Copyright Statement

Analysis Tools for Fatigue & Durability

Prenscia

Analysis Tools for Fatigue & Durability

nCode GlyphWorks

nCode DesignLife

nCode VibeSys

nCode

Agenda

1. Introduction to Durability
2. Measuring and Calculating Fatigue
3. Accelerating Durability Tests

Lunch

4. Fatigue from FEA
5. Validation, Verification and Correlation
6. Product Summary

Introduction to nCode

nCode History

1980s

- nCode established
- nSoft released
- First commercial fatigue calculation package released

nCode

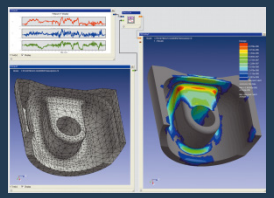
1990s

- ReliaSoft established
- Technology partnership formed with MSC Software

ReliaSoft

2000s

- Technology partnerships formed with Pro/Mechanica PTC, ANSYS, and Altair
- DesignLife introduced



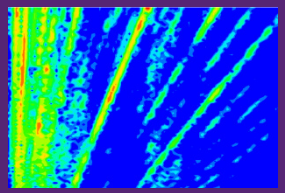
2010s

- Fatigue of **composites**
- Fatigue of **welds**
- **Distributed Processing** and **HPC**
- **Synthesis Platform** introduced

THE SYNTHESIS PLATFORM

2016

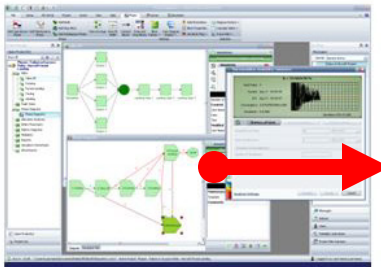
- **Prenscia Access** and **VibeSys** launched
- **Vibration fatigue** enhanced

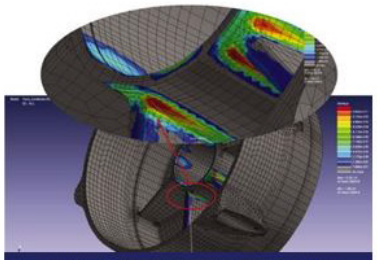


2017+

- **Aqira**
- New AMCT facility

HBM Test & Measurement


Reliability Analysis

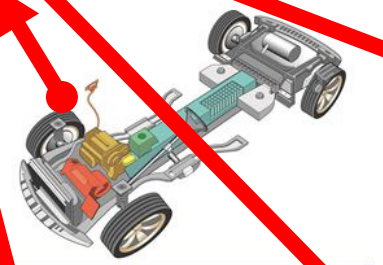

Durability Analysis and Simulation


Aircraft Electric System Testing


Structural and Durability Tests


Power Train Test


Component Test


eDrive


Mobile Data Acquisition

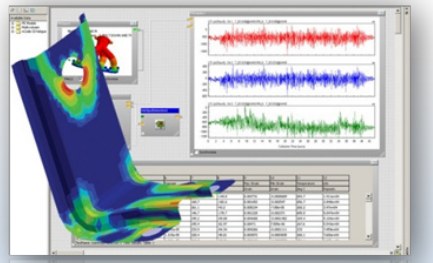

OEM Sensors


Dynamic Weighing


Industrial Measurement and Control


Infrastructure Monitoring

nCode Product Range



nCode DesignLife

CAE DURABILITY

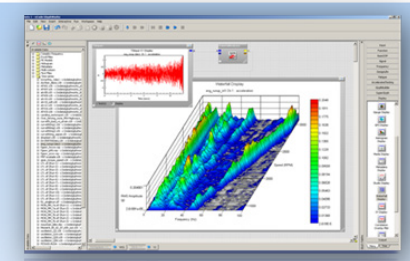
- Fatigue analysis technology for FEA
- Process encapsulation
- Fast, configurable, and scalable

nCode GlyphWorks

DATA PROCESSING FOR DURABILITY

- Complex analysis to report, simply done
- Graphical, interactive & powerful analysis
- World leading fatigue analysis capabilities

