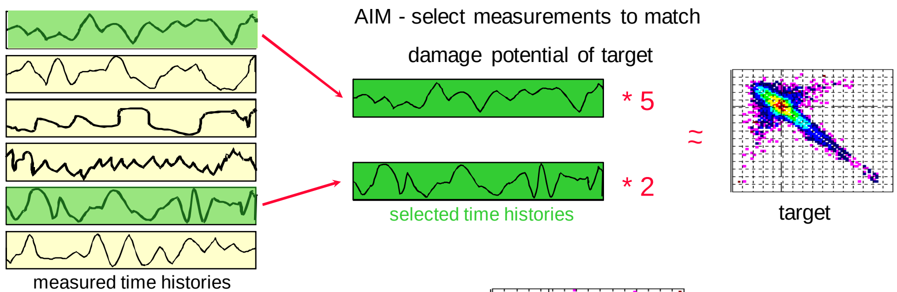
From target to test schedule definition



- Global damage: match damage of the full matrix
- Partial damage: match damage within many overlapping windows for clusters of the matrix

2

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From target to test procedure

[General]

Datum	01/09/2003 09:52:25
Modus	Kollektiv-Optimierung
Laufzeit	15

[Target]

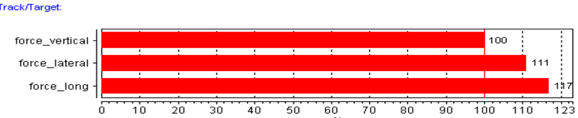
Vergleich	Teil
Lastvariable 1	RAINFLOW | %TECWAREHOME%\demo\combitrack\target.erm | force_vertical
Lastvariable 2	RAINFLOW | %TECWAREHOME%\demo\combitrack\target.erm | force_lateral
Lastvariable 3	RAINFLOW | %TECWAREHOME%\demo\combitrack\target.erm | force_long

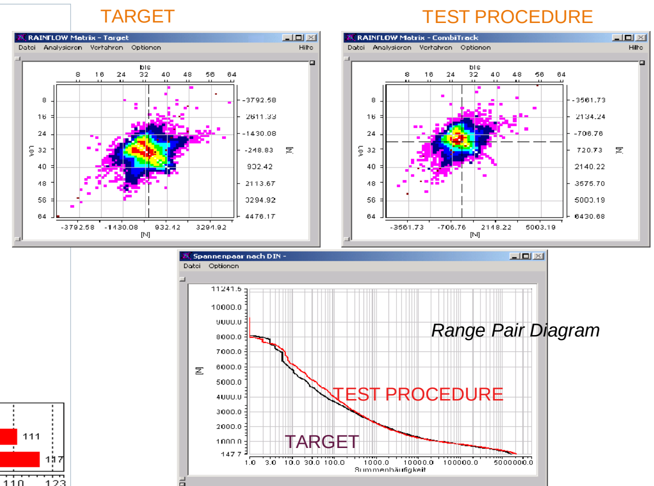
[Coefficients]

Strecke	Gewicht	Strecke	Gewicht
RaceTrackA	1	RaceTrackB	0
NatureTrackAA	0	NatureTrackAB	0
NatureTrackAC	0	NatureTrackBA	1
NatureTrackBB	0	NatureTrackBC	0
NatureTrackCA	0	NatureTrackCB	0
NatureTrackCC	0	Track1	1
Track2	1	Track3	0
Track4	6	Track5	2
Track6	2	Track7	0
Track8	0	Track9	0
Track10	1		

Kanal	Target	CombiTrack
force_vertical	0.0508	0.0508
force_lateral	9.7823E-3	0.0109
force_long	2.1153E-3	2.4674E-3

CombiTrack/Target:



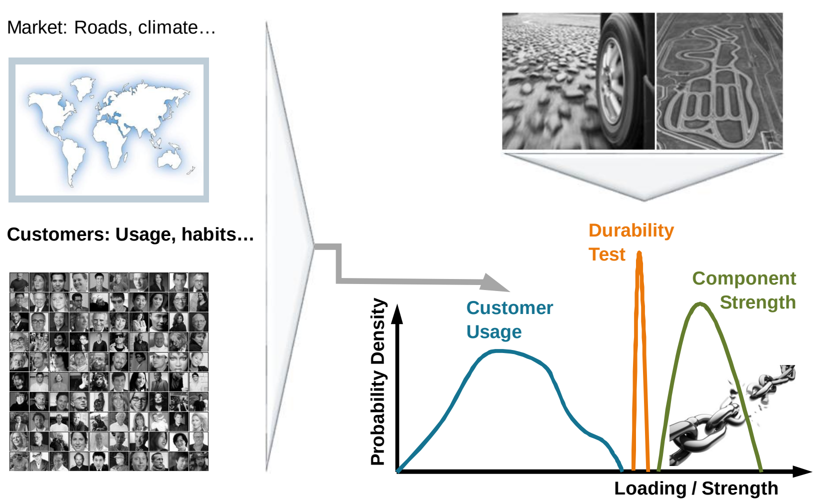


e.g. cycles of small Amplitude are compensated by small amount of cycles of high amplitude in test Schedule

Load Data Synthesis Demo

CombiTrack

Customer correlation
Introduction



Huge Variability of Customer Usage → Statistics

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Statistical Approach → Fleet measurement required

Requires statistical quantification:

Þ Observe many customers

Þ Observe over longer period of time

Þ Fleet Measurement!

Challenge:
Traditional durability measurement = complex, expensive, sensitive

Not applicable for fleet measurement campaign !!!

Statistical Approach → Fleet measurement required

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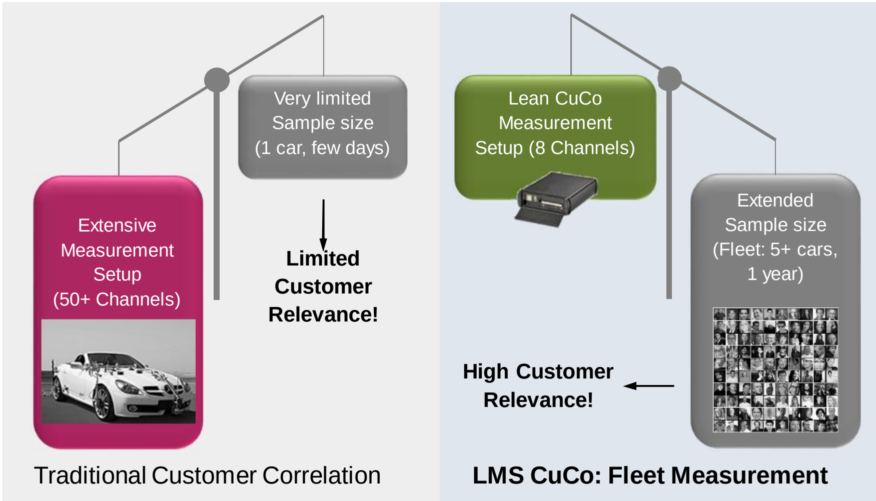

The Traditional Technical Approach

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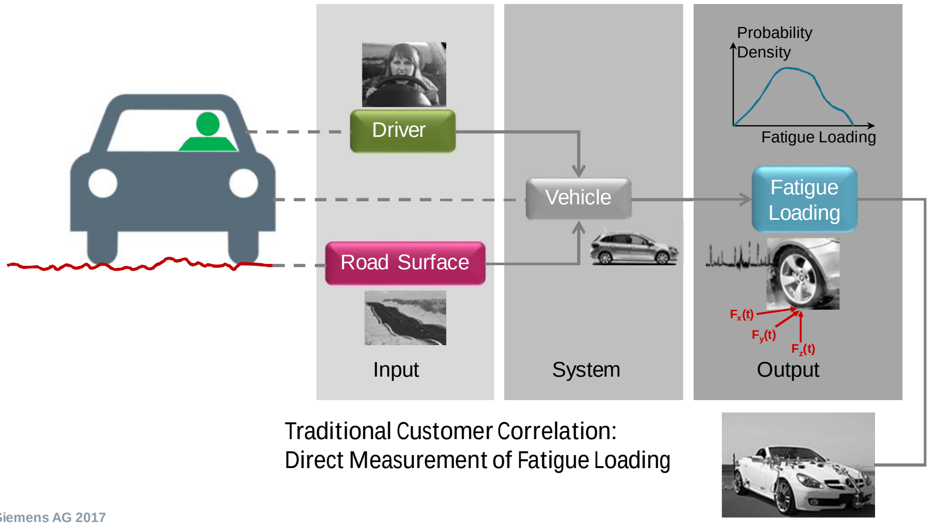

CuCo Project Structure

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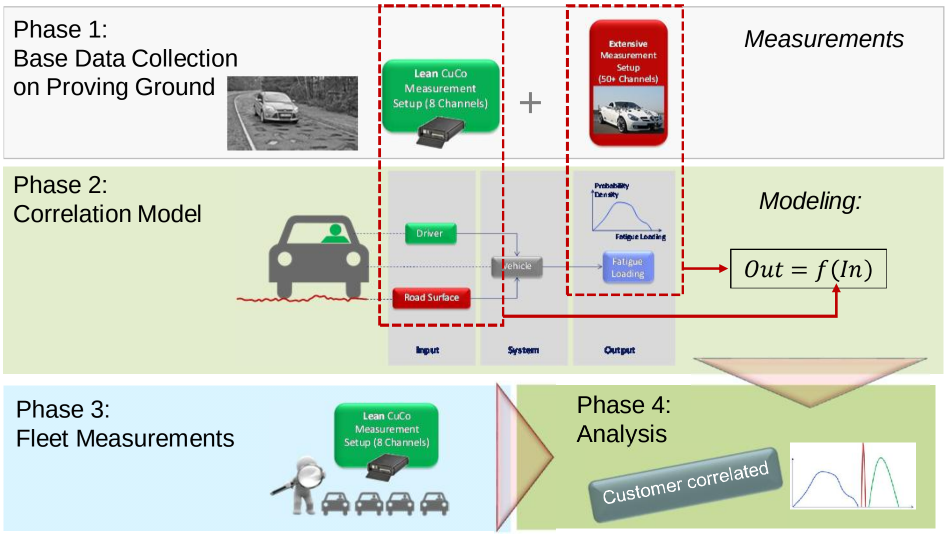

Result:
„Fingerprint" of Customer Representative Loading

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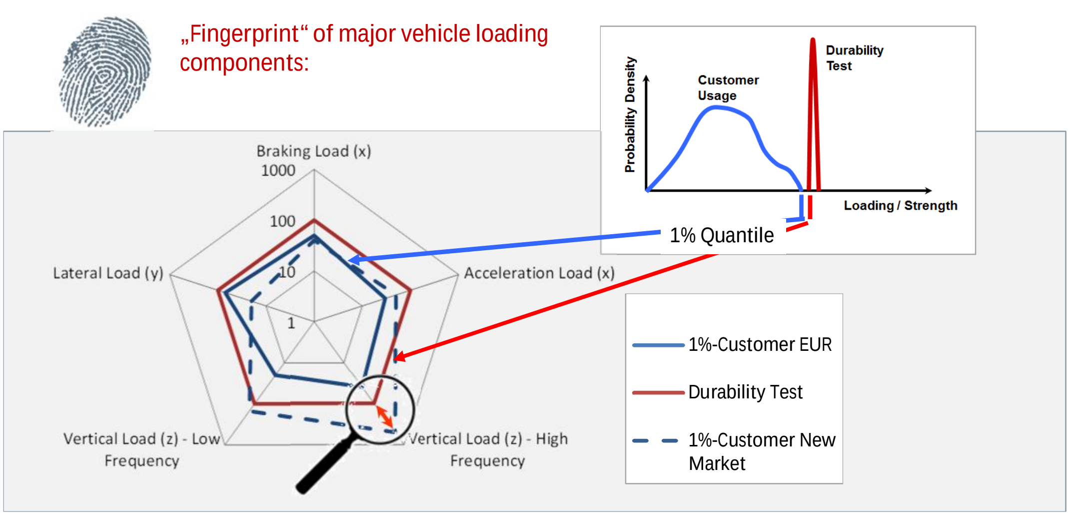

Reference
German OEMs (Audi, BMW, Daimler, Porsche, VW)

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- Long-term Workgroup 1992 – 2009
- Core role of LMS as technical enabler
- Multi-year Fleet campaign with
  - *> 100 vehicles*
  - *> 300 drivers*
  - *> 2 million km accumulated mileage*
- Observed markets: Germany, BRIC, USA
- Today: Established technology at all 5 (User Group)

Patented Technology

LMS entitled to market Technology

Durability Agenda

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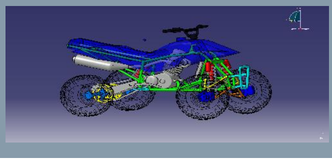
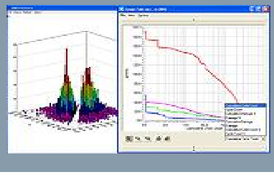
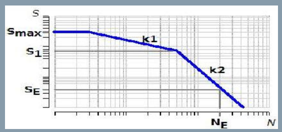
Durability Basics	Load Determination	Loads and Damage
Fatigue, Stress, Strain	Measurements, Multi-Body Simulation	S-N Curve, Cycle Counting
		
Load Characterization	**Fatigue Life Predictions**	**Accelerated Testing & Analysis**
Establishing Durability Targets: Superposition, Extrapolation	Infinite Life, Stress Life, Strain Life	RP-Filter, Mission Synthesis
		

How to design against fatigue ? Principle approaches

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Design for an infinite life
- Keep stress below **endurance limit**
- Infinite lifetime concept ($N > 10^6$)
- Factor of safety

Design for a fixed life
- Finite lifetime concept or “safe-life”
- **High-cycle fatigue (HCF) :**
  stress-life or strain-life approach ($10^4<N<10^6$)
- **Low-cycle fatigue (LCF)**:
  strain-life approach ($N < 10^4$)

Damage tolerant design
- **Crack-growth** or “fail-safe”
- Instruct the user to inspect the part periodically for cracks
- Replace the part once a crack exceeds a critical length.

Failure modes depending on load level

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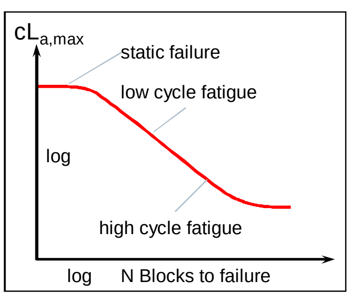
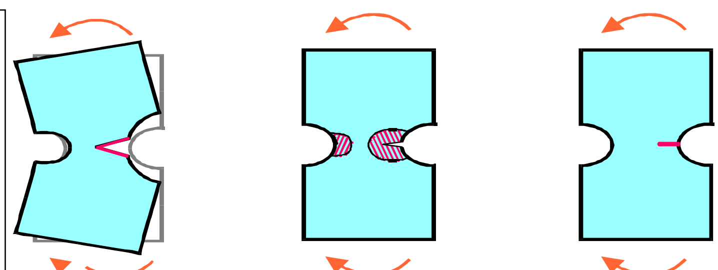
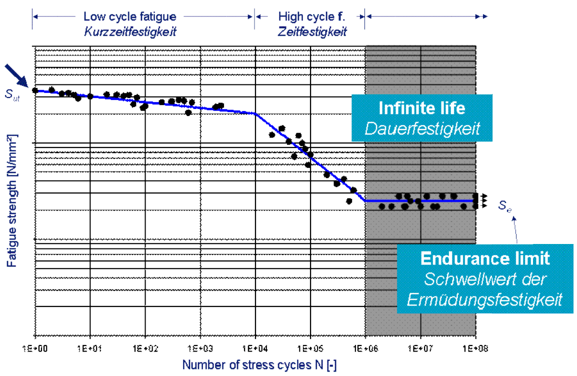


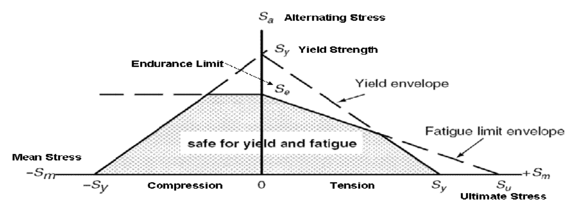


	static failure	low cycle fatigue	high cycle fatigue
appearance	large deformation of total structure	large plastic zone at notch	little plasticity
major parameter	net section resistance	notch severity, material plasticity	notch severity, manufacturing, residual stresses

Design for an infinite life



Keep stress below endurance limit
Infinite lifetime concept ($N > 10^6$)
Factor of safety



Goodman/Haigh diagram

What influences fatigue?

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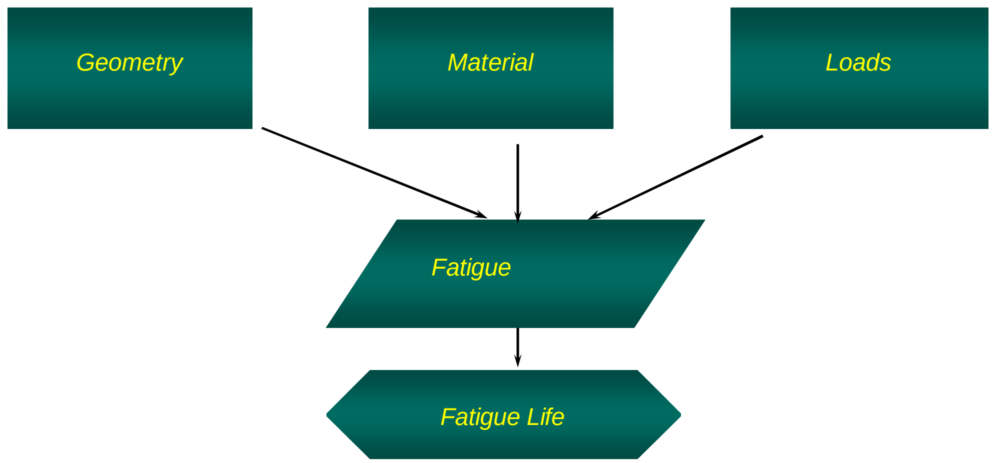

Infinite Life

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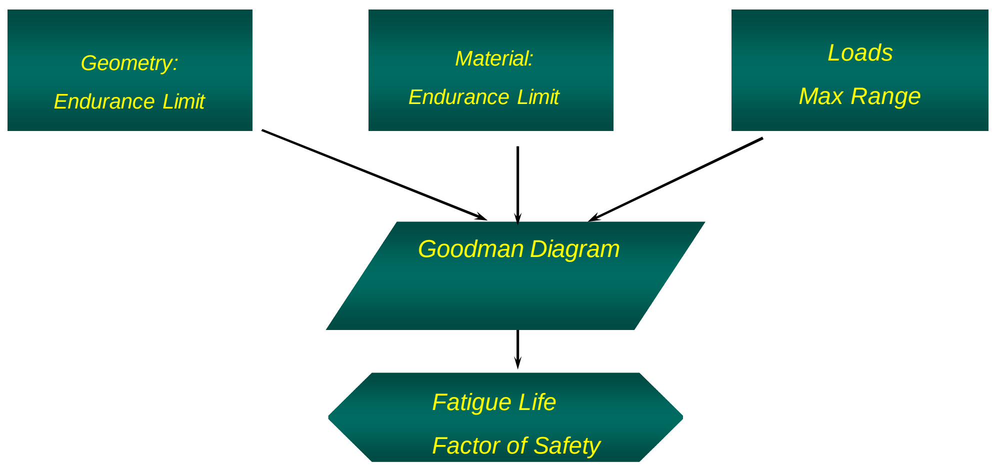

How to design against fatigue ?

Design to keep stress below endurance limit – Flow chart

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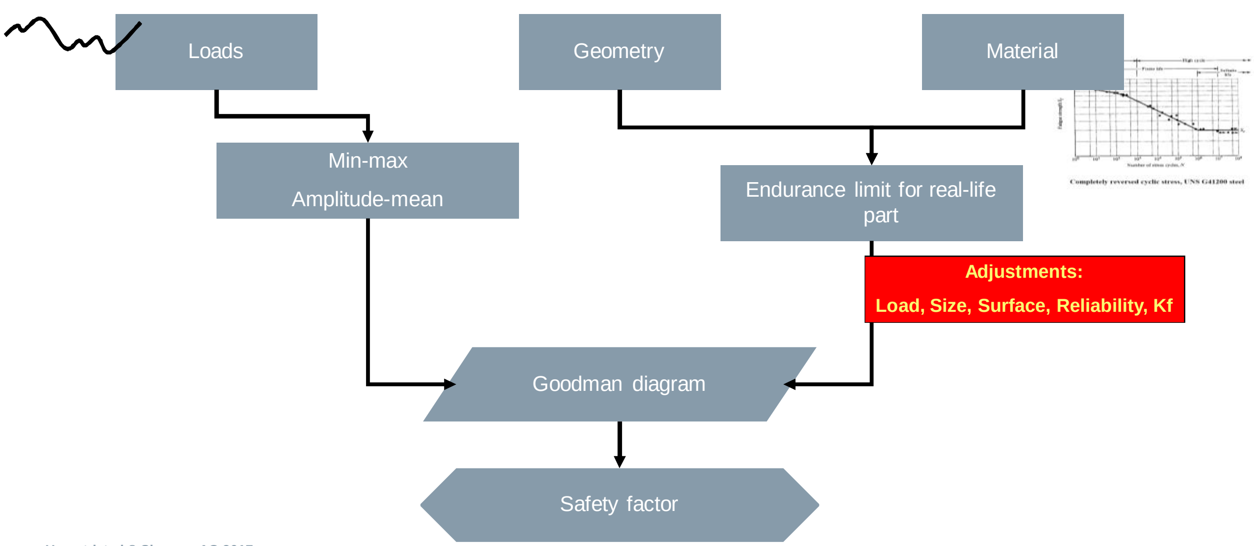

Haigh Diagram for Infinite Life

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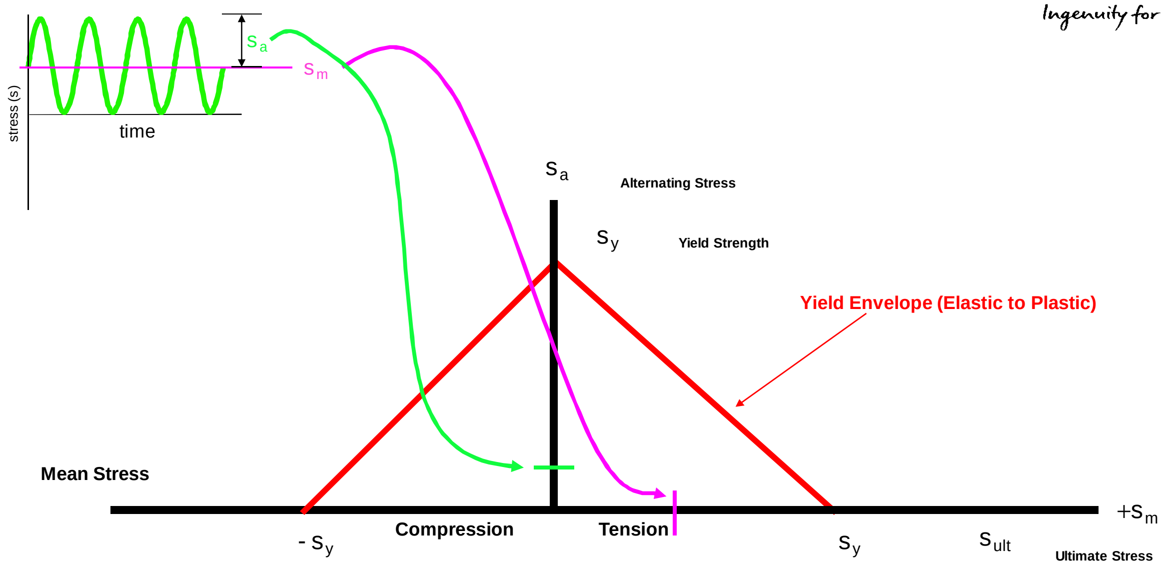

Haigh Diagram for Infinite Life

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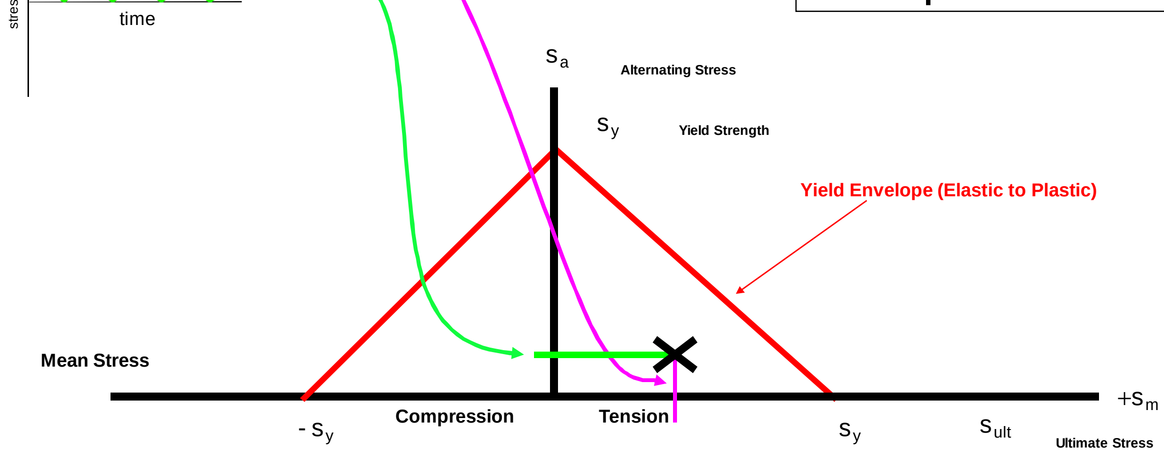
✕ within the Yield Envelope is infinite life.



Haigh Diagram for Infinite Life

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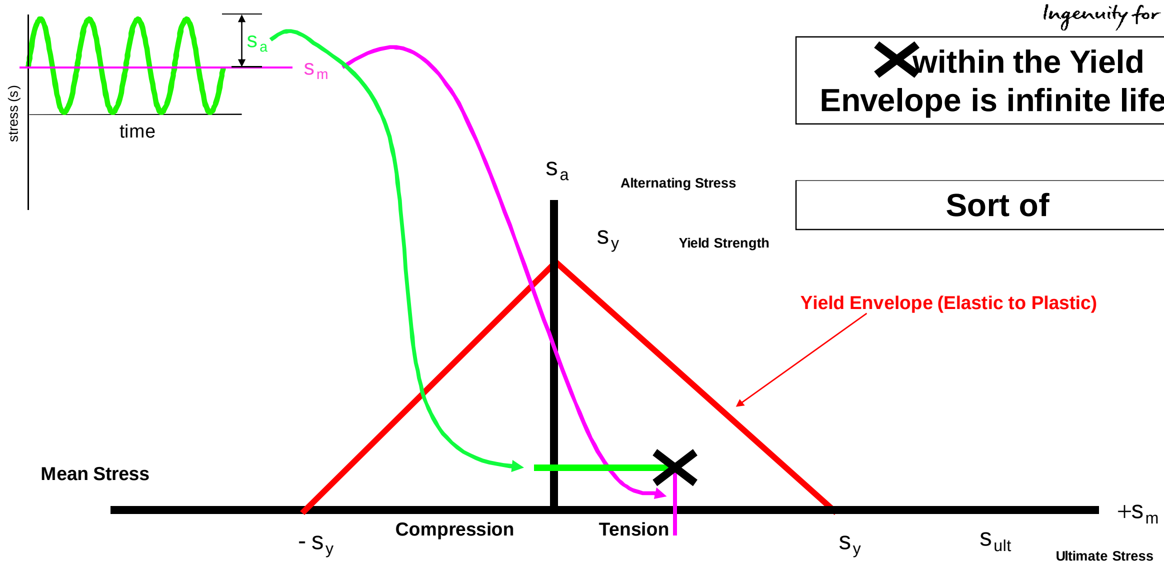
~~X~~within the Yield Envelope is infinite life.

Sort of



Haigh Diagram for Infinite Life

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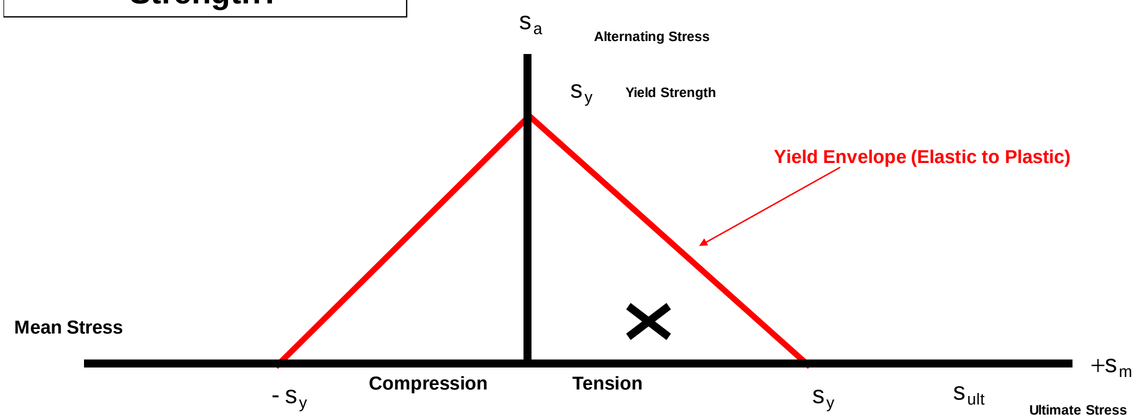
Ingenuity for life

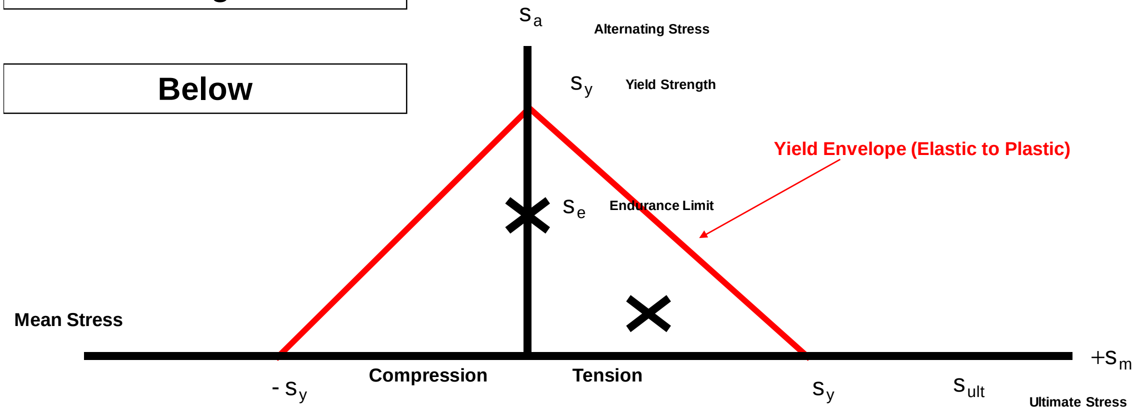
Is Endurance Limit <u>above</u> or <u>below</u> Yield Strength?



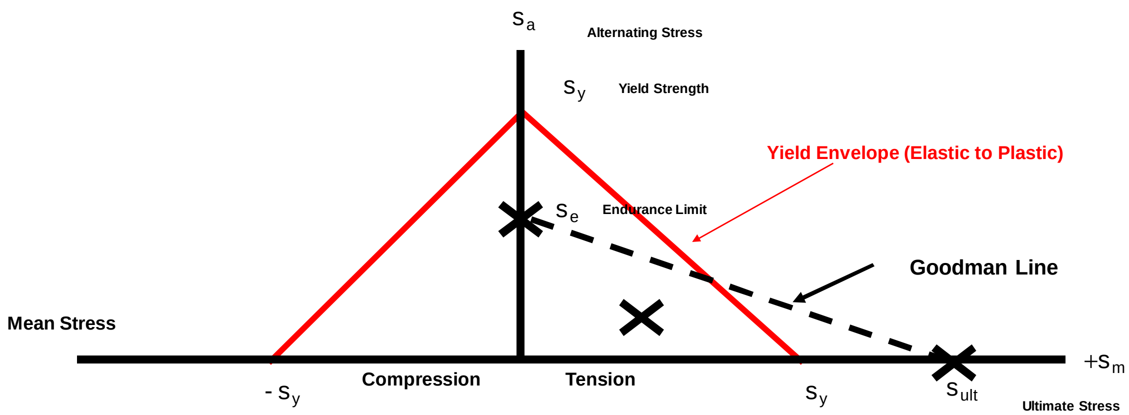
Haigh Diagram for Infinite Life

Is Endurance Limit above or below Yield Strength?

Below



Modified Goodman-Haigh Diagram for Infinite Life



Modified Goodman-Haigh Diagram for Infinite Life

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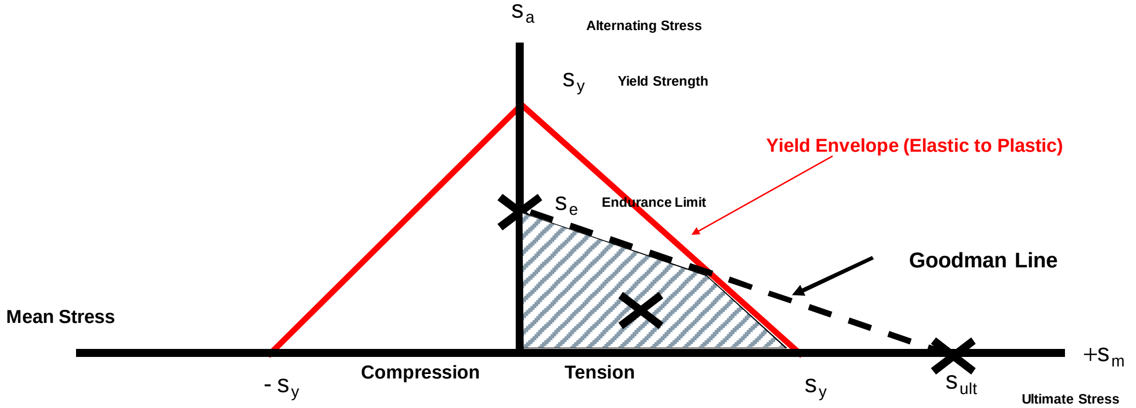

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Modified Goodman-Haigh Diagram for Infinite Life

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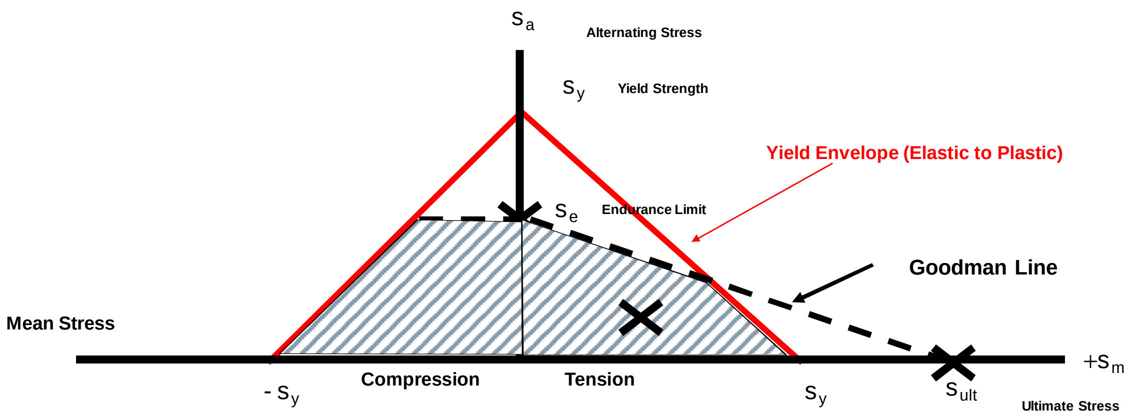
Infinite Life Region



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Modified Goodman-Haigh Diagram for Infinite Life

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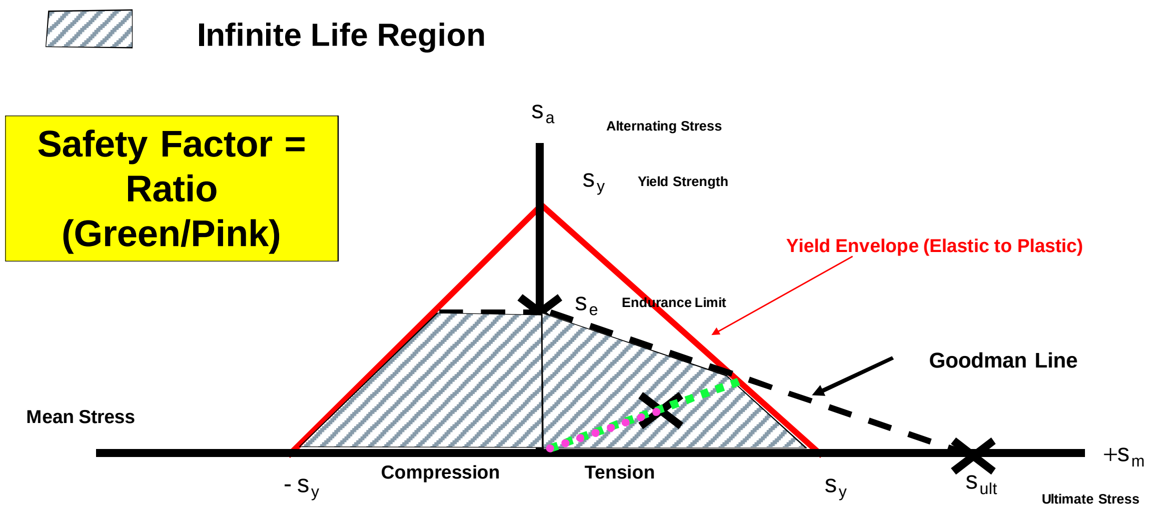

Design to keep stress below endurance limit

Goodman/ Haigh diagram for combined fatigue limit and yield

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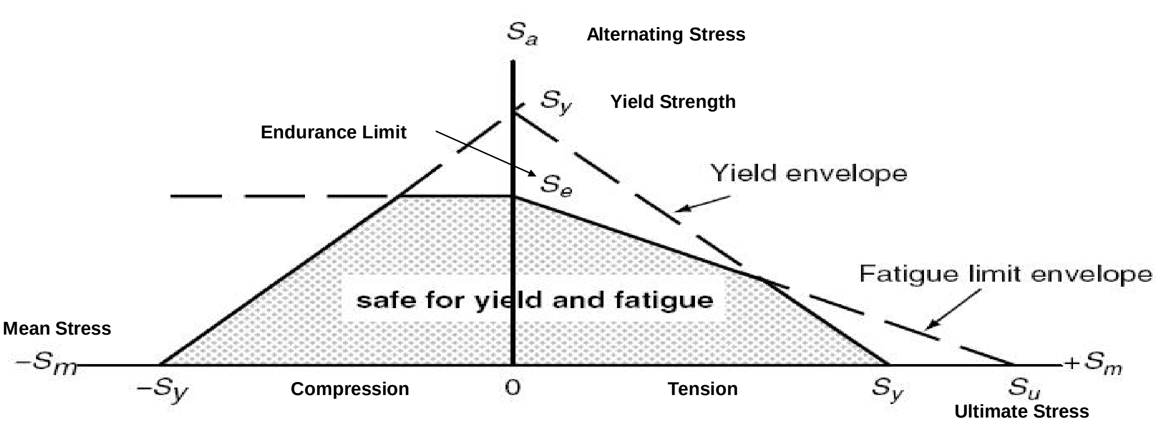
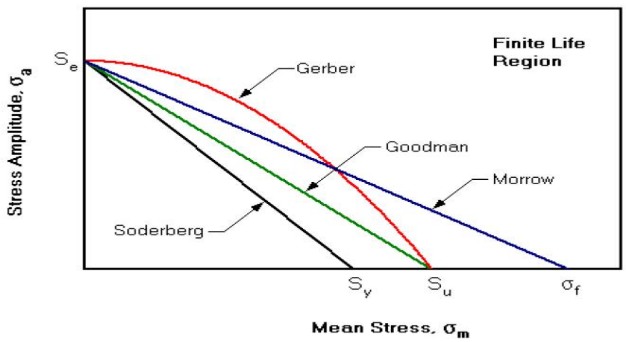


Infinite Life Theories on Failure Envelopes



Goodman (England, 1899): $\frac{S_a}{S_e} + \frac{S_m}{S_u} = 1$

Gerber (Germany, 1874): $\frac{S_a}{S_e} + \left(\frac{S_m}{S_u}\right)^2 = 1$

Soderberg (USA, 1930): $\frac{S_a}{S_e} + \frac{S_m}{S_y} = 1$

Morrow (USA, 1960s): $\frac{S_a}{S_e} + \frac{S_m}{\sigma_f} = 1$

R=-1

Famous People In Fatigue

Sir Robert Hooke
British
(1635-1703)

Hooke's Law of Elasticity in 1660

Goodman
English
(1869 - 1942)

Goodman's Rule in 1899

MA Miner
English
(1915 - 1978)

Miner's Rule in 1945

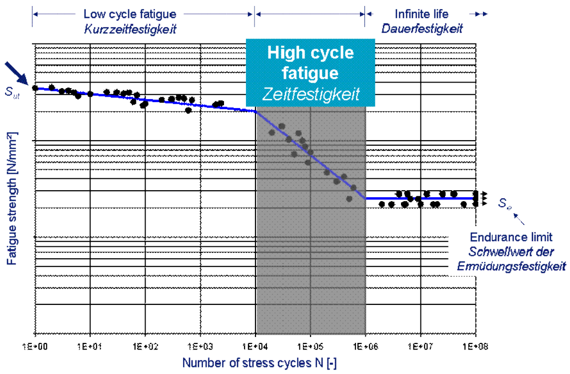
August Wöhler
German
(1819-1914)

Wöhler curves in 1867

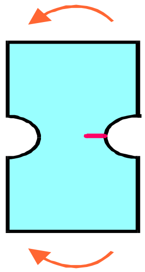
Tatsuo Endo
Japan
(1925 - 1989)

Rainflow Counting in 1968

Design for a finite life.
High cycle fatigue ($N>10^4$ and $N<10^6$)



Finite lifetime concept or “safe-life”
High cycle fatigue : $N>10^4$ and $N<10^6$
Stress-life approach
Little plasticity at notch



What influences fatigue?
High Cycle Fatigue

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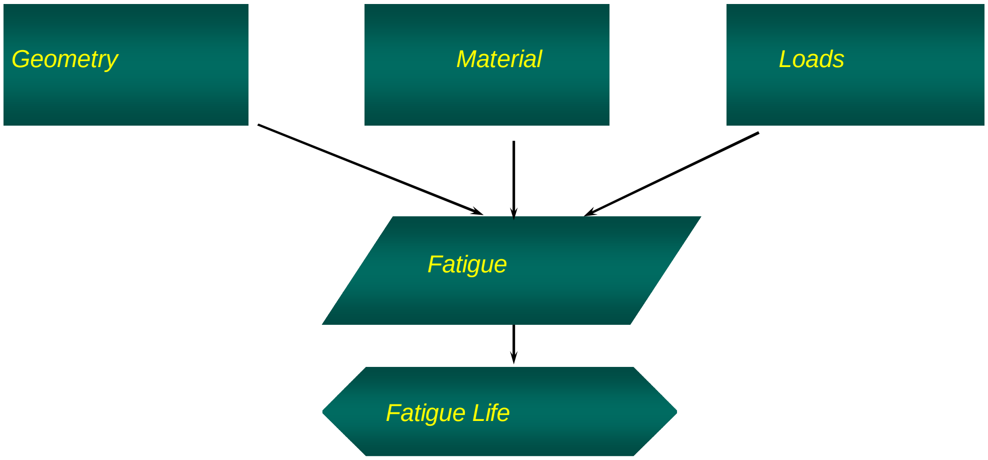

What influences fatigue?
High Cycle Fatigue

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Geometry:
SN-Curve

Material:
SN-Curve

Loads:
Rainflow Count

Fatigue
Stress Life

Assumes Elastic Stresses even in notches

Fatigue Life
Miners Rule

High Cycle Fatigue
Design for a fixed life. (N>10K and N<10M)

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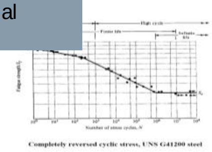
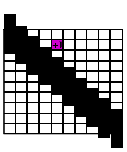
Loads

Geometry

Material





Rainflow counting
® Cycles

Mean Stress Corrections

SN-curve for CA loading
and adjustments

Adjustments:
Load, Size, Surface, Reliability, Kf

Damage
calculation

Miner's damage accumulation rule

Fatigue life

Mean stress influence
Goodman (1890)

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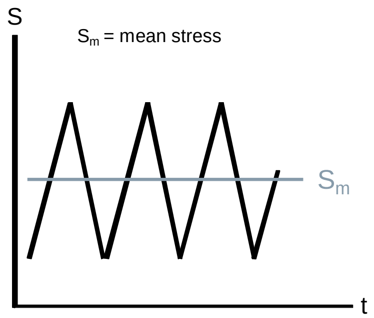
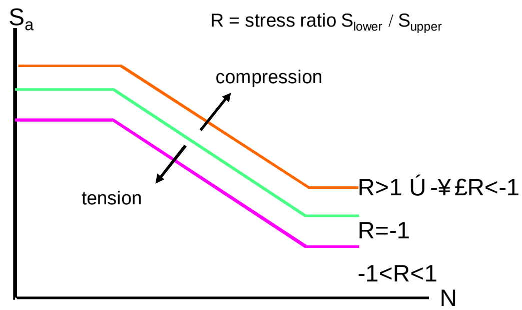
Load history



SN-curves



Tension mean stresses reduce the fatigue life
from that observed with completely reversed loading