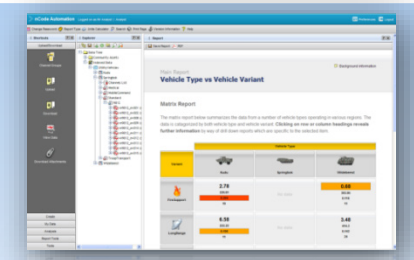
nCode CDS Licensing



nCode VibeSys

ACOUSTIC & VIBRATION ANALYSIS

- Powerful and simple-to-use
- Noise and Vibration analyses including rotating machinery, structural dynamics and human perception



nCode Automation

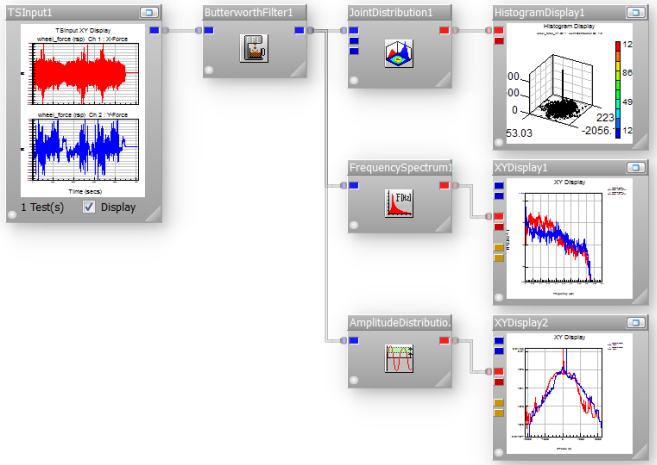
MAXIMIZING ROI ON TEST & DURABILITY

- Enables collaboration, data management, and standardized analyses
- Search, query and reporting through secure web access.
- Data to decisions

Test Data Processing and Durability Analysis

- **Intuitive and powerful** graphical interface to develop processes
- **Efficiently handles** multiple files, channels and formats
- **Pre-defined processes** for time, frequency and statistical analysis
- **Proven analysis methods** for durability and fatigue with specialized capabilities for damage calculation and test profile generation
- **User-defined processes** easily created with open source Python language and MATLAB®

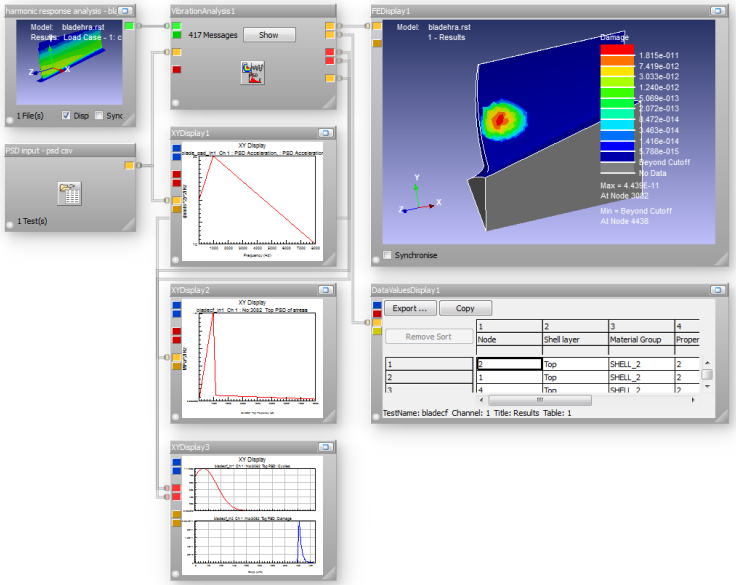
nCode GlyphWorks



Predictive Fatigue for CAE Analysts

- **Intuitive and powerful** graphical interface to perform fatigue analysis from leading FEA results data
- **Efficiently analyze** large finite element models and complete usage schedules
- **Wide range of fatigue analysis capabilities** including stress-life, strain-life, multi-axial, weld analysis, virtual shaker table and more
- **Highly configurable** for the expert user
- **Single environment** for correlating CAE directly with physical test data
- **Enables automation** of complete analysis processes and reporting

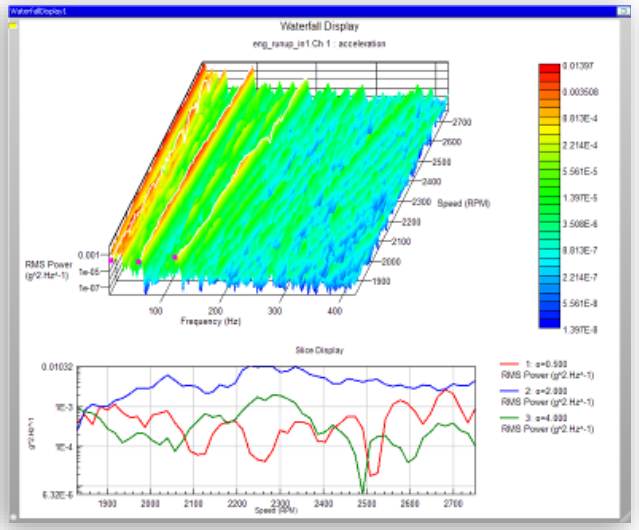
nCode DesignLife

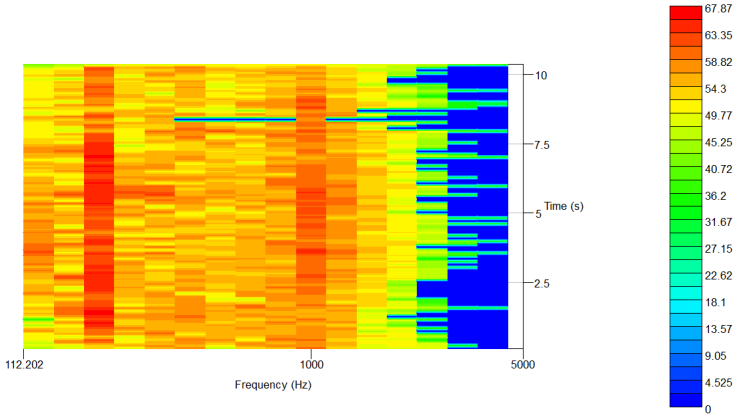


Data Processing System for Acoustic & Vibration Analysis

- **Proven analysis methods** for early fault detection in rotating machinery, understanding human perception of vibration and sound, and characterizing the dynamics of a structure
- **Basic signal processing tools** to visualize data, perform general signal processing and run reports
- **Pre-defined processes** for performing time, frequency and statistical analysis
- **User-defined processes easily created** with MATLAB® or Python Programming Language
- **Interactive displays** for characterizing modal properties to validate or enhance structure FE modelling

nCode VibeSys

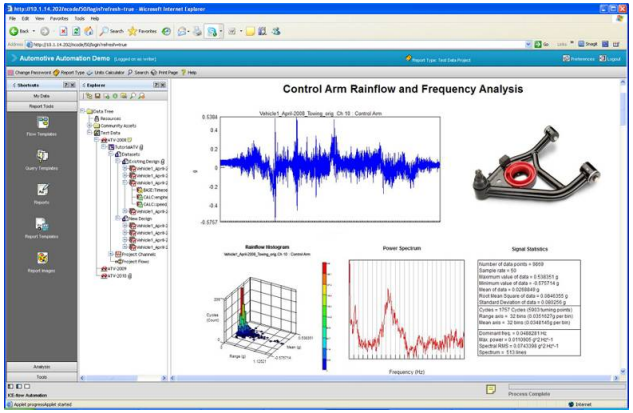




Web-Based Processing of Engineering Data

- Search criteria include content of data and attachments
- **Data Processing** – Runs GlyphWorks processes to generate additional data
- **Characteristic Values** – Define values to describe the data
- **Query Templates** – Returns data, tables and/or charts
- **Report Flows** – Runs GlyphWorks processes for additional report content
- **Report Templates** – Combines Queries and Report Flows with text editor to create complete reports

nCode Automation



Introduction to Durability

Design for Durability

- Designing a part to
  - Last
  - Resist damage
  - Resist wear

- Durability can be described as reliability in relation to certain progressive failure modes
  - Fatigue
  - Creep
  - Wear
  - Fretting
  - Corrosion

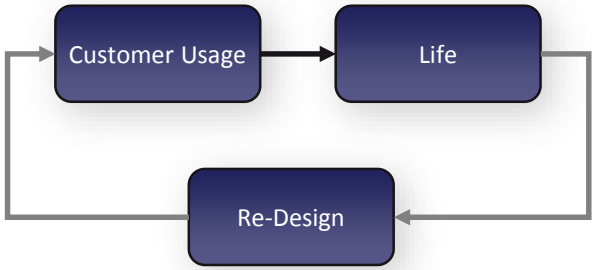
"Anyone who lacks knowledge of fatigue can double or triple design factors and formulate a design that will not fail. However, such designs cannot compete in the marketplace. Neither can the engineers who produce them."