Mean Stress Correction

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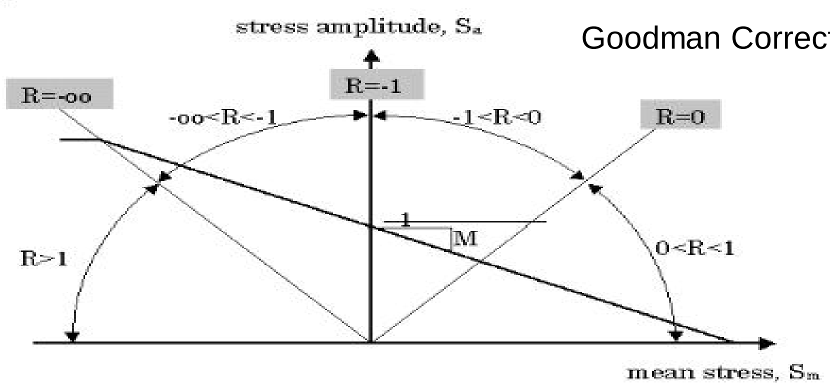
Basic Principle : Relates stress at non zero mean stress to an equivalent stress amplitude at 0 mean stress, based on equivalent fatigue lifetimes

$$R=\frac{\sigma_{lower}}{\sigma_{upper}}$$

Goodman Correction



$$M=\frac{S_{E,R=-1}}{S_{E,R=0}}-1.$$

Goodman Mean Stress Example

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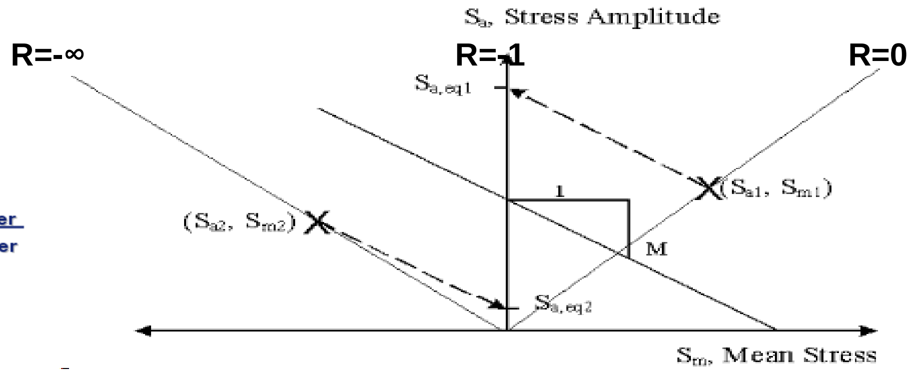
Bins in rain flow matrix with non zero mean stress are projected to the R=-1 axis by following slope M

$R = \frac{\sigma_{lower}}{\sigma_{upper}}$



Mean stress influence
M-factor (example)

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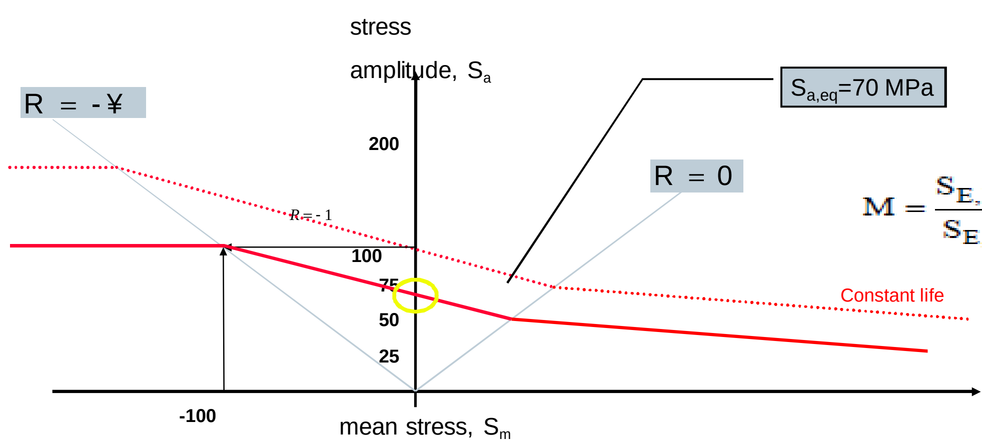
S_a=100 MPa , R = -¥, M_1= M = 0.3, M_3 = 0.1 à $S_{a,\,eq}$(R = -1) = ?

$R = \frac{\sigma_{lower}}{\sigma_{upper}}$



$$M = \frac{S_{E,R=-1}}{S_{E,R=0}} - 1.$$

Mean Shear Stress (Torsion)

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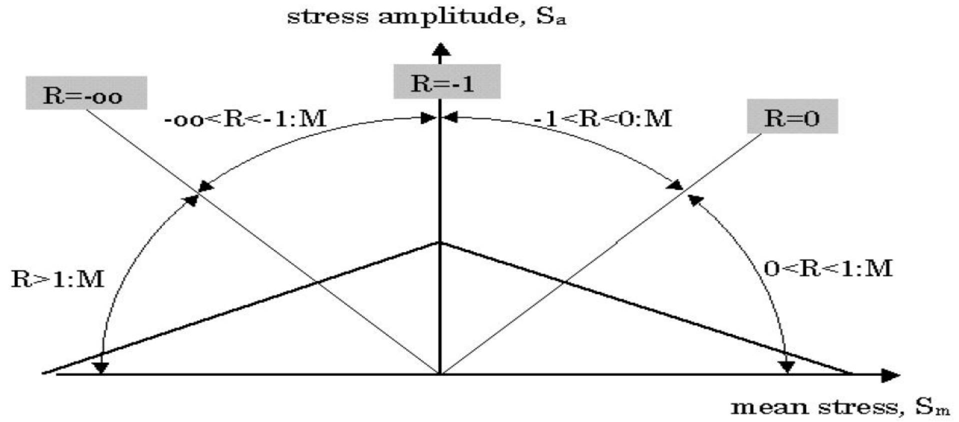

Fig. 41: Mean shear influence for 1 segment

Mean Stress Demo

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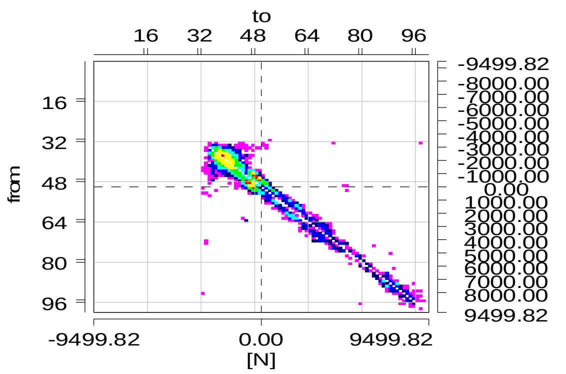

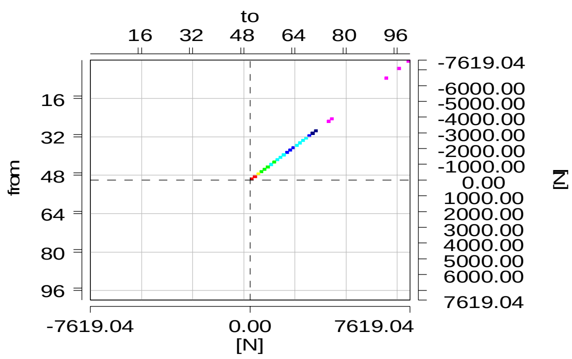

Pros and Cons of Stress Life

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Pros:
- Simple - back of the envelope calculation possible
- A lot of historical data
- Extensively validated for constant amplitude loading

Cons:
- Empirical – care most be taken when extrapolating relationships
- Geometry dependent – SN curve is dependent on component
- Only good in elastic region – does not account for true stress strain relationship

Applications:
- Load data analysis and synthesis
- Test acceleration
- Test rig / test track correlation
- Most commonly used for test-based fatigue
- Frequency based approaches
- Welds

Life Curve

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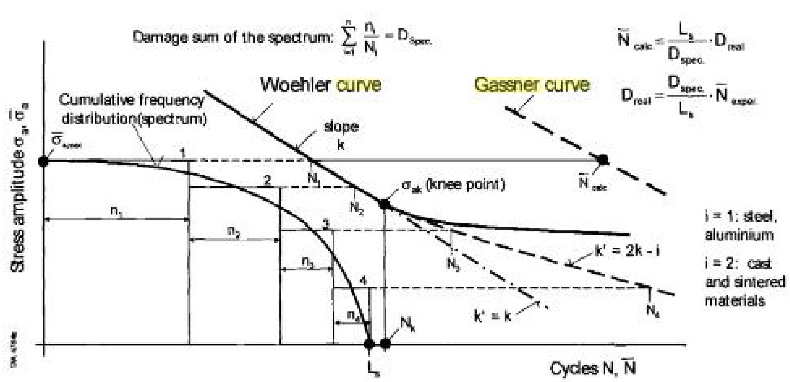

Life Curve

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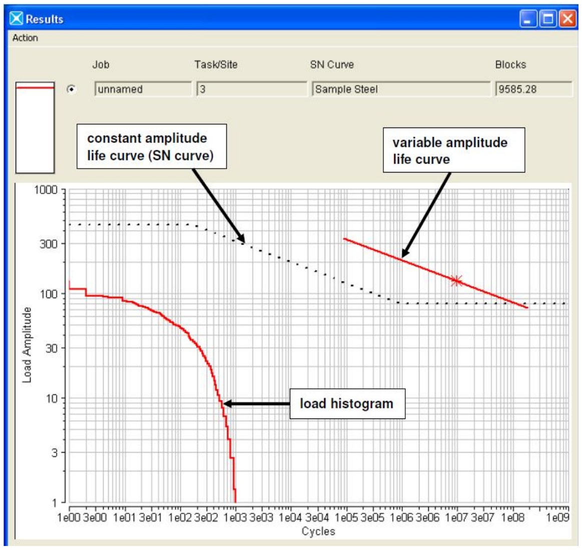

Design for a finite life. Low cycle fatigue ($N<10^4$)

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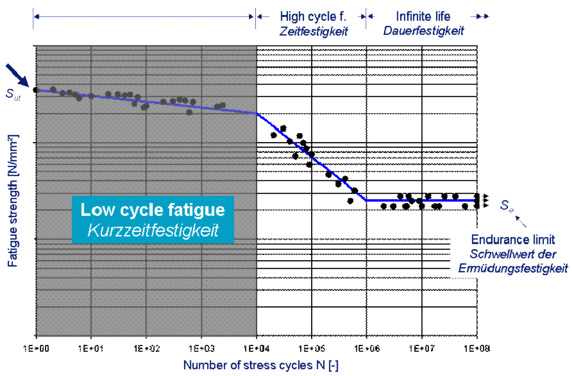
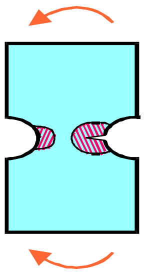


Finite lifetime concept or “safe-life”
Low cycle fatigue: $N<10^4$
Strain-life approach
Large plasticity at notch



What influences fatigue? Low Cycle Fatigue

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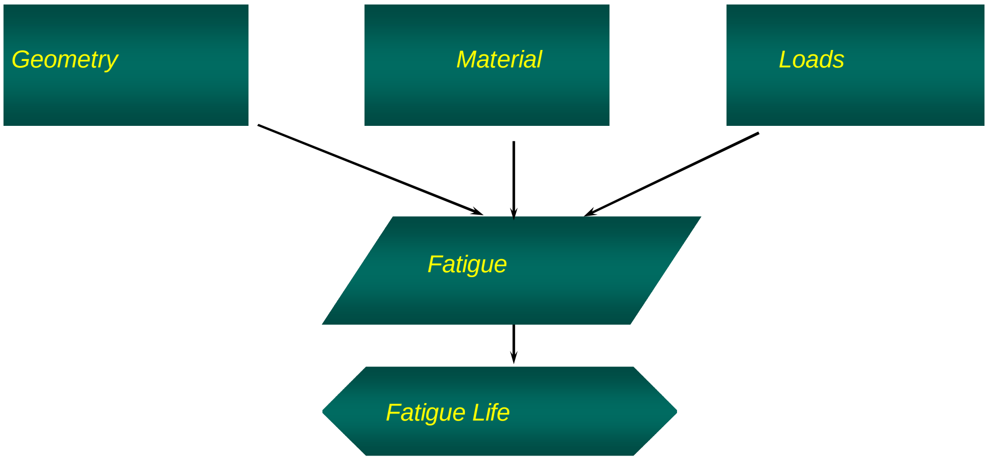

What influences fatigue? Low Cycle Fatigue

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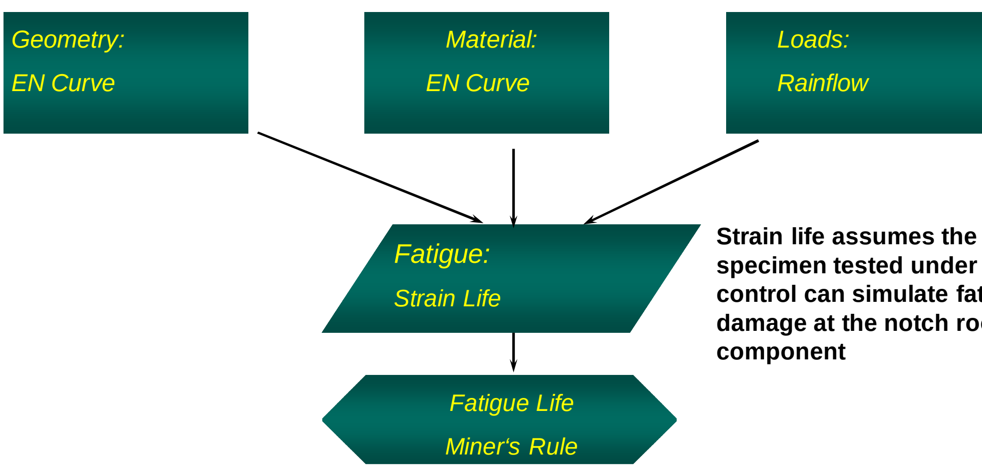
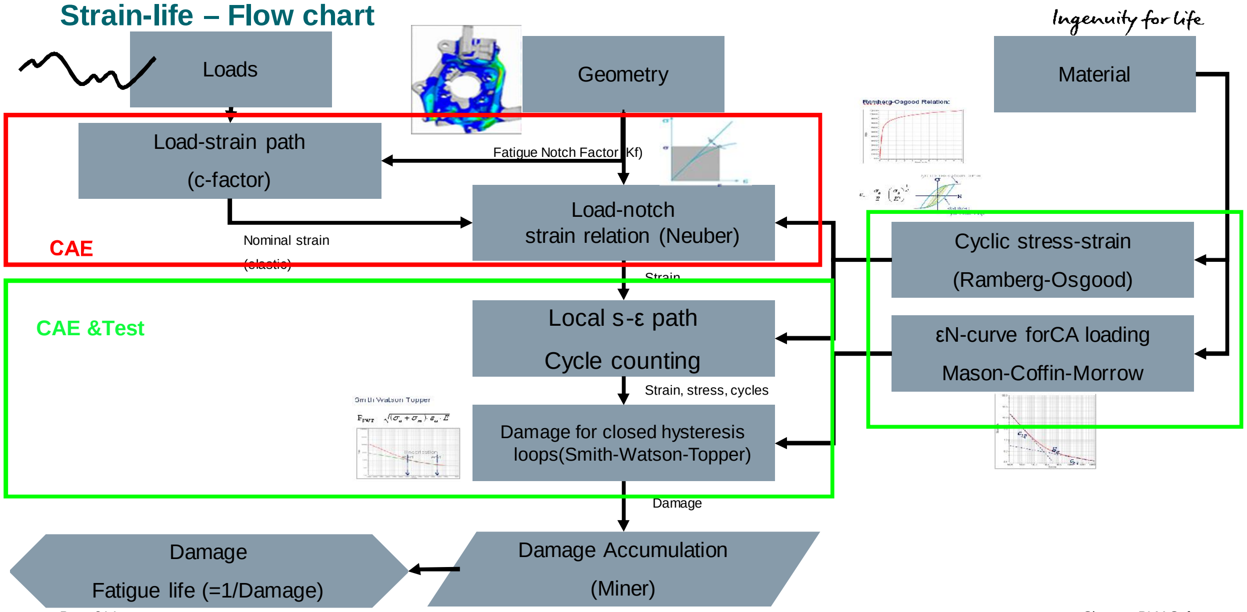
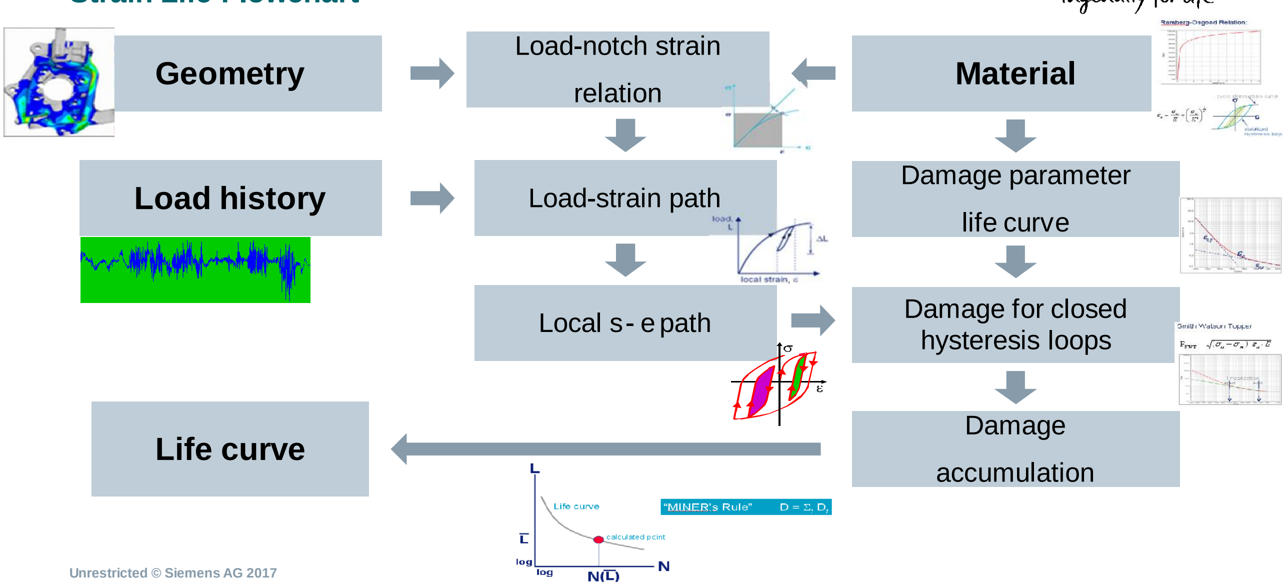


Strain life assumes the smooth specimen tested under strain control can simulate fatigue damage at the notch root of a component

Finite life
Strain-life – Flow chart



Fatigue analysis
Strain Life Flowchart



Strain-Life Approach – Input Data

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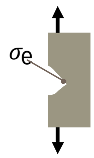
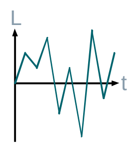
Geometry (load configuration)



$\sigma_e = c \cdot L$

elastic influence factor c

Load History



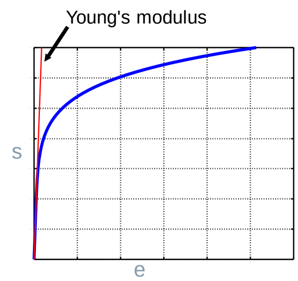
Material

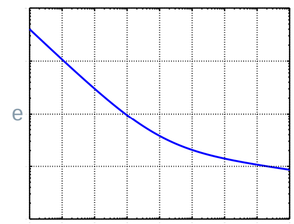
cyclic stress-strain curve
(Ramberg-Osgood)

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'}$$

$$\varepsilon_a = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c$$

strain-life curve
(Manson-Coffin-Morrow)





Strain-Life Approach – Flowchart

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Material

Geometry

Load History

1 Load-notch strain relation
(e.g. Neuber approximation)
Masing- / Memory-Model

2 Create Load-strain path
and derive
Local stress-strain path

3 Damage parameter life curve
(e.g. Smith-Watson-Topper)

4 Calculate and accumulate damage of hysteresis loops
Derive Fatigue Life

1 – Neuber Approximation

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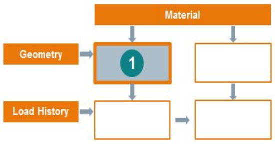

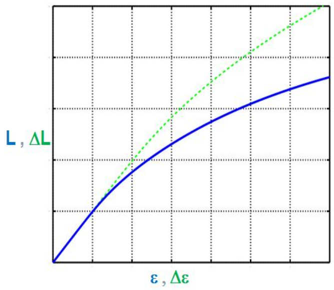

From the universal Neuber approximation

$$\varepsilon = \frac{\sigma}{E}\left(\frac{L \cdot c}{\sigma}\right)^2 \frac{e^*}{S^* / E}; \qquad S^* = \frac{L \cdot c}{K_p}; \qquad e^* = g(S^*)$$

and the Ramberg-Osgood relation

$$\varepsilon = g(\sigma) = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$

derive the Load-notch strain curve. From this and the doubled curve (dashed) the load-strain path can be created (next step).

Note: We have 2 equations with 2 unknowns (σ and ε). This system can be solved for any given external load L.