J. E. Shigley and C. R. Mischke, *Mechanical Engineering Design*, 1989

Design for Durability: The Early Years

- Early fatigue analysis was done after an in-service failure, if at all!

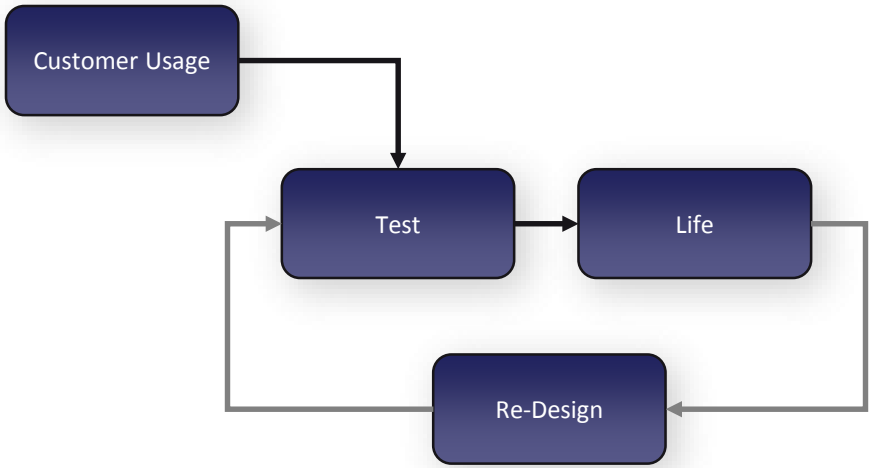
- Engineers in the automotive industry were even known to inspect old vehicles in scrap yards for failures



Design for Durability: Later Development

- Data collection allows engineers to build a definition of who is the “typical” or “severe” customer

- These customer definitions allow engineers to design and validate fatigue test schedules

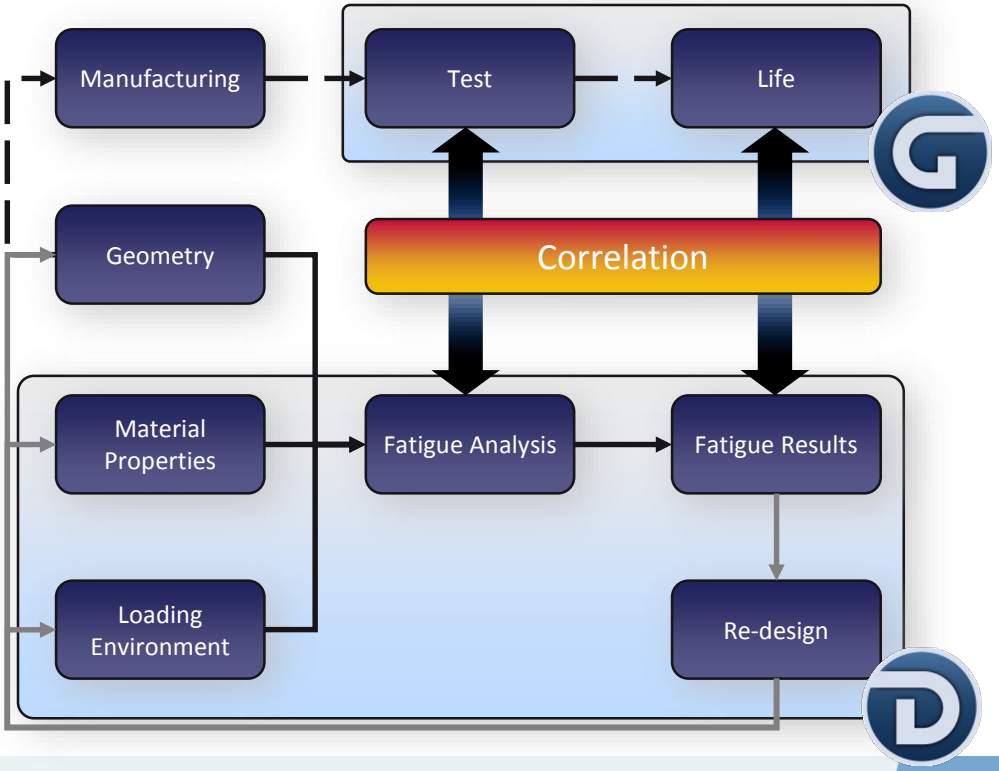


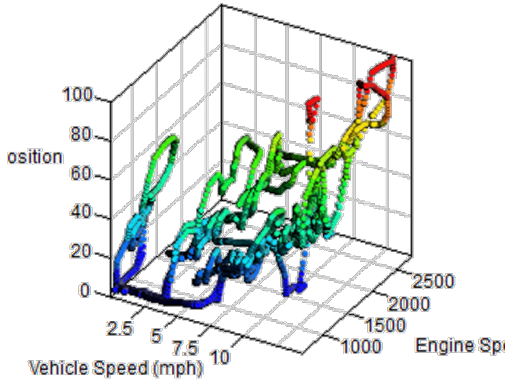
Shortfalls of Physical Testing

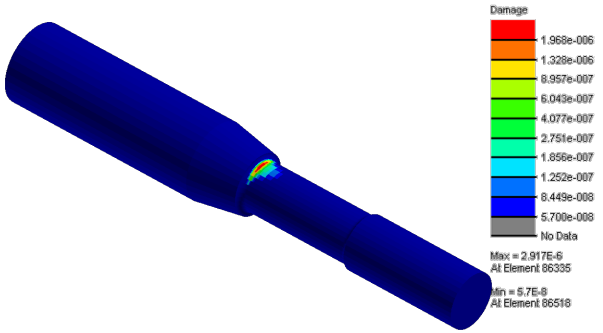
- Requires many physical prototypes
- Realistic tests difficult or impossible to achieve
- Too slow
- Too expensive
- Fails to deal with over-design
- Difficult to handle late changes and design variations

Design for Durability: Present Time

- **GlyphWorks** provides data processing capabilities to understand customers and loading, and test results
- **DesignLife** provides the capability of predicting fatigue in a virtual environment
- Fatigue failures can be addressed before parts are manufactured



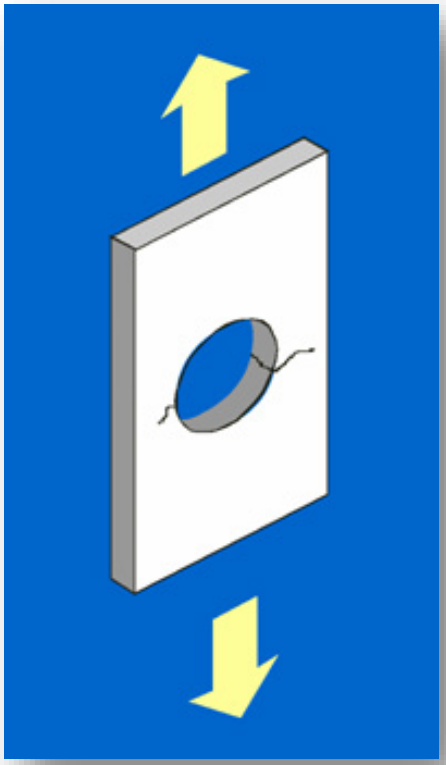




What is Fatigue?

- Weakness in metal or other materials caused by repeated variations of stress: *metal fatigue*