According to the Masing model, the following holds:

$$\Delta\varepsilon = 2 \cdot g(\Delta S / 2) \quad \text{for} \quad \varepsilon = g(S)$$

Cyclic Stress Strain Curve

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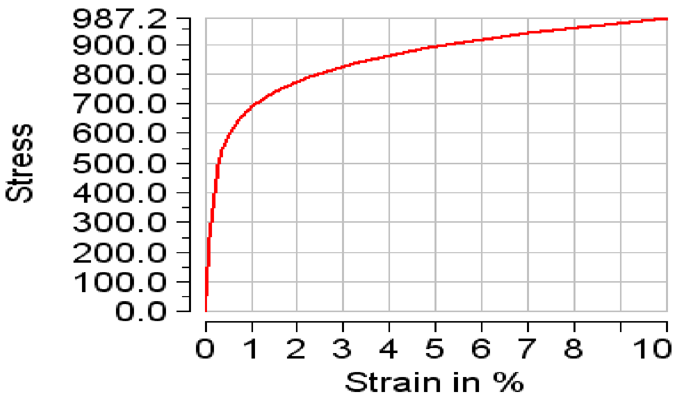
Cyclic stress-strain

(Ramberg-Osgood)

Used to calculate cyclical stress strain behavior and obtain mean stress



$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'}$$

E : Young's Modulus

K': Cyclic Hardening Coeff

n': Cyclic Hardening Exponent

Neuber's Rule

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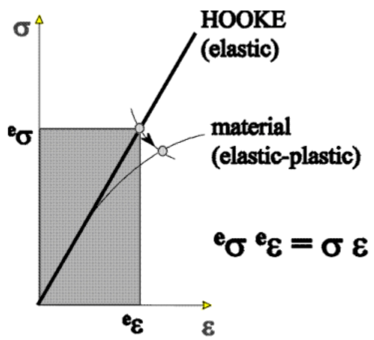
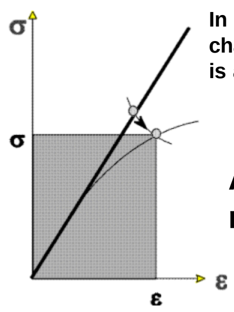
Load-notch strain relation (Neuber)

- Converts elastic stress-strain to plastic stress-strain in notch
  - Not needed in test if gauge is placed plastic zone of notch





In plastic zone for a given change in load (stress) there is a greater change in strain

Area of shaded rectangles are =

2 – Load-Strain Path

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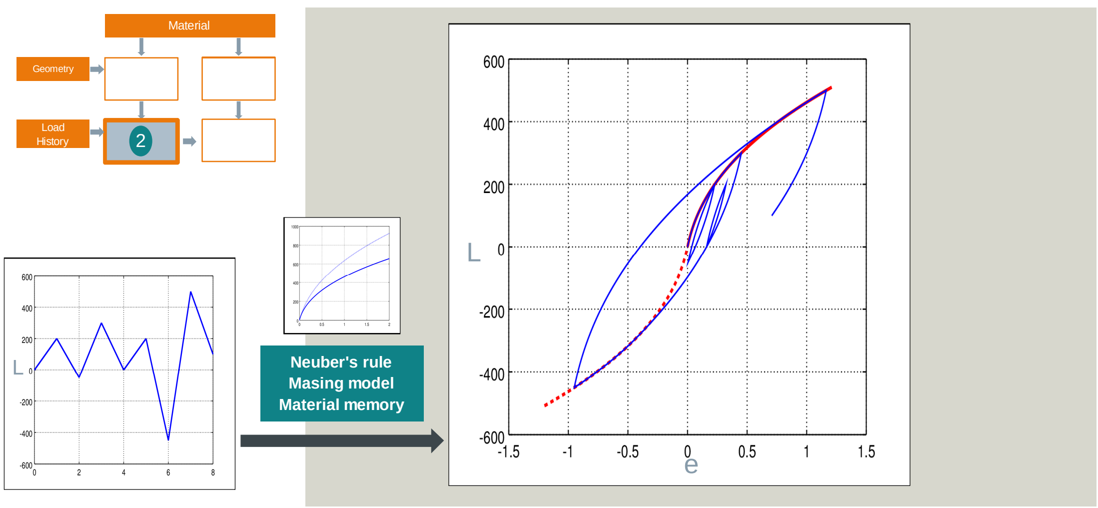
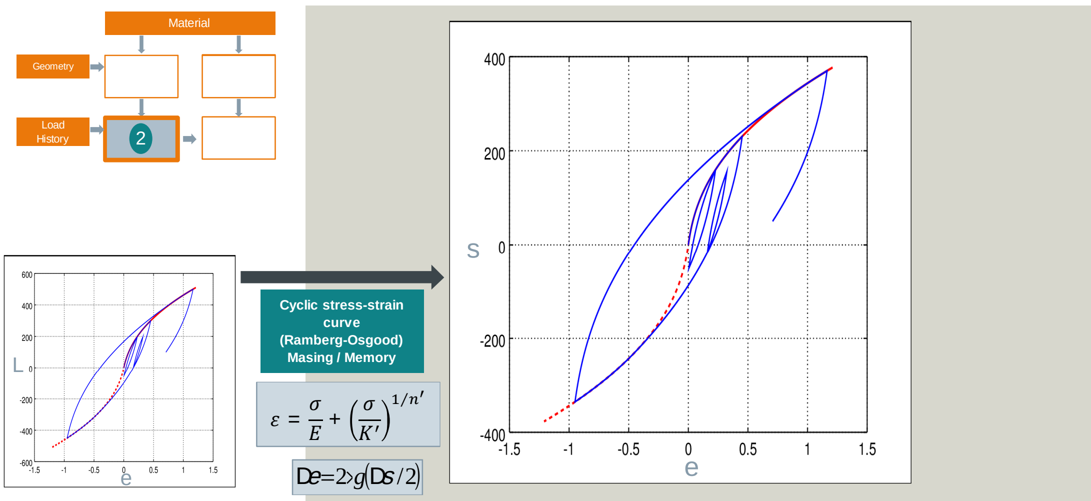


2 – Local Stress-Strain Path



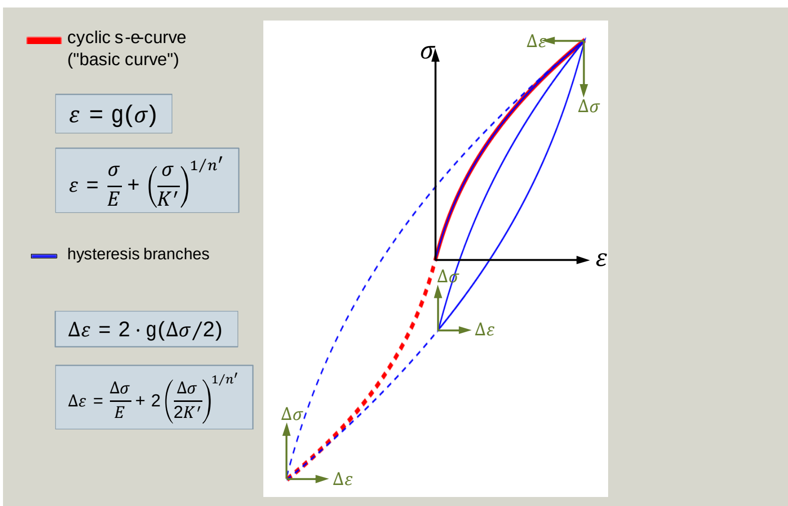
Explanation – Masing Behavior

The hysteresis branches for un-loading or re-loading are derived from "doubling" the cyclic s-e-curve.

The ranges for s and e (Ds and De) on a hysteresis branch correspond to twice the values for s and e on the basic curve:

$$\Delta\sigma = 2 \cdot \sigma$$
$$\Delta\varepsilon = 2 \cdot \varepsilon$$

Next to this the "Material Memory" must be taken into account! (see next page)



Explanation – Material Memory

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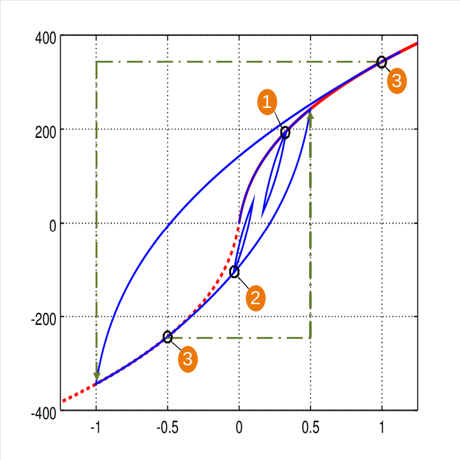
1
After closing a hysteresis loop, which started at the basic curve (cyclic s-e-path), the s-e-path follows again the basic curve.

2
After closing a hysteresis loop, which started at a hysteresis branch, the s-e-path follows again the initial hysteresis branch.

3
A hysteresis branch, which started at the basic curve, ends at the basic curve in the opposite quadrant (point of symmetry). Then, the s-e-path follows the basic curve.



E-N Curve

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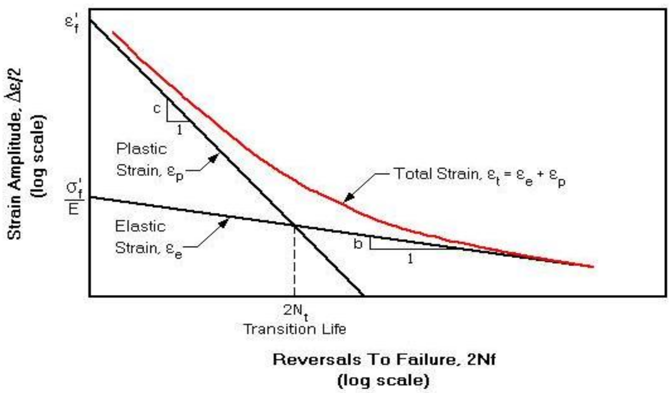
εN-curve for

CA loading

Mason-Coffin-Morrow

E-N Curve relates strain amplitude to cycles to Failure. Will have similar adjustments in level as S-N curve.



Manson-Coffin-Morrow Relation

$$\varepsilon_a = \frac{\sigma'_f}{E}(2N)^b + \varepsilon'_f(2N)^c$$

Fatigue Strength Coefficient	σ'_f	1374	MPa
Fatigue Ductility Coefficient	ε'_f	1.007	
Fatigue Strength Exponent	b	-0.091	
Fatigue Ductility Exponent	c	-0.652	

Mean Stress Corrections

Damage for closed hysteresis loops

(Smith-Watson-Topper)

Allows user to calculate damage from E-N curve with mean and max stress from closed hysteresis loop

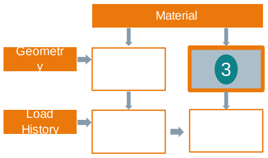
Once adjusted strain amplitude calculate number of cycles to failure is taken from E-N Curve

$$\sigma_{max} \cdot \varepsilon_a = \frac{(\sigma_f')^2}{E} \cdot (2N_i)^{2b} + \cdot \sigma_f' \cdot \varepsilon_f' \cdot (2N_i)^{b+c}$$

Parameter	Solution Parameter Name	Definition
Smith-Watson-Topper	P_SWT original P_SWT linear	$P_{SWT} = \sqrt{(\sigma_a + \sigma_m) \cdot \varepsilon_a \cdot E}$
Smith-Watson-Topper for shear stresses	P_SWT Torsion original P_SWT Torsion linear	$P_{SWT} = \sqrt{\lvert\tau_{max}\rvert \cdot \gamma_a \cdot G}$
Bergmann	P Bergmann	$P_B = \sqrt{(\sigma_a + k\sigma_m) \cdot \varepsilon_a \cdot E}$
No mean stress influence	No mean stress influence	$P = \varepsilon_a$
Morrow type	P_Morrow	$P_{Mor} = \frac{\sigma_a}{E} \frac{1}{1 - \sigma_m / \sigma_f'} + \varepsilon_{a,p}$
Vormwald	P_J	See the formula below

Note: SWT predicts no damage when max stress is <=0

3 – Damage Parameter Life Curve

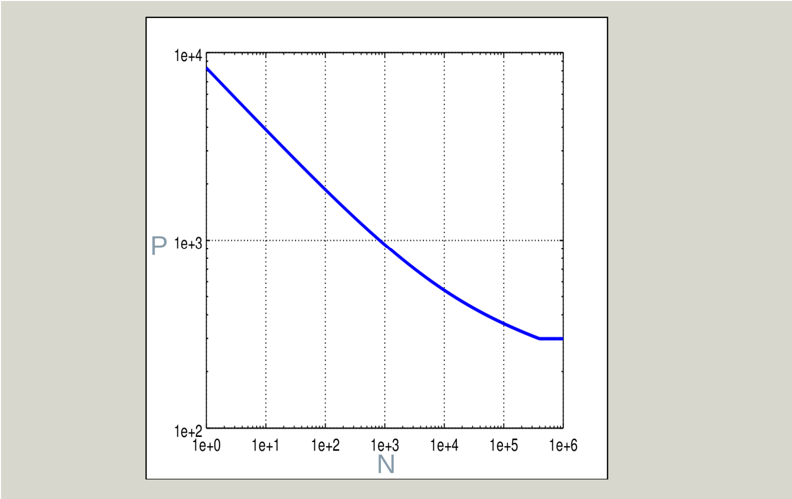


Derive damage parameter life curve from the material data and damage parameter,

e.g. Smith-Watson-Topper

$$P_{SWT} = \sqrt{(s_a + s_m) \times e_a \times E}$$

(use strain-life curve with $s_m = 0$)



4 – Calculate and Accumulate Damage of Hysteresis Loops

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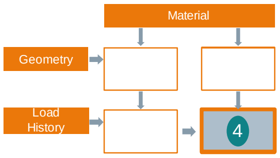


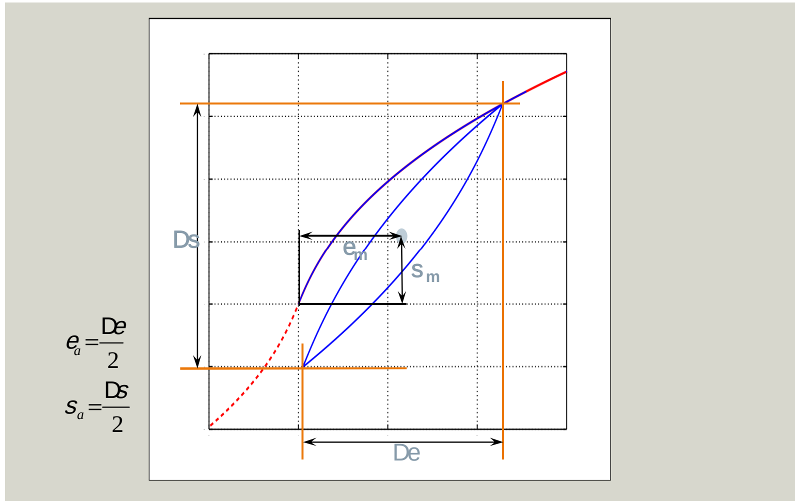
From the local stress-strain path get stress amplitude, strain amplitude and mean stress of each hysteresis loop.

Calculate P value and derive number of cycles N_i from the damage parameter life curve.

Damage $D_i = 1/N_i$

Damage accumulation (Miner's rule):

$$D = \sum_i D_i$$



4 – Derive Fatigue Life

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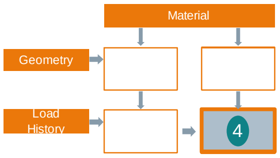
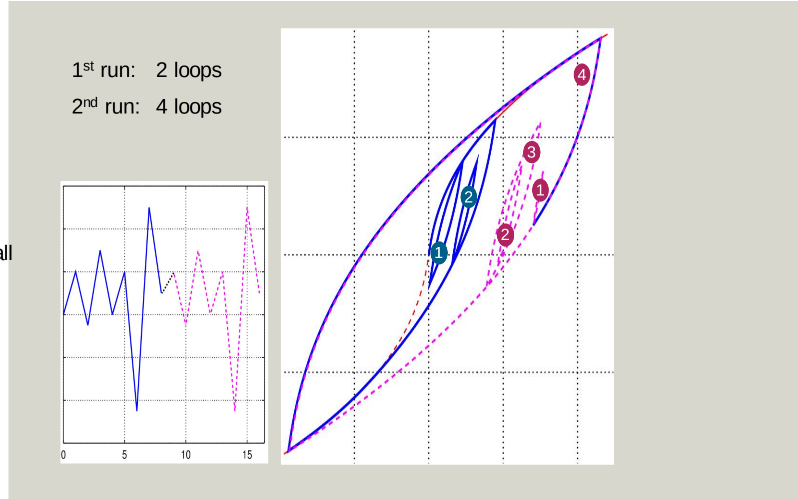


Number and parameters of hysteresis loops in the 1st run differs from loops in 2nd (and all further) runs.

Fatigue Life N = Number of runs ("blocks") until the Miner sum reaches 1:

$$1 = D_{1st} + (N-1) \cdot D_{2nd}$$



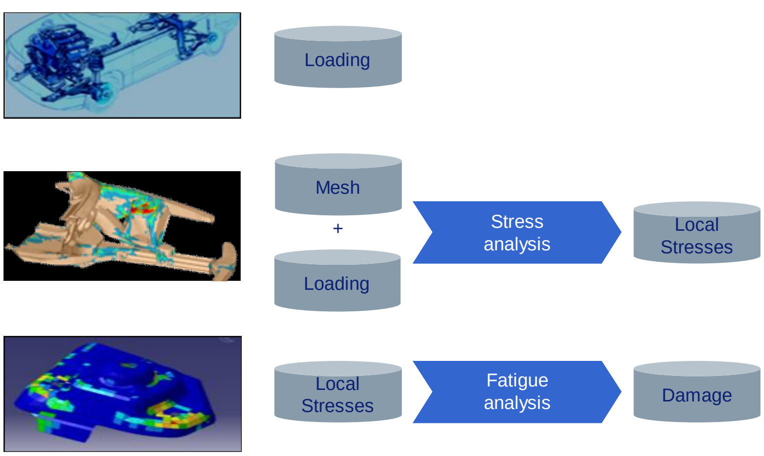
Pros and Cons of Strain Life

Pros:
- Good for both elastic and plastic deformation
- Strain controlled test on smooth specimen closely approximate strain in notches
- Accounts for load sequencing (order of cycles matter) by creating cyclical stress-strain diagram

Cons
- Empirical – many tests required to determine material properties (but uniform material law available)
- Much more difficult to calculate than stress life need computers for iterative solutions

Applications:
- Chassis Durability, Higher cycle amplitudes
- Low cycle fatigue
- AND high cycle fatigue
- Most commonly used for CAE-based fatigue

Simulation Fatigue Process



1. Get realistic load time histories The fatigue damage is highly influenced by the loads applied to the structure.
2. **Get the local stress/strain tensor histories**
   Fatigue depends on the complete stress/strain time histories in the structure:
3. Accumulate damage
   Depending on the fatigue target, the material and loading type fatigue simulation accumulates the damage.

From Component Loads via Local Stresses to Fatigue Life

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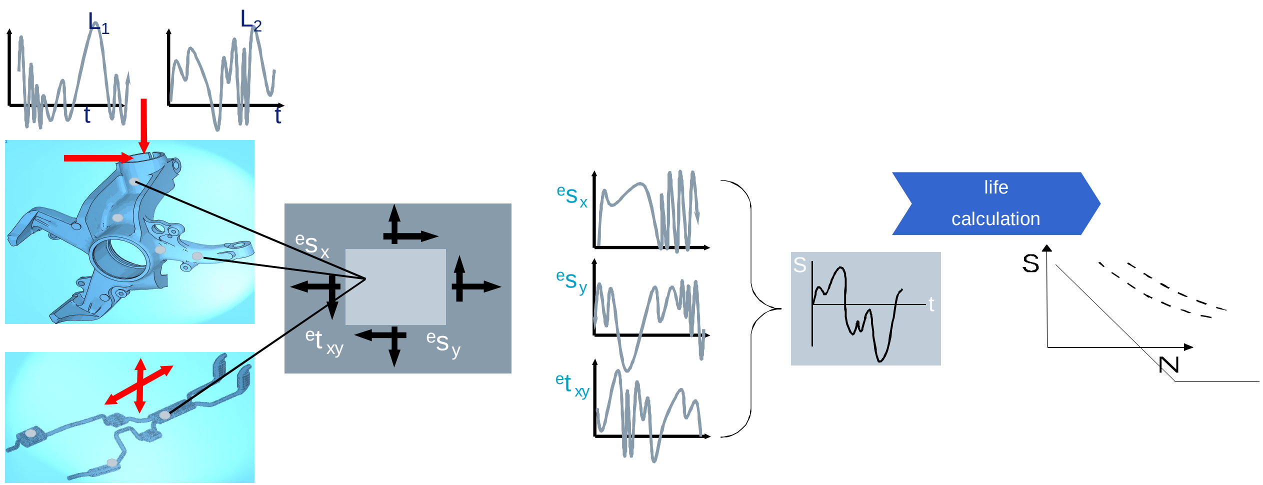

What influences fatigue?

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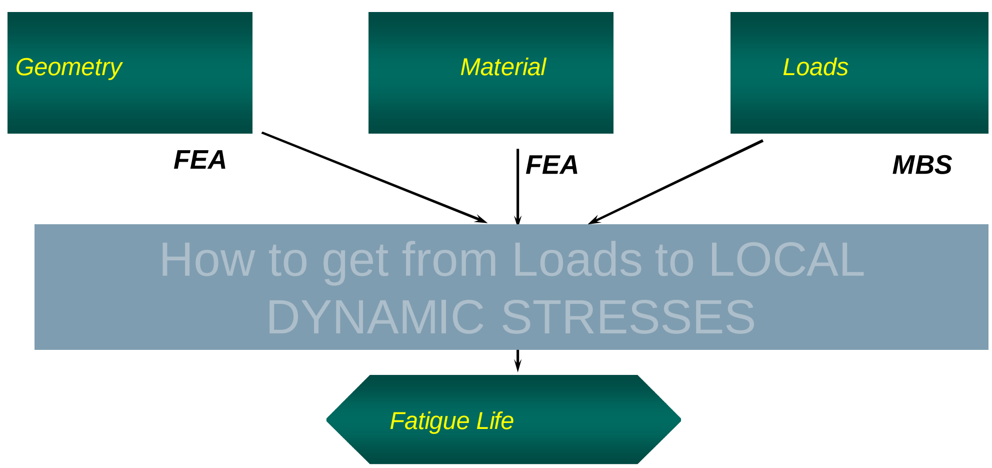

From component loads to stress tensor history

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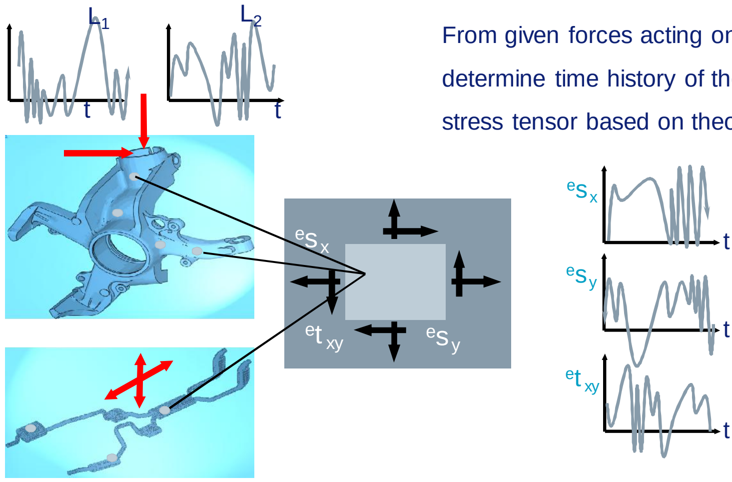

From given forces acting on the component, determine time history of the local pseudo stress tensor based on theory of elasticity.

Loading frequency lowest natural frequency:
quasi-static superposition

Loading frequency lowest natural frequency:
modal superposition

Simulation Calculations

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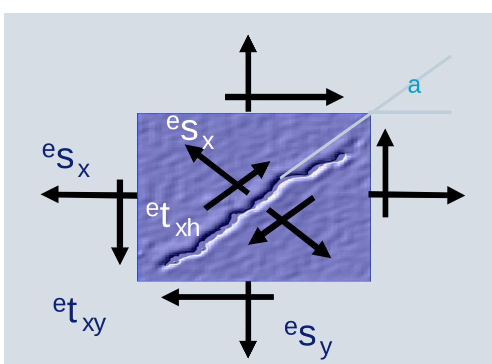
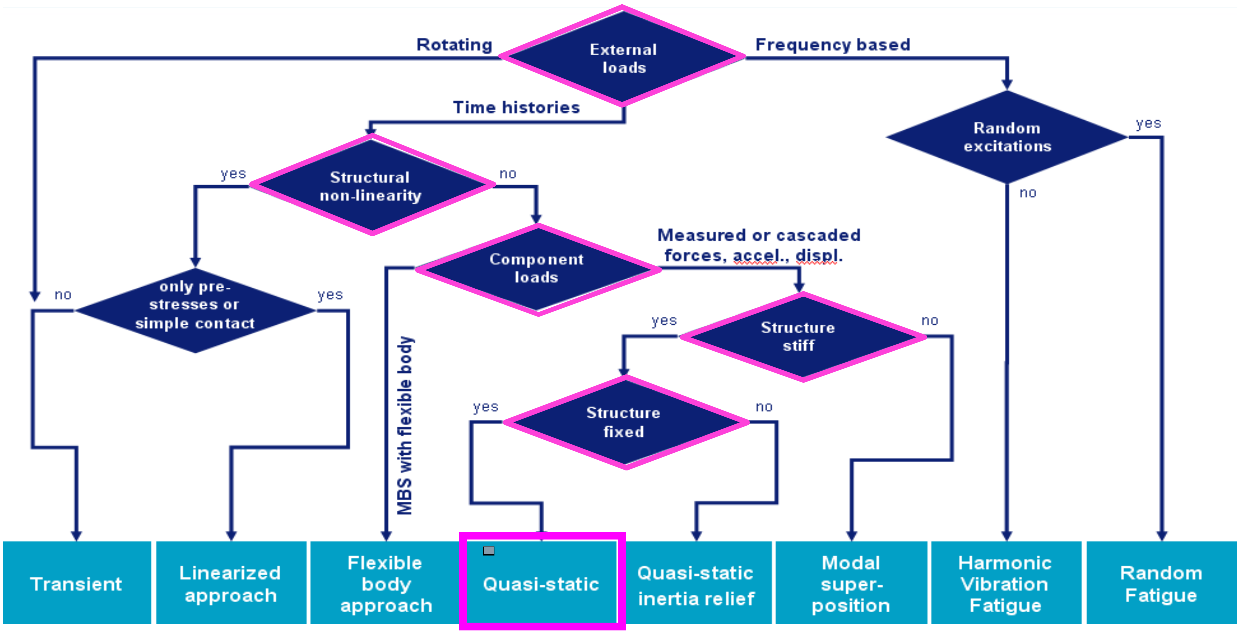


Simulation Calculates a Planar Stress Tensor at each Node

Tensor consist of three terms in diagram



Unit Load

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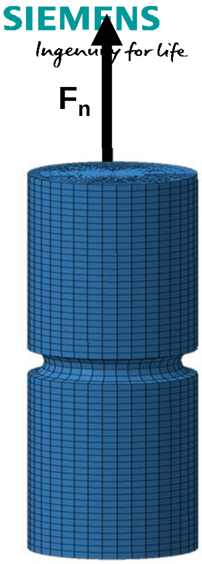
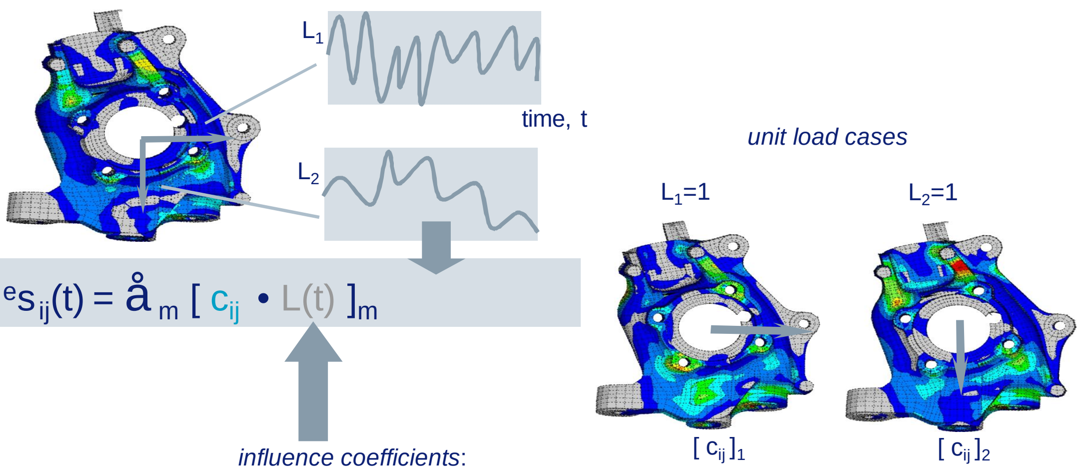
Finite Element Models are used

- **When Fn=1: referred to as a "Static Unit Load Case"**
- **Stress is calculated at each element – as opposed to a predetermined location**
- **because real geometry is more complex than this . . .**



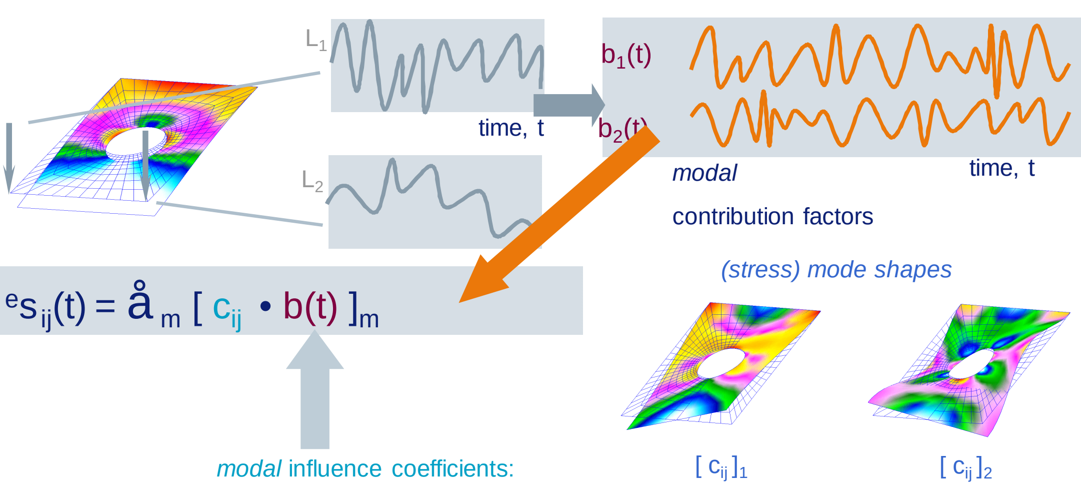
*** Normal Stress**

Quasi-static Superposition



$$^{e}s_{ij}(t) = \mathring{a}_{m} [c_{ij} \bullet L(t)]_{m}$$

Modal Superposition



$$^{e}s_{ij}(t) = \mathring{a}_{m} [c_{ij} \bullet b(t)]_{m}$$

How do Analyze the Stress Tensor?
Classification of Loading Types

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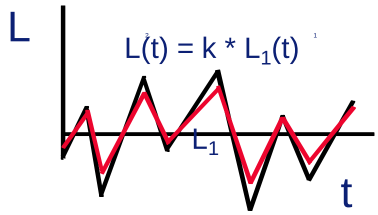
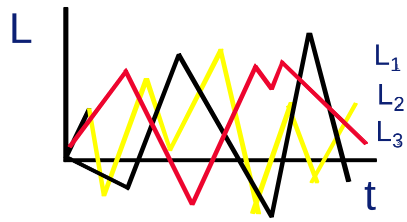
proportional



non-proportional



Von Mises Stress

$$\sigma_q(t) = SGN * \left[\sigma^2{}_x - \sigma_x \sigma_y + \sigma^2 + 3\tau_{xy}^2\right]^{1/2}.$$

Classification of Loading Types

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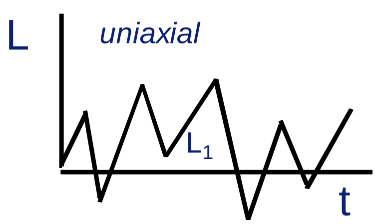
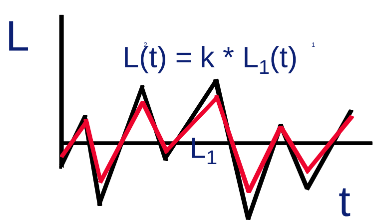
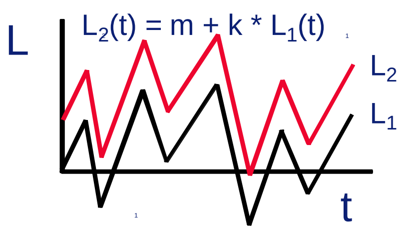
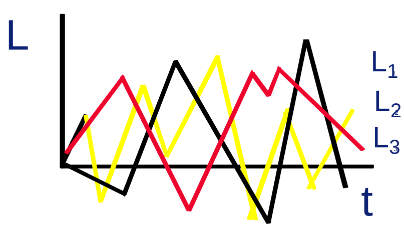




proportional



synchronous

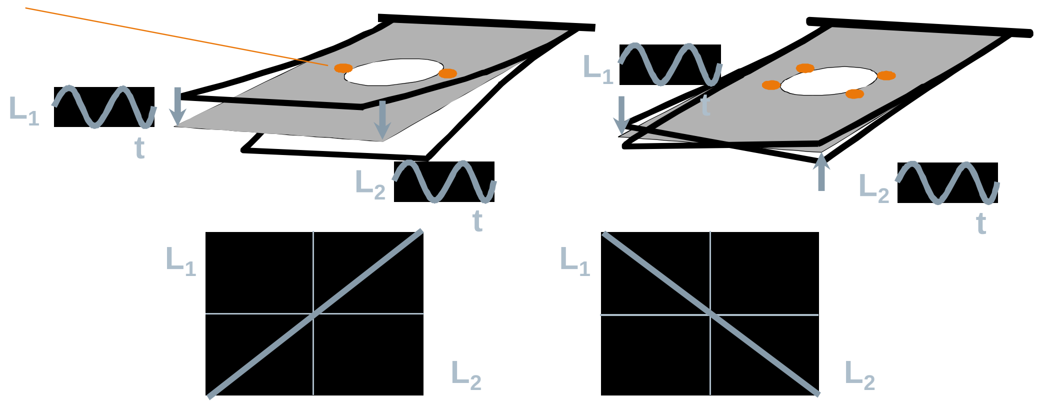


non-proportional

$$\sigma_q(t) = SGN * \left[\sigma^2{}_x - \sigma_x \sigma_y + \sigma^2 + 3\tau_{xy}^2\right]^{1/2}.$$

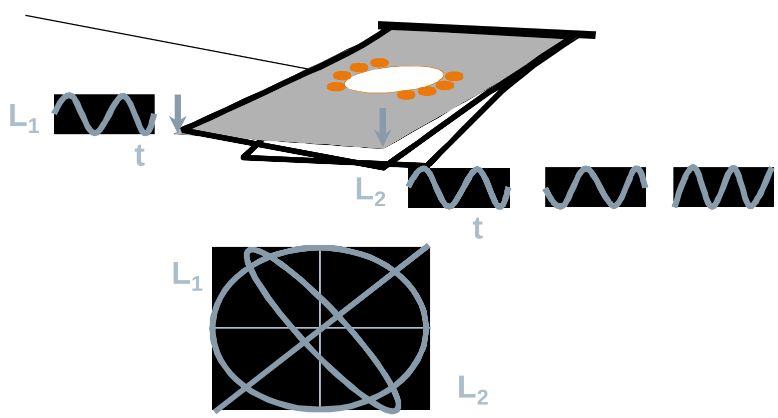
Phasing Between Load Channels Determines Critical Locations (1)

proportional loading:
critical locations determined by static stress analysis



Phasing Between Load Channels Determines Critical Locations (2)

non-proportional loading:
critical locations determined by load history (time domain)



Critical Plane Approach

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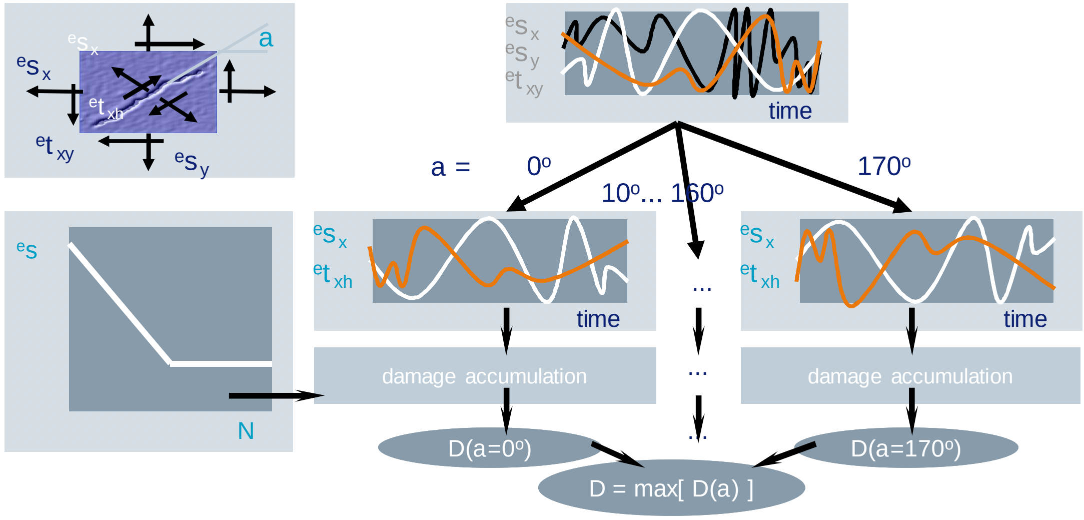

Component Fatigue

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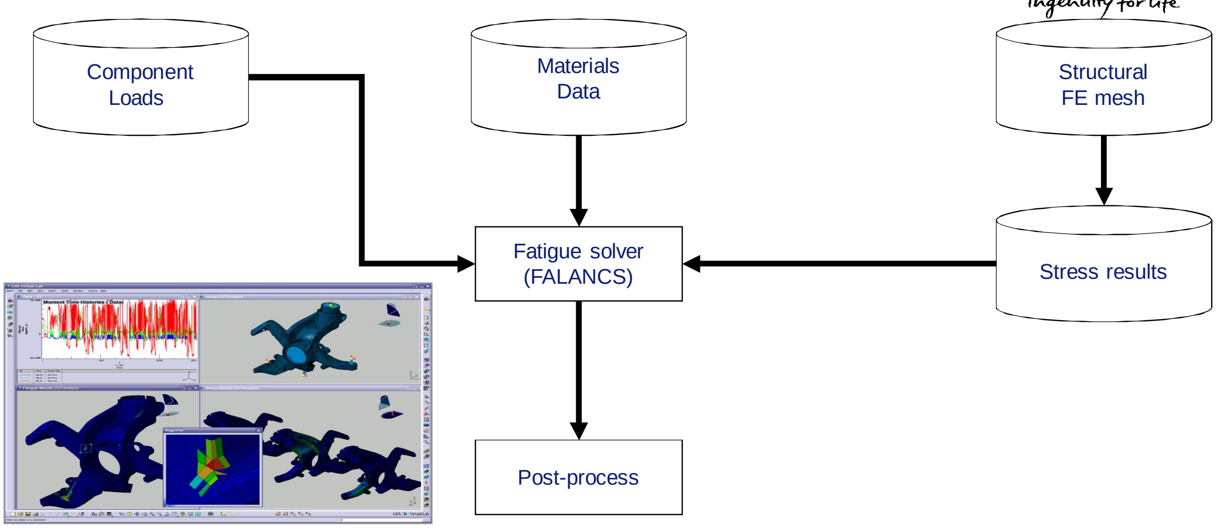
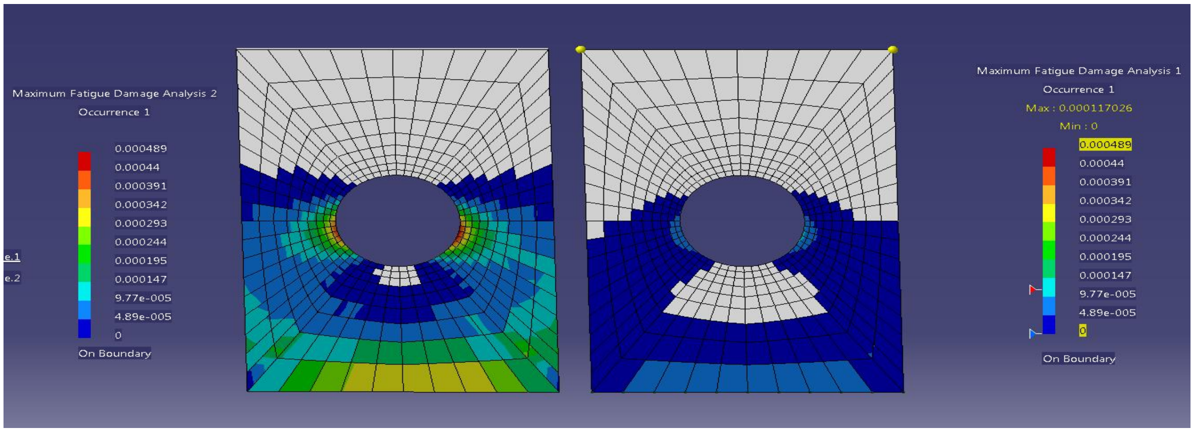
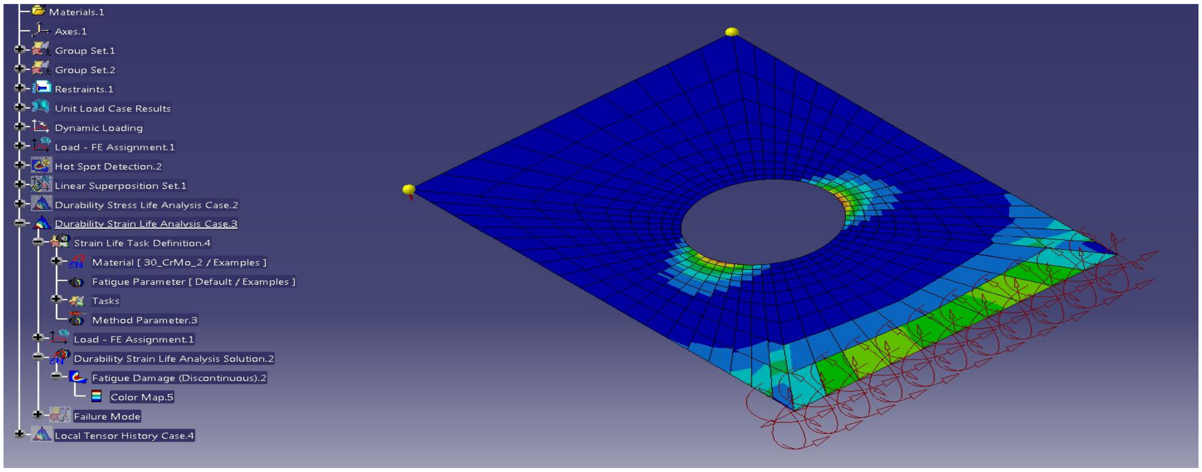


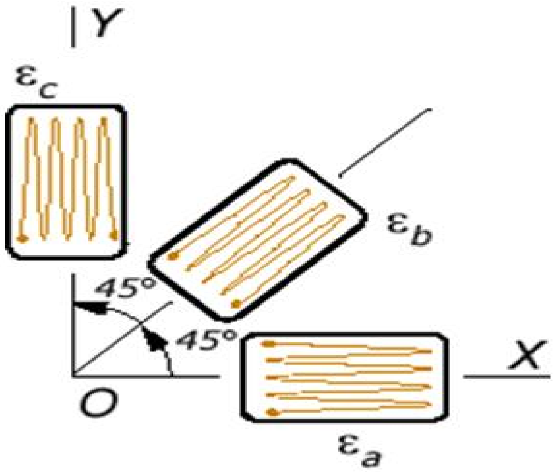
Why a Fatigue Solver Demo



Simulation Stress and Strain Life Demo

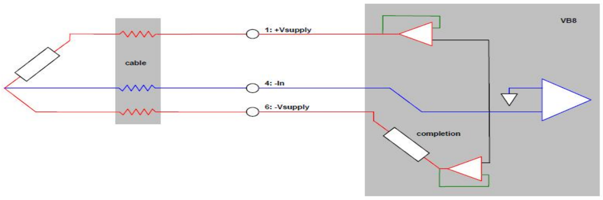


Understanding the Rosette



The Rosette – What Is It?

1. Typically three 3-wire quarter bridges



Why Would I use a Rosette?

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1. I do not have a uniaxial strain field
2. I need to do multi-axial fatigue
3. I need to understand the planar strain and stress field to correlate to simulation

Types of Rosettes

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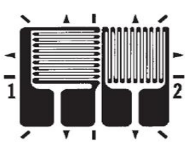
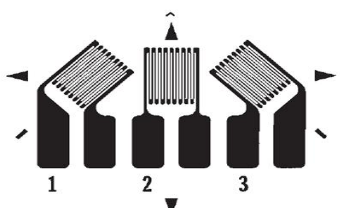


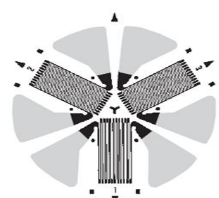
Tee

0/90



Rectangular

0/45/90



Delta

0/60/120

The tee rosette should be used only when the principal strain directions are known in advance from other considerations. Cylindrical pressure vessels and shafts in torsion are two classical examples

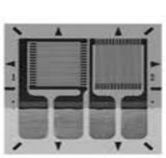
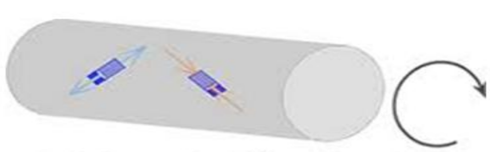


Fig. 3 B

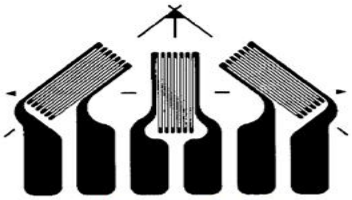
Fig. 3 C



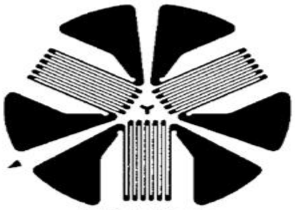
Strain Gauges Bonded to a Torque Shaft

Rectangular vs Delta

1. Rectangular the math is a little easier
   - Historically more popular
2. Delta – maximum angle difference provides optimum sampling of underlying strain distribution
   - Modern computers negate additional math difference
3. Practically little difference

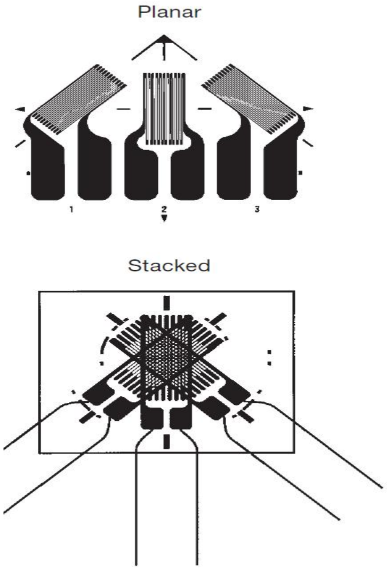


(a) Rectangular Rosette



(b) Delta Rosette

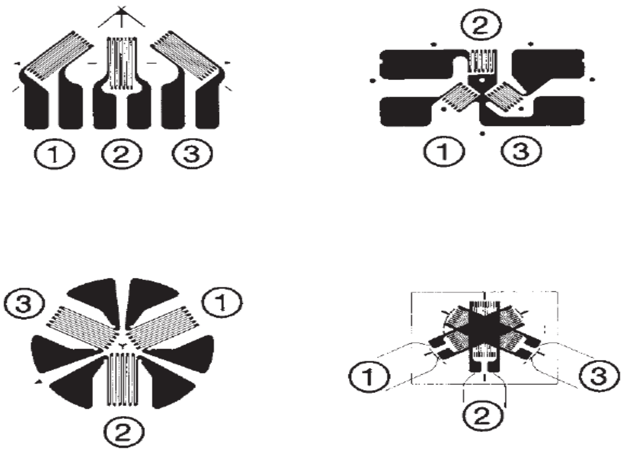
Planar vs Stacked



1. Planar – when strain gradients are not too severe
   1. Thin and flexible, with greater conformability to curved surfaces;
   2. Minimal reinforcing effect;
   3. Superior heat dissipation to the test part;
   4. Available in all standard forms of gage construction,;
   5. Optimal stability;
   6. Maximum freedom in lead wire routing and attachment.
   7. Same transverse sensitivity coefficient for arms 1 and 3, while arm 2 typically has other coefficient

Stacked –Large strain gradients
   1. Minimum surface area available
   2. Large strain gradients
   3. Same transverse sensitivity coefficient for all 3 arms

Numbering Rosettes



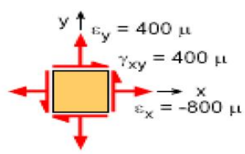
- Number Gauges in Counter Clockwise (CCW) Orientation common convention
- With Rectangular Gauge 1 & 3 must be 90 deg apart
- With Delta Gauge 2 and 3 must be 60 deg apart

So How Do We Get from a Rosette to a Plane Strain State?