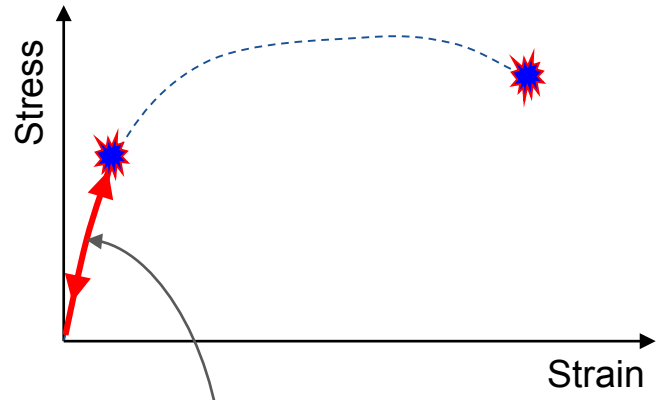
  The New Little Oxford Dictionary



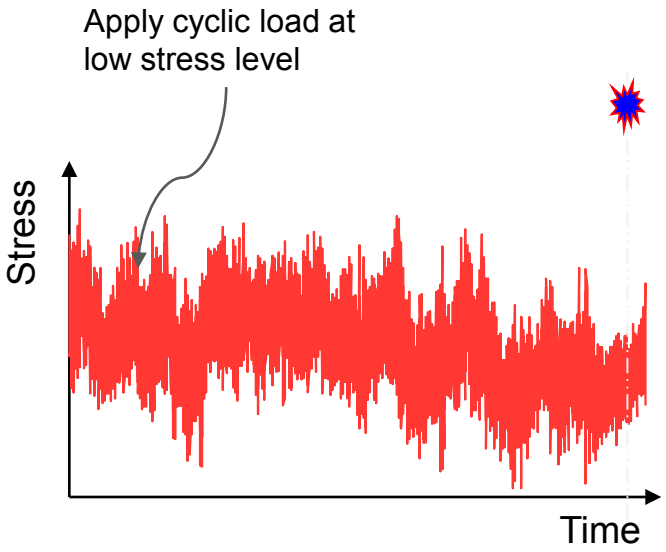
- The initiation and subsequent growth of a crack, or growth from a pre-existing defect, until it reaches a critical size
  - Fatigue cracks are caused by cyclic loading
  - The part can fail even though stresses are not that high
  - Over time, fatigue cracks can start and then grow large enough to cause sudden failure

Two Failure Modes

- **Static Failure**
  - Failure when stress exceeds tensile strength in a single pass

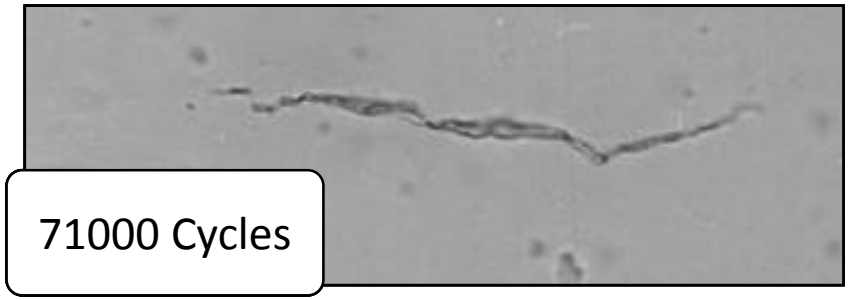


- **Fatigue Failure**
  - Failure occurs after a period of time even in cases of low stress
  - The component appears to get tired, hence the name *fatigue*



What is Fatigue?

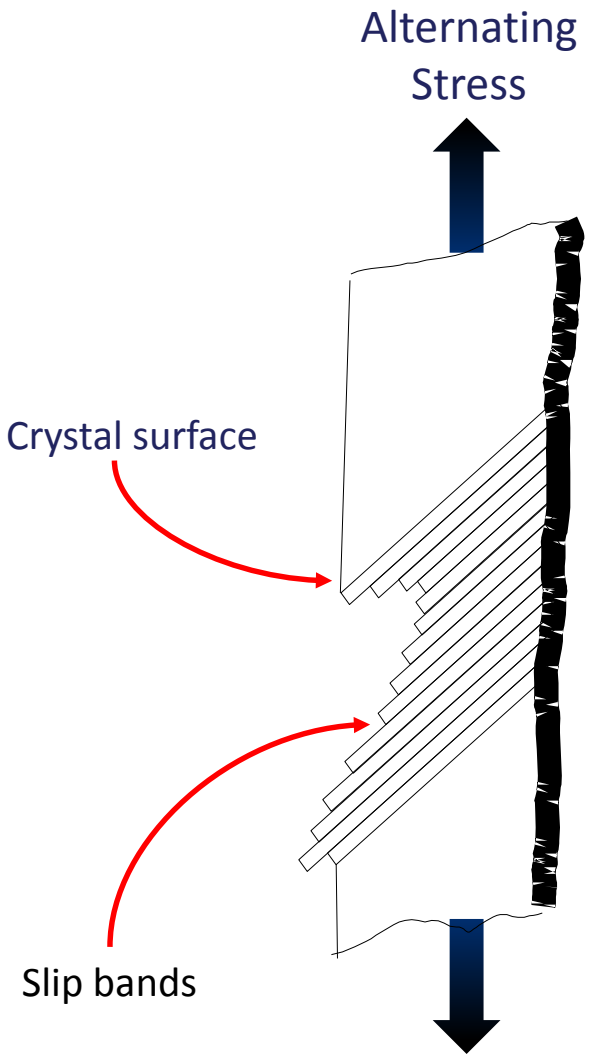
- Failure under a repeated or otherwise varying load which never reaches a level sufficient to cause failure in a single application
- Fatigue cracks in metals initiate and grow as a result of cyclic loads that cause highly localized plastic deformation



- Fatigue can be modeled in two stages
  - Stage 1: Crack Initiation
  - Stage 2: Crack Growth

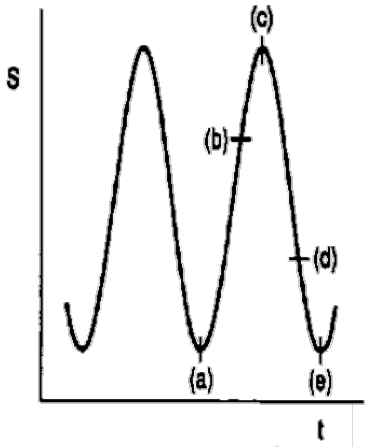
Crack Initiation

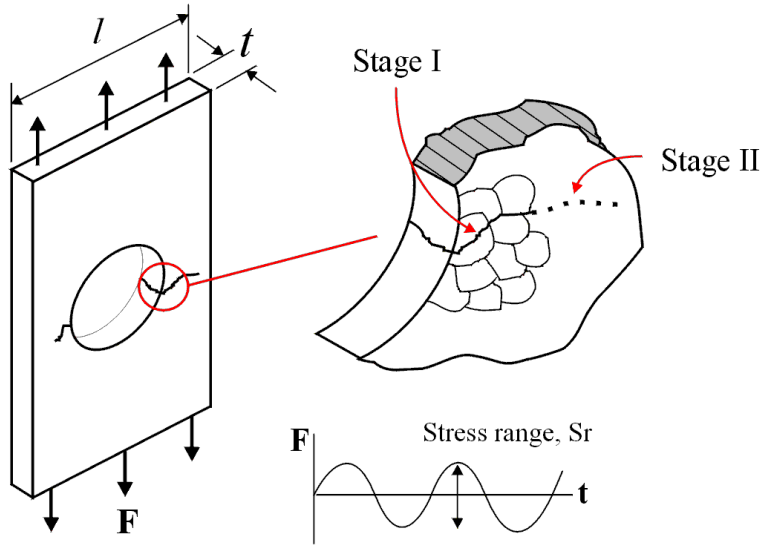
- Cracks usually initiate from microscopic defects
- Defects then create persistent slip bands that propagate along the maximum shear plane
- Material behavior is like a shifting deck of cards

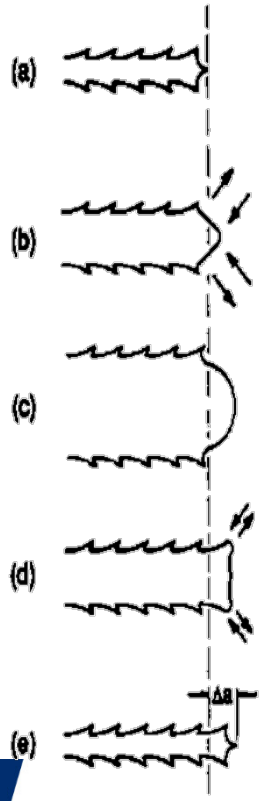


Crack Growth

- The crack becomes physically large relative to the microstructure of the material
- This causes an interruption to the flow of stress and results in a large tensile stress concentration at the crack tip
- The crack now propagates along the plane of maximum tensile stress