- 2D planar strain state can be defined by either

1. Strain Tensor - Simulation Output

$$\begin{bmatrix} \varepsilon_x & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_y \end{bmatrix}$$



Initial Local Strain Element

$$\boldsymbol{\varepsilon_{xy} = 0.5 * \gamma_{xy}}$$

2. Two principal strains and their direction

Mathematically Deriving Rosette EQN's

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Principal strain and angle quantities can be derived form Rosette measurements using the 2-D strain transformation equations below:

$$\varepsilon_{x'} = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + \gamma_{xy} \sin\theta\cos\theta$$

$$\varepsilon_{y'} = \varepsilon_x \sin^2\theta + \varepsilon_y \cos^2\theta - \gamma_{xy} \sin\theta\cos\theta$$

$$\gamma_{x'y'} = 2(\varepsilon_y - \varepsilon_x)\sin\theta\cos\theta + \gamma_{xy}(\cos^2\theta - \sin^2\theta)$$

An alternative method which we will cover is to use Mohr's Circle

Sample Rectangular Rosette Data

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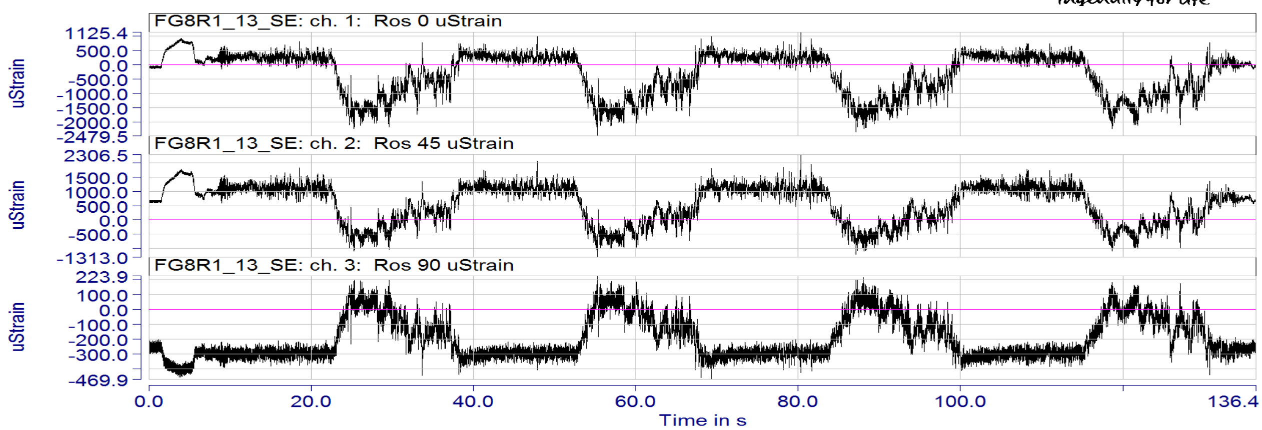

Note: Make sure angle in channel name, many algorithms use for processing.

Calculation done for each Point in Time, Rosette quantities constantly changing

Definition of Terms – Focus on Rectangular Rosette

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Rectangular Rosette			
K1	Gauge at 0 deg		
K2	Gauge at 45 deg		
K3	Gauge at 90 deg		
Strain Tensor		**Stress Tensor**	
d11	Normal Strain x	S11	Normal Stress x
d22	Normal Strain y	S22	Normal Stress y
d12	Shear Strain	S12	Shear Stress
Principal Strains		**Principal Stress**	
E1	Principal Strain 1	S1	Principal Stress 1
E2	Principal Strain 2	S2	Principal Stress 2
E3	Principal Strain 3		
Angle			
ϕ	Angle from K1 to E1		
Biaxiality Ratio			
Λ	Principal Stress Ratio		
VonMises Strain		**VonMises Stress**	
E_vM	VonMises Strain	S_vM	VonMises Stress
Tresca Strain		**Tresca Stress**	
E_tresca	Tresca Strain	S_Tresca	Tresca Stress
Mohr's Circle			
E_{avg}	Average Strain		
γ	Mohr's Circle Shear Strain		
τ	Mohr's Circle Shear Stress		
r	Radius of Mohr's Circle		
Material Propoerties			
E	Young's Modulus		
G	Shear Modulus		
ν	Poisson's Ratio		

Can have up to 17 outputs from rosette inputs

Rosette Quantities from Mohr's Circle Step 1 – Strain Tensor

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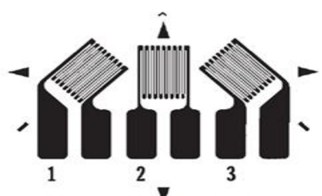
From rectangular rosette calculate the strain tensor

Test



Rectangular

Rosette Values (uE)	
K1	-800
K2	0
K3	400

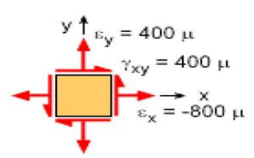
$d11 = K1 = -800$

$d22 = K3 = 400$

$d12 = \frac{1}{2}\gamma_{xy} = K2 - \frac{1}{2}(K1 + K3) = 200$

Strain Tensor	
d11	-800
d22	400
d12	200

Simulation



Initial Local Strain Element

$$\begin{bmatrix} \varepsilon_x & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_y \end{bmatrix}$$

Rosette Quantities from Mohr's Circle Step 2 – Average Strain

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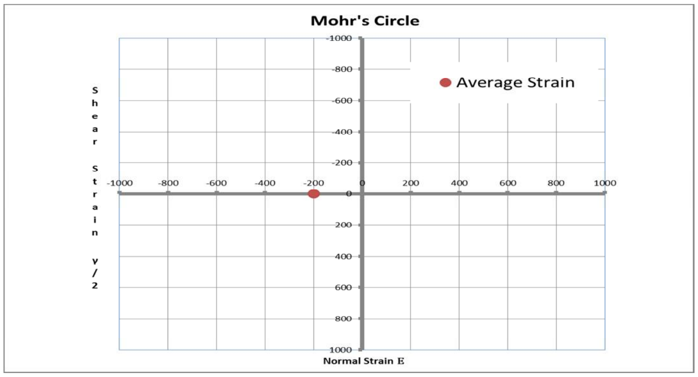
From Strain Tensor Calculate the Average Strain



Strain Tensor	
d11	-800
d22	400
d12	200

Average Strain

$$E_{avg} = \frac{(d11 + d22)}{2} = -200$$

Note: Mohr's circle is constructed with positive shear strain plotted downward. This is done so that the positive rotational direction in Mohr's circle is the same (CCW) as for the rosette, while maintaining the usual sign convention for shear

Rosette Quantities from Mohr's Circle Step 3 – Define Points on Circle

Define Point's on Mohr's circle

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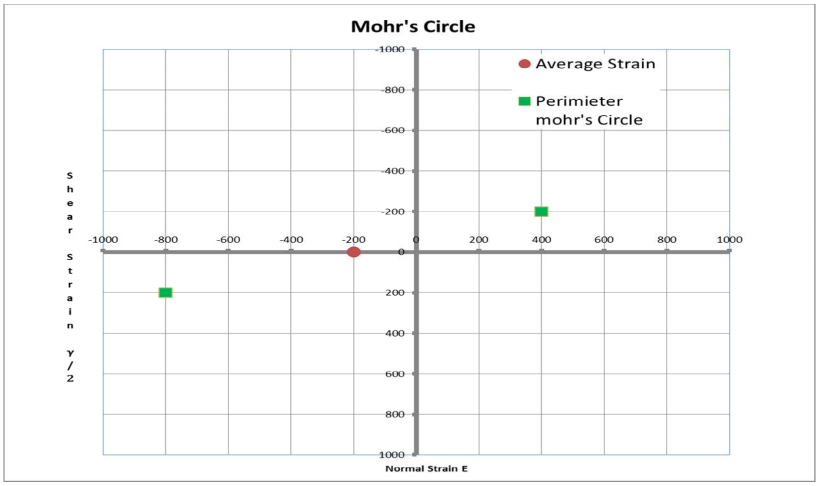

Strain Tensor	
d11	-800
d22	400
d12	200

Perimeter Points

		E	d12
Either	d11,d12	-800	200
or	d22,-d12	400	-200

Note: We only need 1 perimeter point to define Mohr's Circle

Rosette Quantities from Mohr's Circle Step 4 – Calculate Radius and Draw Mohr's Circle

Calculate Radius and Draw Circle

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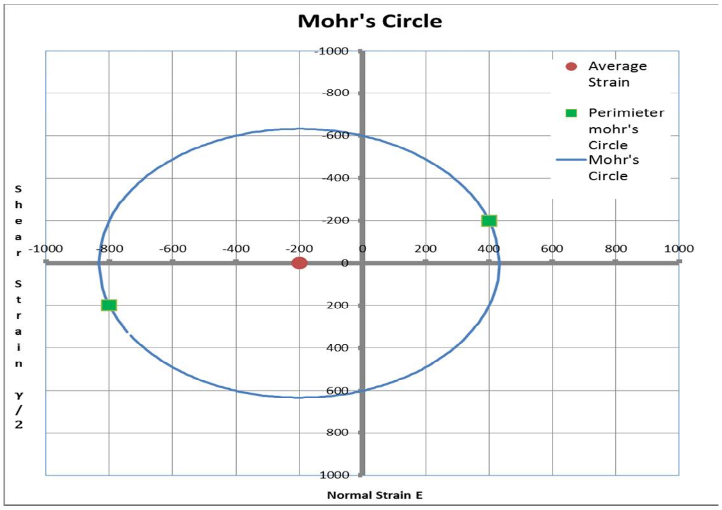

Strain Tensor	
d11	-800
d22	400
d12	200

Radius of Circle

$E = 200 + 400$

$\frac{\gamma}{2} = -200$

$$radius = \sqrt{E^2 + \left(\frac{\gamma}{2}\right)^2} = 632.5$$

Rosette Quantities from Mohr's Circle Step 5 – Calculate Principal Strains

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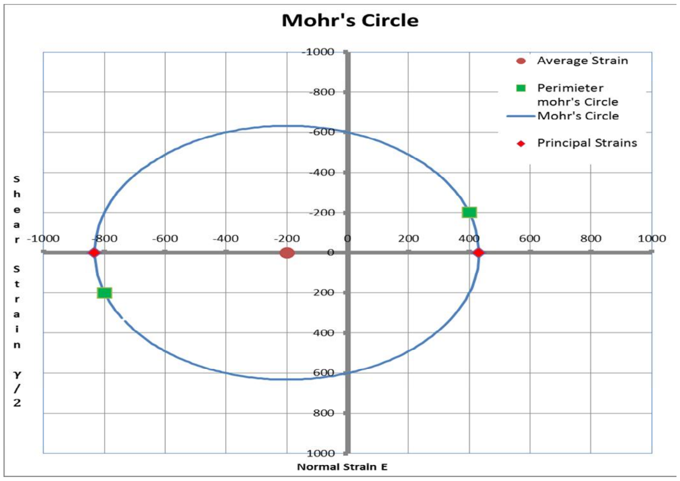
Principal Strains are the intersection of Mohr's circle and the x-axis



Principal Strains

$E1 = E_{avg} + r = 432.5$

$E2 = E_{avg} - r = -832.5$

Notes:

- Principal Strains are located along x-axis at 0 Shear Strain
- Alternative definition: Principal strains are the eigenvalues of the strain tensor, with E1 >= E2

Rosette Quantities from Mohr's Circle Step 5 – Calculate Principal Strains

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Principal Strains equations calculated directly from the rectangular rosette and strain tensor

Rectangular Rosette:

$$E1 = \varepsilon_1 = \frac{K1+K3}{2} + \frac{1}{\sqrt{2}}\sqrt{(K1-K2)^2+(K2-K3)^2}$$

$$E2 = \varepsilon_2 = \frac{K1+K3}{2} - \frac{1}{\sqrt{2}}\sqrt{(K1-K2)^2+(K2-K3)^2}$$

Strain Tensor:

$$E1 = \varepsilon_1 = \frac{\varepsilon_x+\varepsilon_y}{2} + \sqrt{\left(\frac{\varepsilon_x-\varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2}$$

$$E2 = \varepsilon_2 = \frac{\varepsilon_x+\varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x-\varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2}$$

Rosette Quantities from Mohr's Circle Step 6– Calculate Maximum Shear Strain

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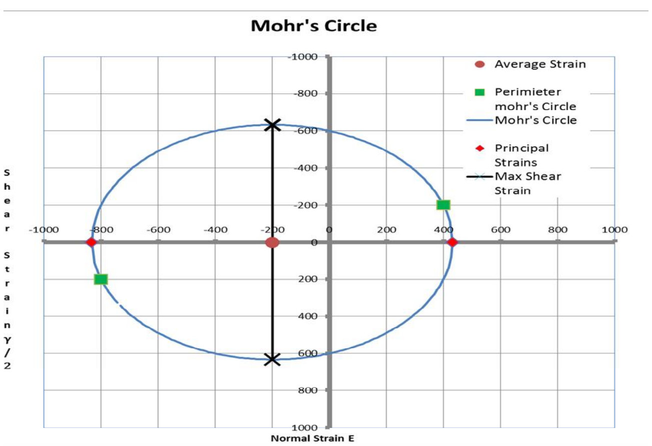
Max Shear Strain is simply the diameter of the Mohr's Circle



Maximum Shear Strain

Diameter of Mohr's Circle

$2r$ =1265

OR

The Magnitude of the Difference in Principal Strains

$|E1 - E2| = |432.5 - (-832.5)| = 1265$

Rosette Quantities from Mohr's Circle Step 7a– Calculate Angle

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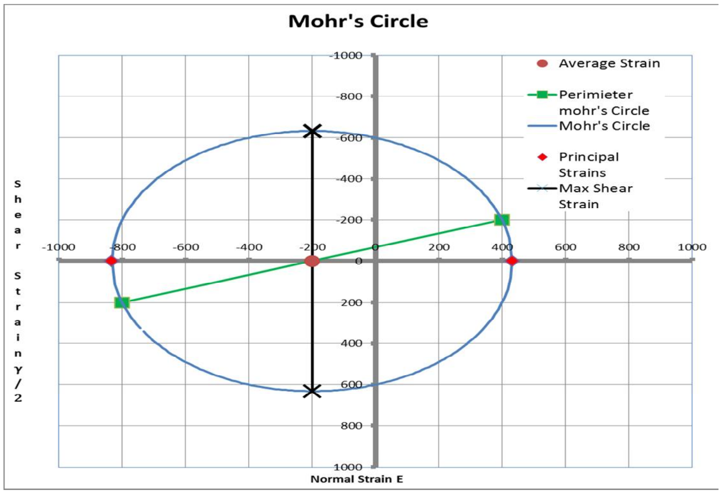
- The angle tells us how much to rotate the rosette to align with the axis corresponding to the 1st principal strain $\boldsymbol{E1}$
  - CCW is Positive
  - CW is Negative



Rosette Quantities from Mohr's Circle Step 7b– Calculate Angle

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Unfortunately, since tan 2ϕ ≡ tan 2(ϕ + 90 °), the calculated angle can refer to either principal axis. Therefore, extra conventions are needed:

ε_0	K1	-800
ε_{45}	K2	0
ε_{90}	K3	400

Angle: with $N = 2 \cdot K2 - K1 - K3\,,\quad D = K1 - K3\,,\quad \psi = \left|\arctan\left(\frac{N}{D}\right)\right| \cdot \frac{180°}{\pi}\,,\quad \psi = 90°$ if $D = 0$

$\varphi = \frac{1}{2}\psi$ if $N \geq 0$ and $D > 0$

$\boxed{\varphi = \frac{1}{2}(180° - \psi) \quad \text{if } N > 0 \text{ and } D \leq 0}$

$\varphi = \frac{1}{2}(180° + \psi)$ if $N \leq 0$ and $D < 0$

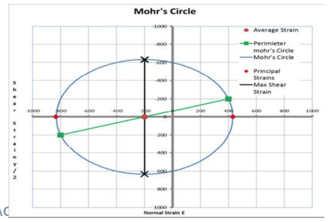
$\varphi = \frac{1}{2}(360° - \psi)$ if $N < 0$ and $D \geq 0$

$\varphi = 0°$ if $N = 0$ and $D = 0$

N	400	
D	-1200	
0.32	18.43	deg

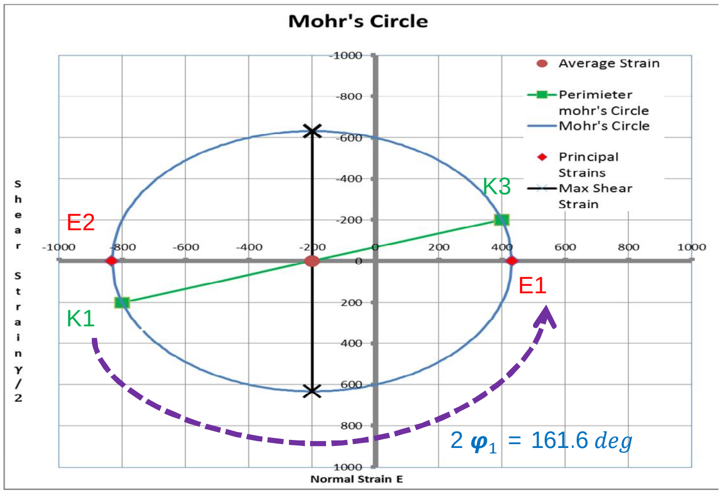
$\varphi = \frac{1}{2}(180° - \psi)$ if $N > 0$ and $D \leq 0$

80.78 deg



Angle Illustration

Strain Tensor	
d11 = K1	-800
d22 = K3	400
d12	200



Okay let's Convert these Strains to Stresses: E

We will discuss 3 terms first:

1. Young's modulus = Modulus of Elasticity = Elastic Modulus = Tensile Modulus = E
   - A. The ratio of the stress along an axis over the strain along that axis in the range of stress in which Hooke's law holds
   - B. Measure of Stiffness

$$E \equiv \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{F L_0}{A_0 \Delta L}$$

where

E is the Young's modulus (modulus of elasticity)
F is the force exerted on an object under tension;
A_0 is the original cross-sectional area through which the force is applied;
ΔL is the amount by which the length of the object changes;
L_0 is the original length of the object.

Units: GPa

Steel ≈ 200

AL ≈ 69

Rubber ≈ .01-.1

Okay lets convert these Strains to Stresses: G

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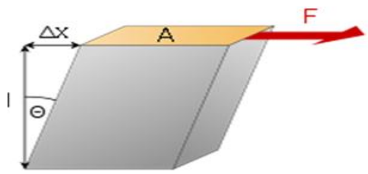
3. Shear Modulus or Modulus of Rigidity: G

C. The ratio of shear stress to the shear strain

$$G \stackrel{\text{def}}{=} \frac{\tau_{xy}}{\gamma_{xy}} = \frac{F/A}{\Delta x/l} = \frac{Fl}{A\Delta x}$$



where

$\tau_{xy} = F/A$ = shear stress;
F is the force which acts
A is the area on which the force acts
in engineering, $\gamma_{xy} = \Delta x/l = \tan\theta$ = shear strain. Elsewhere, $\gamma_{xy} = \theta$
Δx is the transverse displacement
l is the initial length

Units: Gpa

Steel ≈ 79.3

AL ≈ 25.5

Rubber ≈ .0006

Okay lets convert these Strains to Stresses: v

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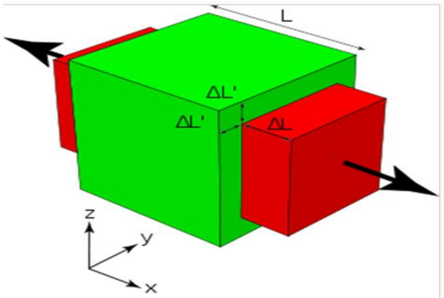
ν

2. Poisson's Ratio

A. The negative ratio of transverse to axial strain. When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression

$$\nu = -\frac{d\varepsilon_{\mathrm{trans}}}{d\varepsilon_{\mathrm{axial}}} = -\frac{d\varepsilon_{\mathrm{y}}}{d\varepsilon_{\mathrm{x}}} = -\frac{d\varepsilon_{\mathrm{z}}}{d\varepsilon_{\mathrm{x}}}$$



Units: Non Dimensional

Steel ≈ .27-.3

AL ≈ .33

Rubber ≈ .5

Convenient Relationship of Material Properties

With any two material properties you can calculate the third

$$G = \frac{E}{2(1+v)}$$

$$E = 2G(1+v)$$

$$v = \frac{E}{2G} - 1$$

Hooke's Law

Hooke's Law of Elasticity for Isotropic Materials with a Linear Stress-Strain Relationship

1-D

$$\sigma = E\varepsilon$$

2-D

$$\sigma_x = \frac{(\varepsilon_x + \nu\varepsilon_y)E}{(1-\nu^2)}$$

$$\sigma_y = \frac{(\varepsilon_y + \nu\varepsilon_x)E}{(1-\nu^2)}$$

$$\tau = G\gamma = \frac{E\,\gamma}{2(1+\nu)}$$

3-D

$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_x + \nu(\varepsilon_y + \varepsilon_z)\right]$$

$$\sigma_y = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_y + \nu(\varepsilon_z + \varepsilon_x)\right]$$

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_z + \nu(\varepsilon_x + \varepsilon_y)\right]$$

$$\tau_{xy} = G\gamma_{xy};\quad \tau_{yz} = G\gamma_{yz};\quad \tau_{xz} = G\gamma_{xz}$$

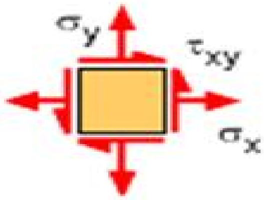
Stress Tensor from the Rosette

Stress Tensor

$$s11 = \sigma_x = \frac{E}{1-\nu^2}(K1+\nu \cdot K3)$$

$$s22 = \sigma_y = \frac{E}{1-\nu^2}(K3+\nu \cdot K1)$$

$$s12 = \tau = G\gamma = \frac{E}{1+\nu}\left[K2-\tfrac{1}{2}(K1+K3)\right]$$



Rosette Values (uE)	
K1	-800
K2	0
K3	400

Material Properties		
Poisson Ratio	0.3	
Youngs Modulus	200	GPa
Shear Modulus	79.3	GPa

Stress Tensor		
s11	-149	MPa
s22	35	MPa
s12	31	MPa

Rosette Quantities from Mohr's Circle Step 8– Calculate Principal Stresses

Using Hooke's law for a Biaxial Stress State

must have linear stress/strain relationship

From Principal Strain

Principal Strains	
E1	432.5
E2	-832.5

$$S1 = \frac{E}{(1-\upsilon^2)}(E1+\upsilon E2)$$

$$S1 = \frac{E}{(1-\upsilon^2)}(E2+\upsilon E1)$$

Principal Stresses

Principal Stresses		
S1	40	MPa
S2	-154	MPa

Max Shear Stress

$$\tau_{max} = \frac{|S1-S2|}{2} = 97\ MPa$$

Rosette Quantities from Mohr's Circle Step 8– Calculate Principal Stresses

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We can also calculate principal stresses from the rosette data and the stress tensor

From Rectangular Rosette:

$$S1 = \frac{E}{1-\nu} \cdot \frac{K1+K3}{2} + \frac{E}{\sqrt{2}(1+\nu)} \cdot \sqrt{(K1-K2)^2+(K2-K3)^2}$$

$$S2 = \frac{E}{1-\nu} \cdot \frac{K1+K3}{2} - \frac{E}{\sqrt{2}(1+\nu)} \cdot \sqrt{(K1-K2)^2+(K2-K3)^2}$$

From Stress tensor:

$$S1 = \sigma_1 = \frac{\sigma_x+\sigma_y}{2} + \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + \tau^2}$$

$$S2 = \sigma_2 = \frac{\sigma_x+\sigma_y}{2} - \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + \tau^2}$$

What Else Can I Calculate From a Rosette: Von Mises

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Von Mises Stress Sometimes Called Equivalent Stress or Maximum Distortion Energy Theory

$$S\_vM = \sigma_{vM} = \sqrt{\frac{1}{2}\left[(S1-S2)^2 + S2^2 + S1^2\right]}$$

VonMises Stress 178 MPa > max principal stress 154 MPa

When do we use it

- Proportional Loading
- To visualize stress field makes the Tensor into one Term
- If used for fatigue we use Signed Von Mises

What Else Can I Calculate From a Rosette: Von Mises

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VonMises Strain

$$\text{E\_vM} = \varepsilon_{vM} = \frac{1}{1+\nu}\sqrt{\frac{1}{2}\left[(E1-E2)^2+(E2-E3)^2+(E3-E1)^2\right]}$$

For rosette

$$\text{E3} = -\frac{\nu}{1-\nu}(K1+K3)$$

For Stress Tensor

$$\text{E3} = \varepsilon_3 = -\nu\frac{\sigma_x+\sigma_y}{E}$$

Where E3 is: the analytical calculation (derived from Sigma_x, Sigma_y, and the material properties

VonMises Strain is larger than the magnitude of the maximum principal strain

1. =1054 uE > 832 uE max principal

Assumption: plane stress situation (sigma_z = 0).

What Else Can I Calculate From a Rosette: Tresca

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1. Tresca Max Shear Stress Theory

$$\text{S\_Tresca} = \sigma_e = 2\tau_{\max} = \max\left(|S1-S2|,|S2|,|S1|\right)$$

Principal Stresses		
S1	40	MPa
S2	-154	MPa

Tresca Max Shear Stress $2\tau_{max} = |S1 - S2| = 194\ MPa$

What Else Can I Calculate From a Rosette: Tresca

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Tresca Max Shear Strain

$$\text{E\_Tresca} = \varepsilon_e = \frac{1}{1+\nu} \cdot \max\left(|E1 - E2|, |E2 - E3|, |E3 - E1|\right)$$

	Strain	
Max E1-E2	973	muE
Max E2-E3	-772	muE
Max E3-E1	-201	muE

Note max Values Scaled by 1/(1+v)

What Else Can I Calculate From a Rosette

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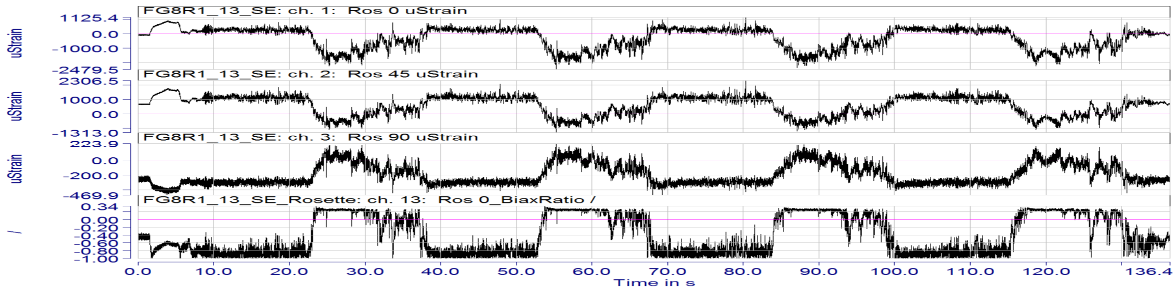
1. Bi-axiality Ratio
   - Ratio of Principal Stresses (smallest versus largest)
   - Number between -1 and 1
   - = 0 -> uniaxial tension or compression
   - = -1 -> pure shear (torsion)
   - =+1 -> equi-biaxial

$$\text{BiaxRatio} = \Lambda = \frac{\sigma_2}{\sigma_1}$$

with $\sigma_1 = S1$, $\sigma_2 = S2$ if $|S2| < |S1|$, else $\sigma_1 = S2$, $\sigma_2 = S1$

Principal Stresses		
S1	40	MPa
S2	-154	MPa

-0.26



Biaxiality Plot

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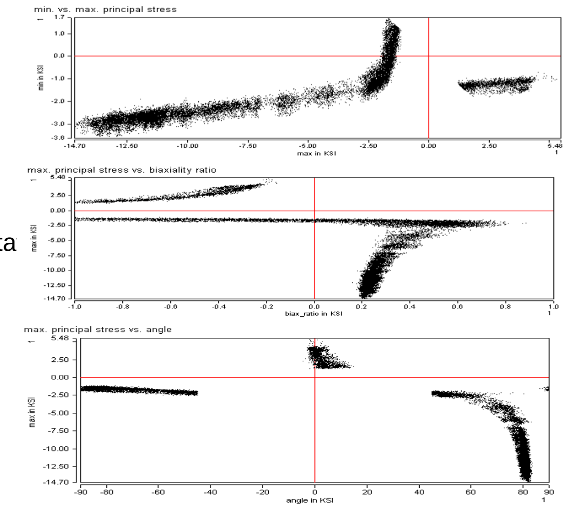
To identify local stress behavior
3 types of plots
1. Max principal stress S1 over angle (f)
2. Max principal stress S1 over S2/S1
   (= biax ratio)
3. Max principal stress S1 over
   min principal stress S2

Out of plot 1 and 2, you can identify whether the local stress sta
- Uniaxial
  biax ratio ~0; f nearly constant
- Proportional
  biax ratio and f nearly constant
  but biax ratio^1 0
- Non-proportional
  biax ratio and f varying -> multi-axial



Sources of Error

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1. Transverse Sensitivity + Gage Poisson coefficient
2. Thermal Effects
   1. Gage Factor Variation
   2. Gauge and wire resistance change with temperature
   3. Different thermal expansion between grid thermal conductor and test part.
   4. Thermal expansion of material (Thermal stress)
3. Grid Alignment
4. Uniform strain field under gauge
5. Large Strains
   1. Less than 2000 uE -> small error
   2. Greater than 10000 uE -> big error
      1. Non linear stress-strain, Hooke's law significant error

Conclusions

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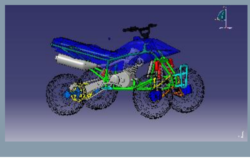
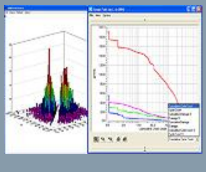
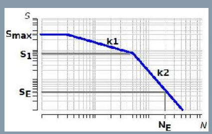
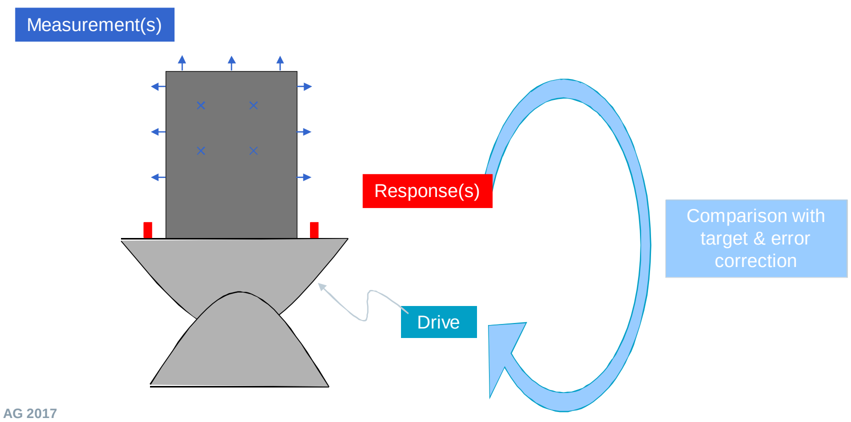
1. If you do not know the strain field use a Rosette
2. Test Rosette comparable to CAE Stress Tensor
3. Bi-Axiality ratio and angle can be used to determine type of loading
   1. Uniaxial
   2. Torsional
   3. Proportional
   4. Multi-Axial

Durability Agenda

Durability Basics	Load Determination	Loads and Damage
Fatigue, Stress, Strain	Measurements, Multi-Body Simulation	S-N Curve, Cycle Counting
		
Load Characterization	**Fatigue Life Predictions**	**Accelerated Testing & Analysis**
Establishing Durability Targets: Superposition, Extrapolation	Infinite Life, Stress Life, Strain Life	RP-Filter, Mission Synthesis
		

What is durability laboratory testing ?

Durability laboratory testing =
the reproduction of service loads or spectra, measured during in-field data acquisition,
on uni- or multi-axial shaker configurations,
in order to load the test object with the same fatigue content as seen during real-life.



OK…BUT WHY DO WE TEST?

Vibration Control Modes

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Swept Sine Control
Dwell Sine Control
Random Control
Combined Modes
Shock Control
Time Wave Form Replication

Why do you need laboratory testing ?

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Physical validation
- will always be needed, no matter how good the simulations are
- Can be performed in a laboratory environment or during in-field measurements

Comparison in-field measurements vs. laboratory testing

Laboratory testing	**In-field testing**
Automated	Manpower required
24/7, monitored testing	Discontinue measurements
Controlled environment, reproducible	Varying conditions (driver, weather, traffic,...)
Component or subassembly testing possible	Whole car needed (cumbersome for supplier)
Worst case scenario testing for multiple user requirements (parallel)	Sequential testing of user requirements
Accelerated testing	Real-time testing

Main differences Rig Testing – Vibration Control

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	Rig Testing	Vibration Control
Test Articles	-Full system -Sub-assemblies	- Component testing -Qualification testing
Failure mode	externally induced (e.g. Road surface)	resonance-induced (e.g. Engine)
Excitation method	- Hydraulic shakers - High displacements (up to 1m)	- Electro-dynamic shaker - High accelerations (100 g)
Excitation area	- Uni-axial - Multi-axial	- Uni-axial
Control strategy	- Time domain - Off-line update	- Time or frequency domain - On-line update
Frequency band	- Below first eigenmode - Low-frequency (<150Hz)	- All modes - High-frequency (20- 2000 Hz)
Target signals	- Strains - forces/moments - Displacements	- accelerations
Accelerated testing	Rainflow-based	Mission synthesis

How can you accelerate a test?

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Basic principle = conservation of damage

How?

- Increase the testing speed - ‘compress’ the time series
- Increase the amplitude – less repetitions needed for the same amount of damage
- Omit non-damaging events
- Simplify the test – from variable loading to constant loading
- Worst-case scenario testing – envelope of different user requirements
- Mission Synthesis

Durability load data processing
Rainflow counting - methods

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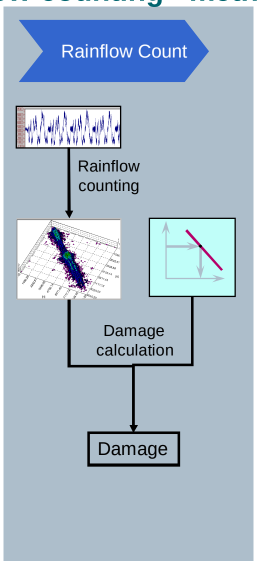
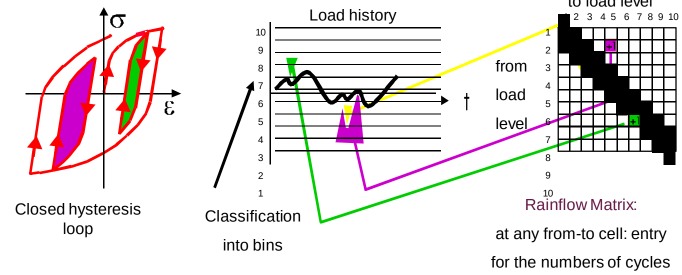
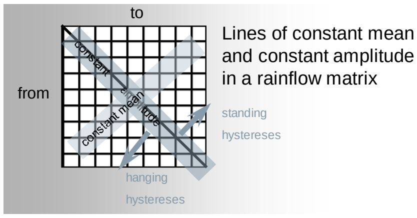


- **Basic damage event : closed hysteresis loop**

- Rainflow counting = counting of closed hysteresis loops in time signal





Increase test speed

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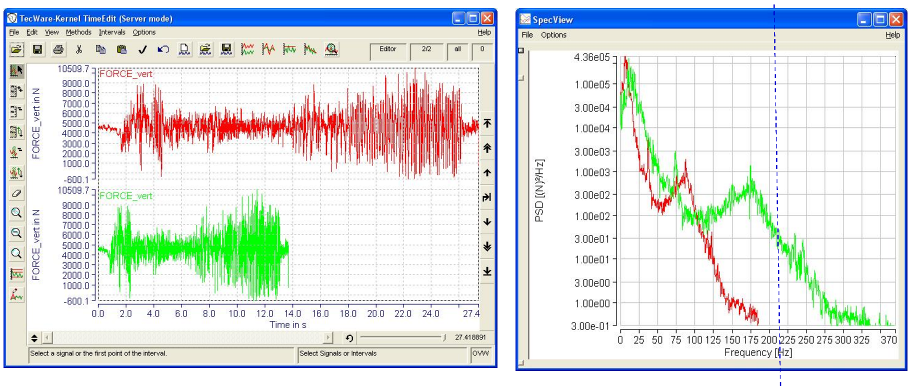
Time signal compression
- Red signal = original one
- Green = time length reduced with factor 2

Remark: avoid too high compression
- Frequency content should stay reasonably below 1st natural frequency



Increase amplitude Time or Frequency Domain

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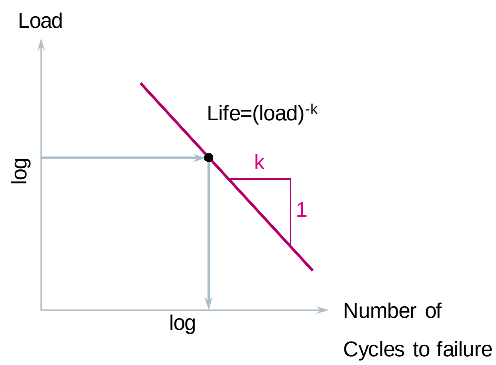

Number of cycles to failure
in function of Load and k factor

Load \ k	5
1	1
1.15	0.5
0.87	2

Increasing the cyclic load applied to an optimally shaped steel component with 15% accelerates a test with factor 2

Simplify the test

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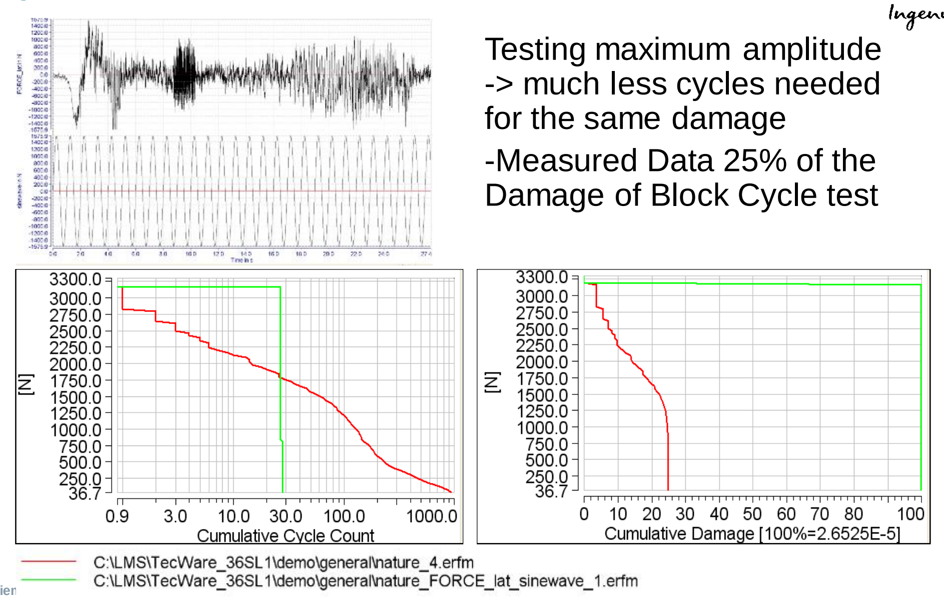
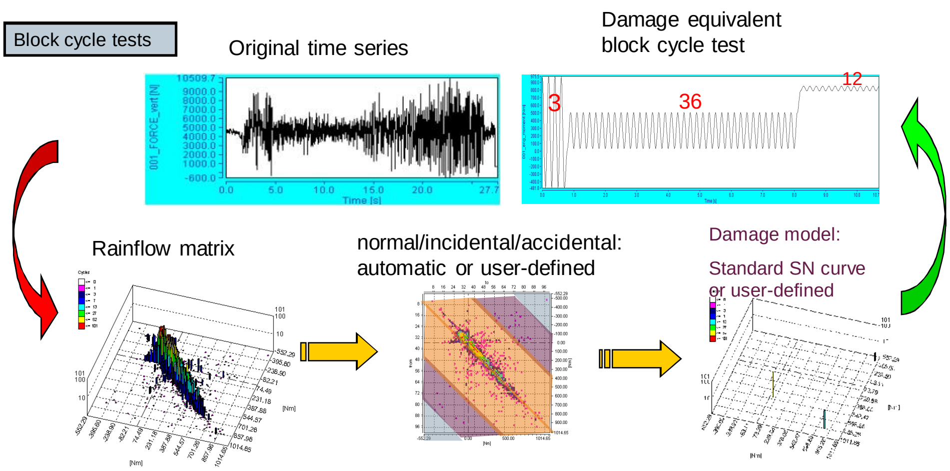
Testing maximum amplitude -> much less cycles needed for the same damage

-Measured Data 25% of the Damage of Block Cycle test



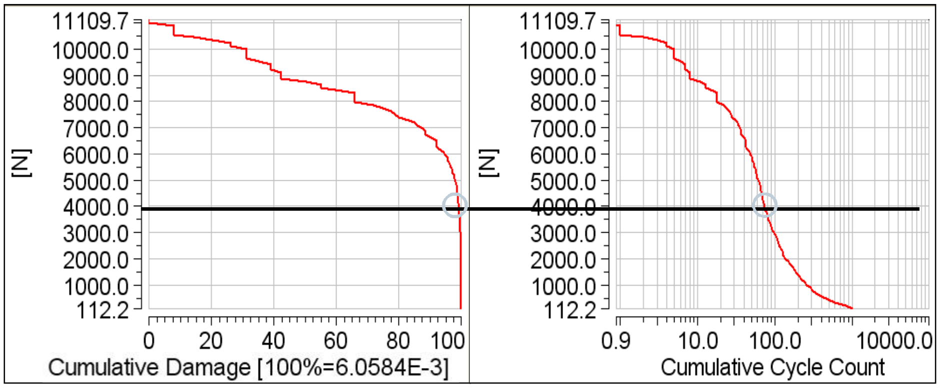
Simplify the test (2)
Block cycle test

Mix of different Constant-Amplitude Tests for **more accurate results**
Suitable for **highly non-linear structures** such as bushings



Omit non-damaging events

Left-hand side: only 0.5% of all damage resulting from cycles < 4000N
If you remove these from the loading, you end up with 70 cycles instead of 1000



Examples accelerated testing
Damage based Time Compression

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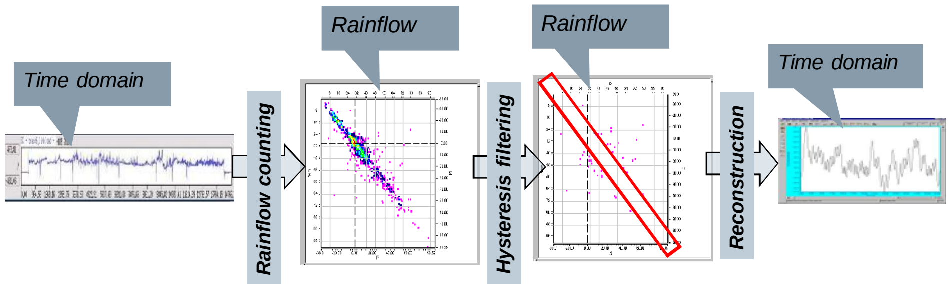
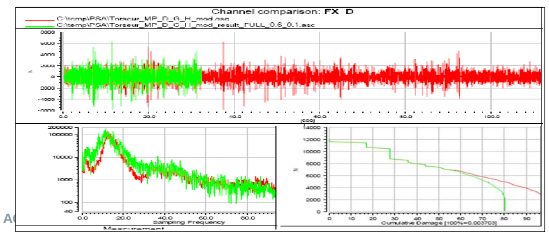


§ Uni- or multi-axial, keep sequence, phase and frequency content



TIME ACCELERATION DEMO

PSD / Swept Sine Based Techniques (Mission thesis)
Frequency Domain Technique

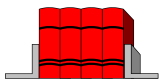
1. Derive vibration qualification specs based from measurements
2. Compare to current standards

- Based on measurements in the real-life environments (instead of generic standards)
- Principle of "damage equivalence"

Real life

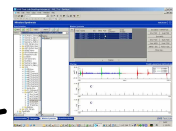
Recording

HOW ?



Standards

Shakertable



Analysis and

Synthesis

of the environments

Test tailoring in a mechanical environment

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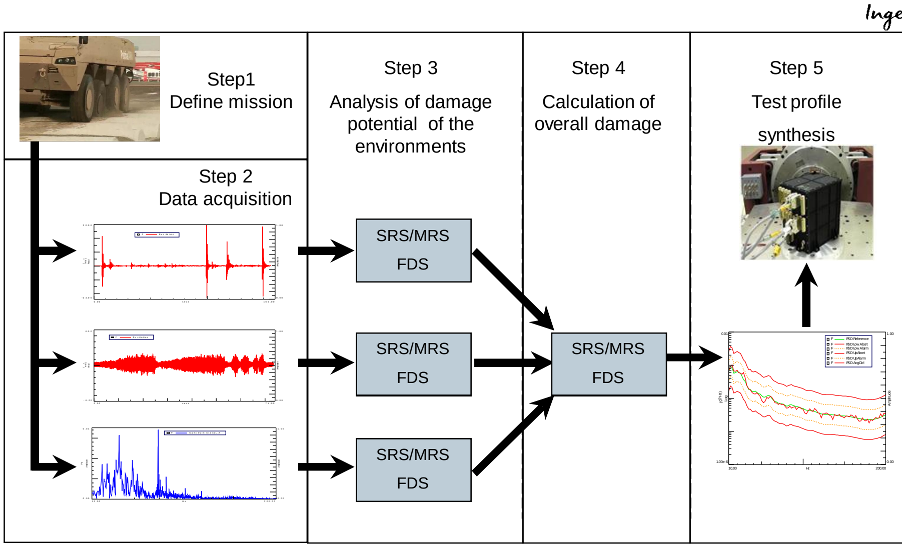
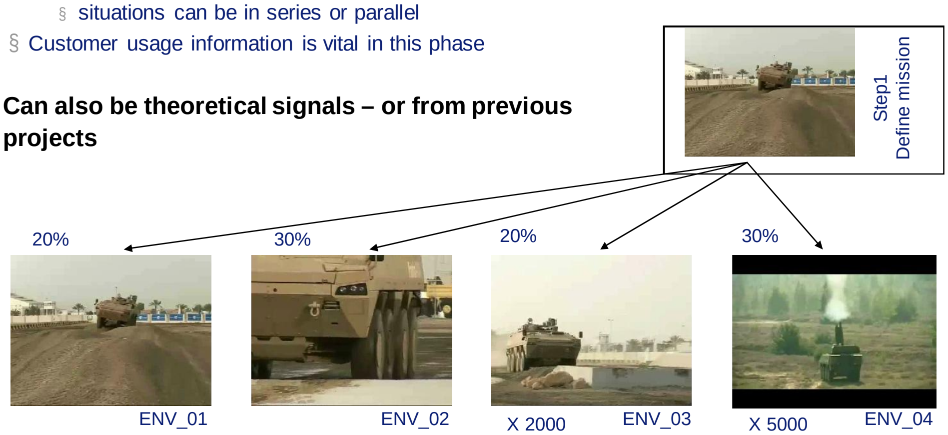


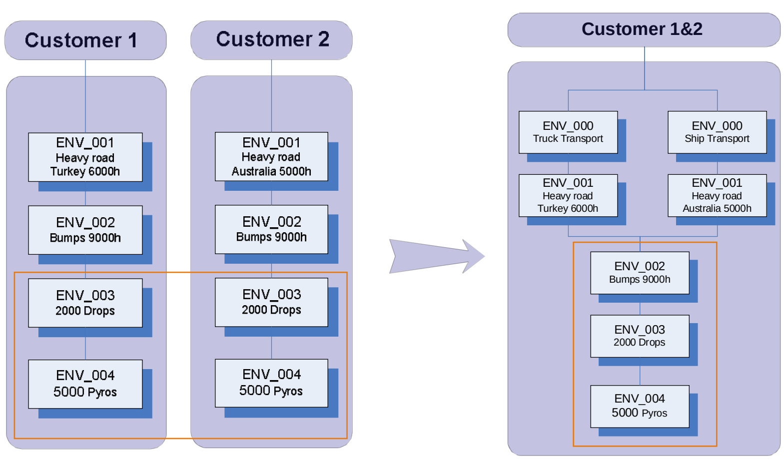
Step 1: Define mission

- Characterize a mission for the product
  - break life cycle of equipment down into separate situations
  - quantify each phase (environment) in terms of relative importance/contribution
  - situations can be in series or parallel
- Customer usage information is vital in this phase

Can also be theoretical signals – or from previous projects



Step 1: Define mission



Test tailoring in a mechanical environment

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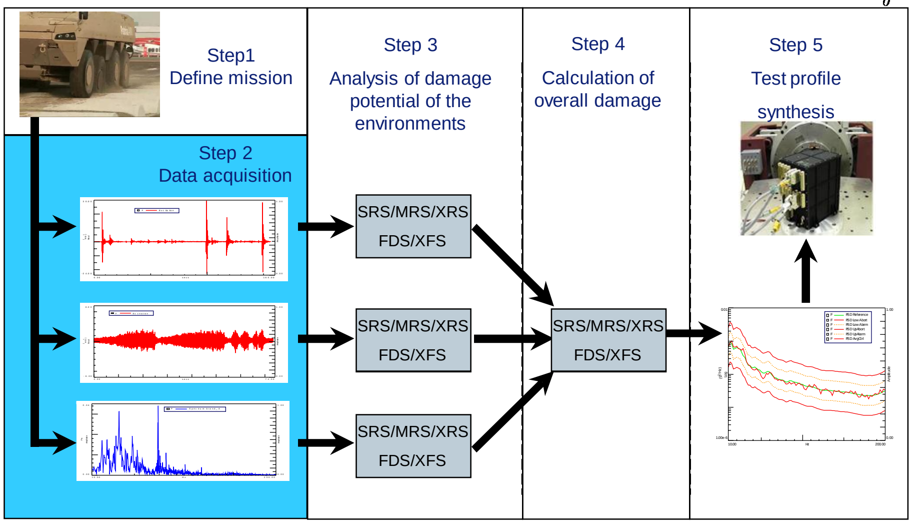

Step 2: Data acquisition

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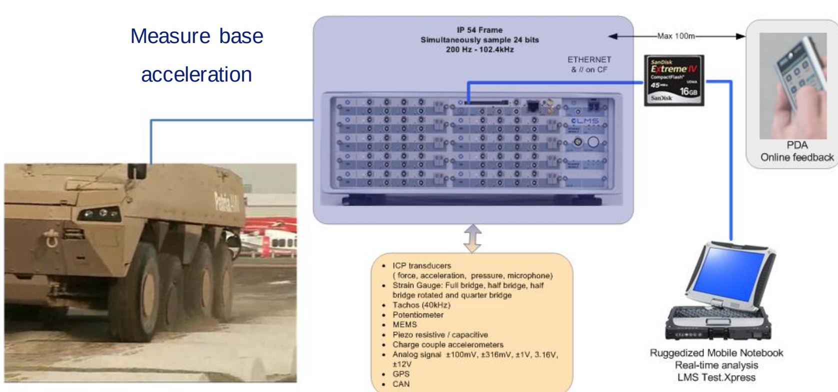
Each of the phases in the life profile should be quantified with in-situ measurements
As an alternative, standards can be used



Step 2: Data acquisition

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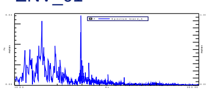
Acquisition

- Time series (deterministic)
- PSD recording (stochastic)

Post-processing of data

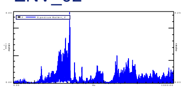
Step 2
Data acquisition

ENV_01



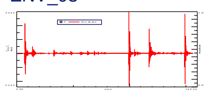
- PSD of ENV_01
- 1h of recording
- Corresponds to 20% of total life (30.000 h)

ENV_02



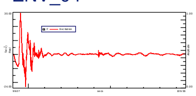
- PSD of ENV_02
- 10min of recording
- Corresponds to 30% of total life (30.000 h)

ENV_03



- Time of ENV_03
- 1 drop test
- 2000 drops for total life

ENV_04



- Time of ENV_04
- 1 pyro shock test
- 5000 pyro for total life

Test tailoring in a mechanical environment

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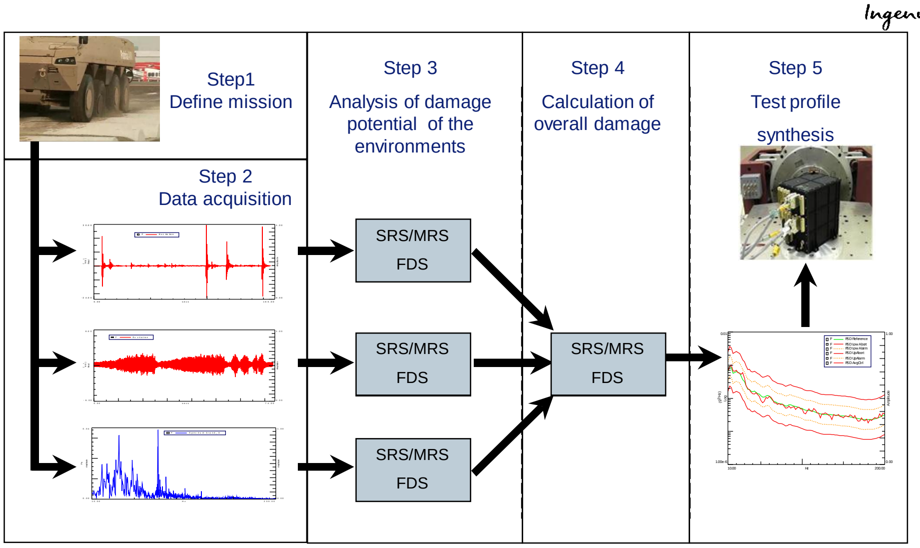

Fatigue Damage Spectrum

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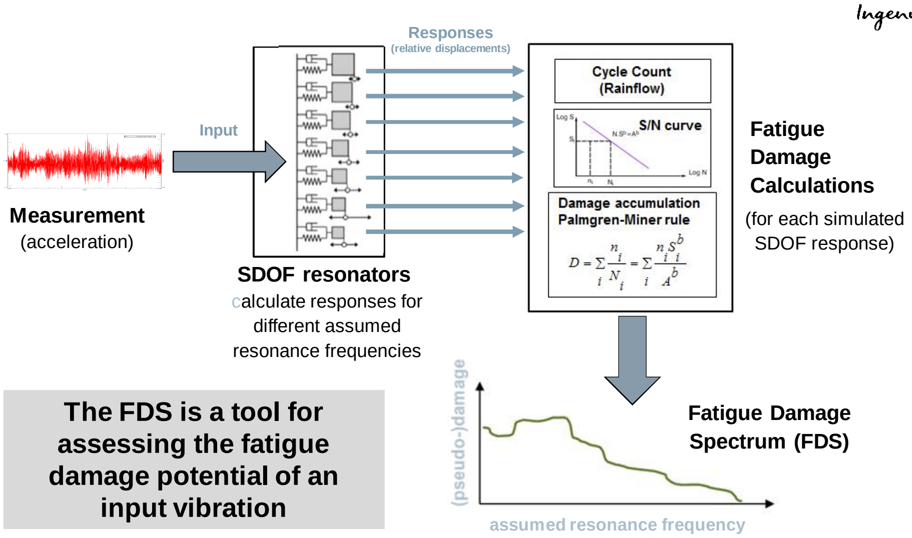

The FDS is a tool for assessing the fatigue damage potential of an input vibration

Shock Response Spectrum

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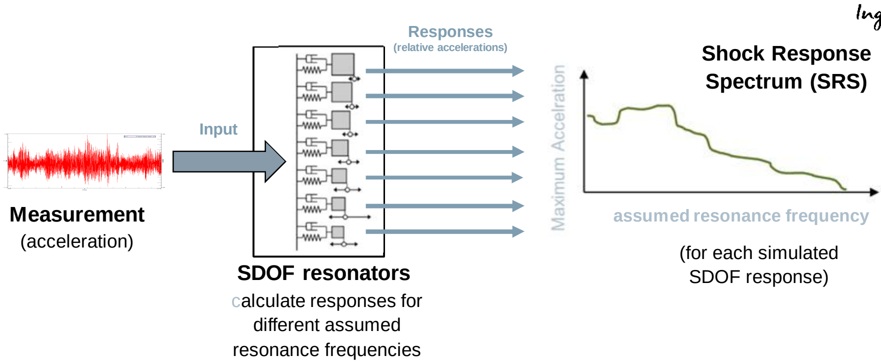

Maximum Response after each assumed resonance

Maximum Response Spectrum

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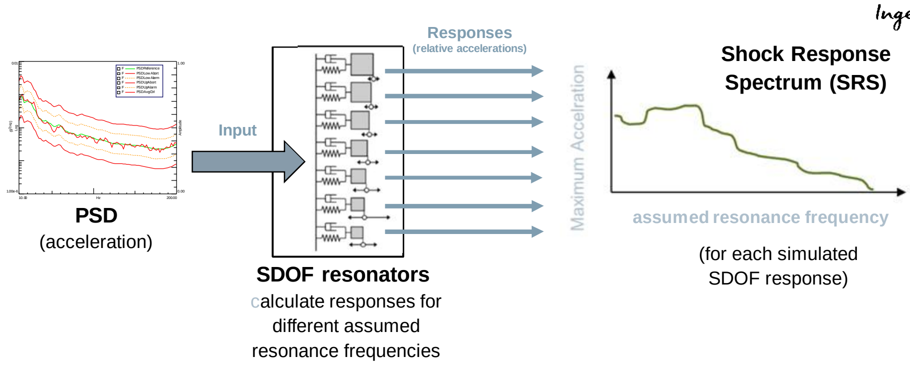

Maximum Response after each assumed resonance

Test tailoring
Step 4

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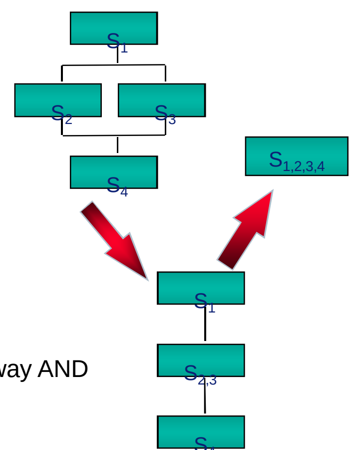
Combine spectra of the different situations to an overall life cycle

Situations in parallel:
- Specimen will undergo situation 1 OR situation 2
- E.g. car equipment designed for both Brazilian and European market
- envelope of the MRSs (worst case for each natural frequency)
- envelope of the FDSs

Situations in series:
- Specimen will undergo situation 1 AND situation 2
- E.g. dashboard should sustain 500,000 km of highway AND 20,000 km Belgian blocks
- Envelope of the MRSs
- Sum of the FDSs (Miner's rule: sum of damage values)



Test tailoring
Step 5 Test profile synthesis

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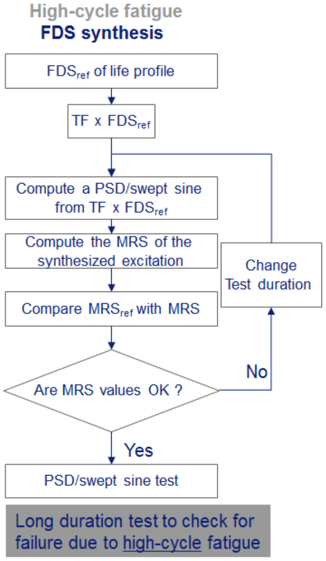

Test profile synthesis *(step 5)*

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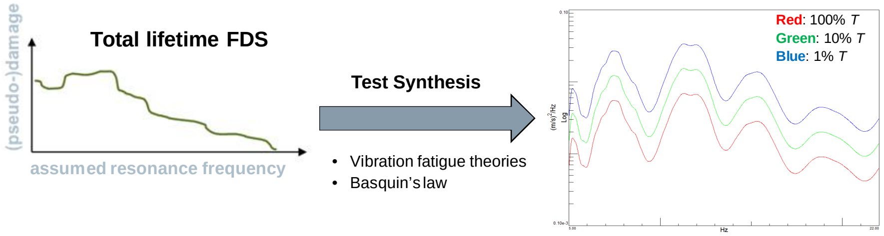

PSD specification matching lifetime FDS
(parameter: test time duration T => accelerated testing)

Test Profile Synthesis:

- Random Control Test (PSD) or Sine Sweep Test
- Create shaker profile based on Total Lifetime FDS: damage equivalence
- Test time duration T chosen based on MRS result (avoid unrealistic failures)

2 Methods for Developing Ferquency Domain Tests

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PSD Enveloping

- Damage proportional to rms level of shaker profile
- Damage proportional to Acceleration
- Designed for Stationary Random Signals
- Uses Basquin's Law to accelerate

Mission Synthesis

- Damage proportional to displacement
- Uses rain flow counting and Miners rule to get damage
- Works on transient data
- Time is an input in process
- Slope of SN curve affects test acceleration

Material Review

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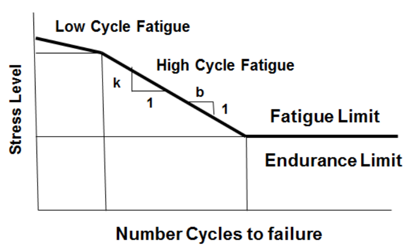
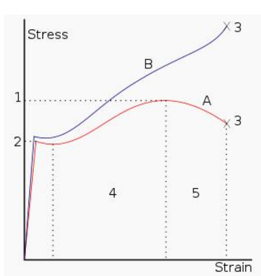


Basquin's law $Ns^{b} = C$

SN Curve Formulae $\frac{N_2}{N_1} = \left(\frac{S_1}{S_2}\right)^{b}$



Relationship for Ultimate Strength to Endurance Limit $\frac{S_u}{S_e} \approx 2$

Step 5 : Test Profile Synthesis

Validation of the reduction of the test time (Exaggeration Factor)

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$$\ddot{x}_{rms\_reduced} = \ddot{x}_{rms\_real}\left(\frac{T_{real}}{T_{reduced}}\right)^{\frac{1}{b}}$$

PSD Envelope Method for time reduction

$$E = \frac{\ddot{x}_{rms\_reduced}}{\ddot{x}_{rms\_real}}$$

Exaggeration Factor

$$TRF = \left(\frac{T_{real}}{T_{reduced}}\right)$$

Time Reduction Factor

Exaggeration Factor Should not exceed 2-3 Range based on relationship between Ultimate Strength and Endurance Limit

Step 5 : Test Profile Synthesis

Validation of the reduction of the test time (Exaggeration Factor)

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$$\frac{\ddot{x}_{rms\_reduced}}{\ddot{x}_{rms\_real}} = \left(\frac{T_{real}}{T_{reduced}}\right)^{\frac{1}{b}}$$

TRF	b	Exaggeration Factor		Exaggeration Factor	b	TRF
64	4	2.83		2	4	16.00
64	6	2.00		2	6	64.00
64	8	1.68		2	8	256.00
64	10	1.52		2	10	1024.00
64	12	1.41		2	12	4096.00
64	14	1.35		2	14	16384.00
16	4	2.00		1.5	4	5.06
16	6	1.59		1.5	6	11.39
16	8	1.41		1.5	8	25.63
16	10	1.32		1.5	10	57.67
16	12	1.26		1.5	12	129.75
16	14	1.22		1.5	14	291.93
8	4	1.68		1.25	4	2.44
8	6	1.41		1.25	6	3.81
8	8	1.30		1.25	8	5.96
8	10	1.23		1.25	10	9.31
8	12	1.19		1.25	12	14.55
8	14	1.16		1.25	14	22.74

Constant TRF — Constant Exaggeration Factor

Time Reduction more difficult on lower b materials

MISSION SYNTHESIS DEMO

Step 5 : Test Profile Synthesis

Validation of the reduction of the test time (MRS Comparison)

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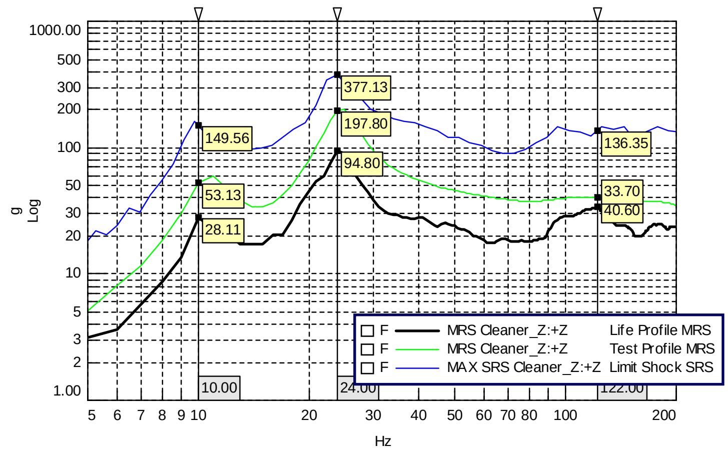
MRS (Excitation) <= 2* MRS (Life Profile)



Mission Synthesis and Test Based Fatigue References

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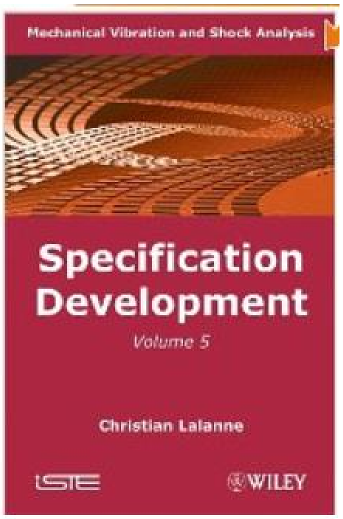

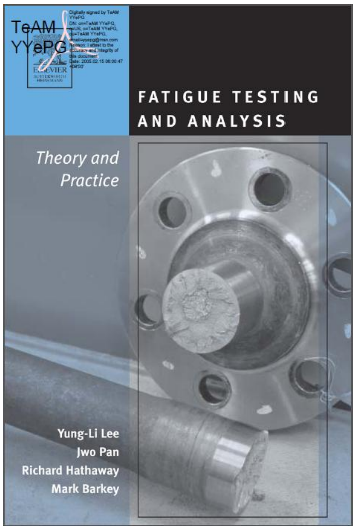

Conclusions

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1. Small change in load big change in damage log-log
2. Most variability in the durability process is in understanding loads
3. Basic damaging event is a closed hysteresis loop on a stress strain plot
4. We use rain flow counting extracts damaging cycles form time wave forms
5. Understanding the strain field is critical in understanding the fatigue damage from a test
6. Accelerating a test in the frequency domain requires us to increase the amplitude
7. When changing the amplitude user must be careful to not generate an uncharastic failure mode


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Thank You
John Hiatt, Keith Moss