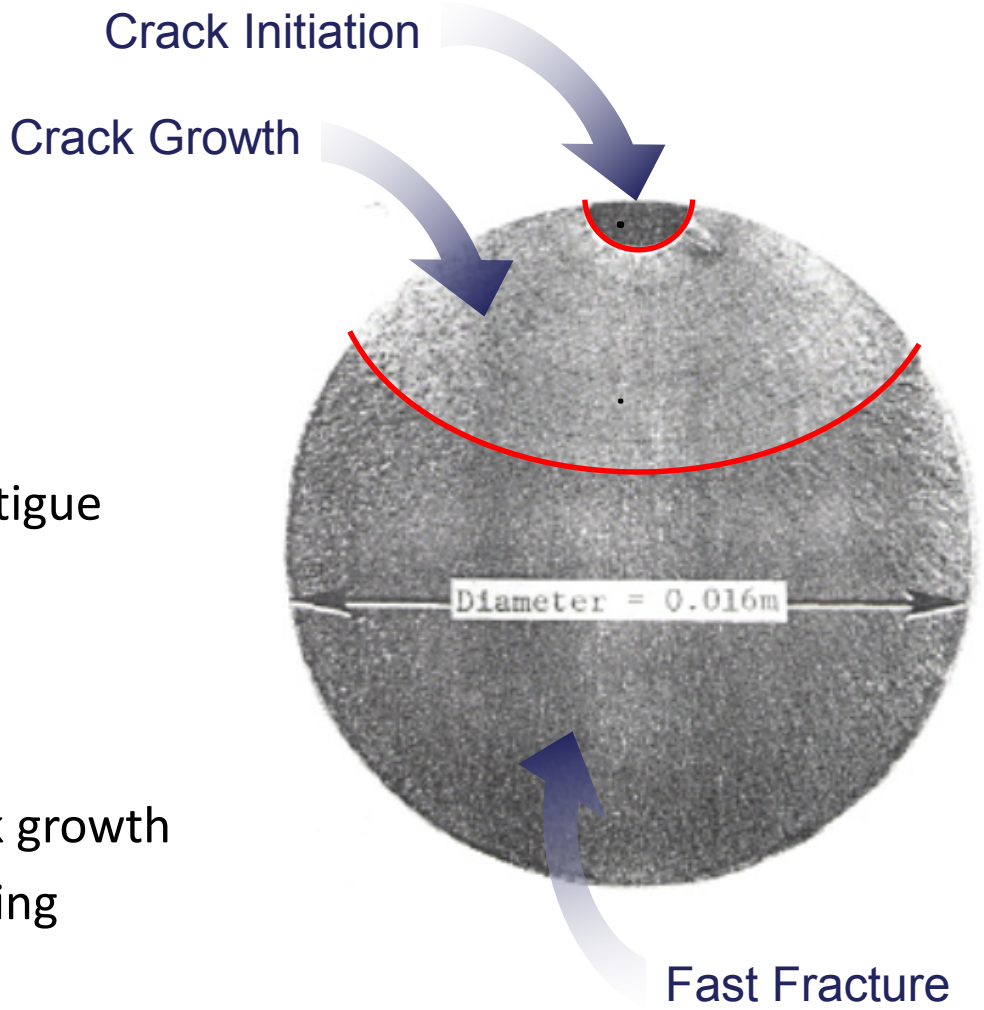




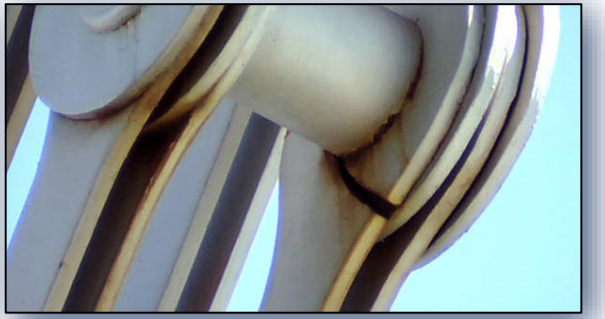


Fatigue Analysis Methods

- Stress-Life (SN)
  - Stress drives crack initiation
  - Works best for high cycle fatigue
- Strain-Life (EN)
  - Strain drives crack initiation
  - Models plasticity and low cycle fatigue
- Crack Growth
  - Stress intensity factor drives crack growth
  - Assumes the existence of an existing crack or flaw



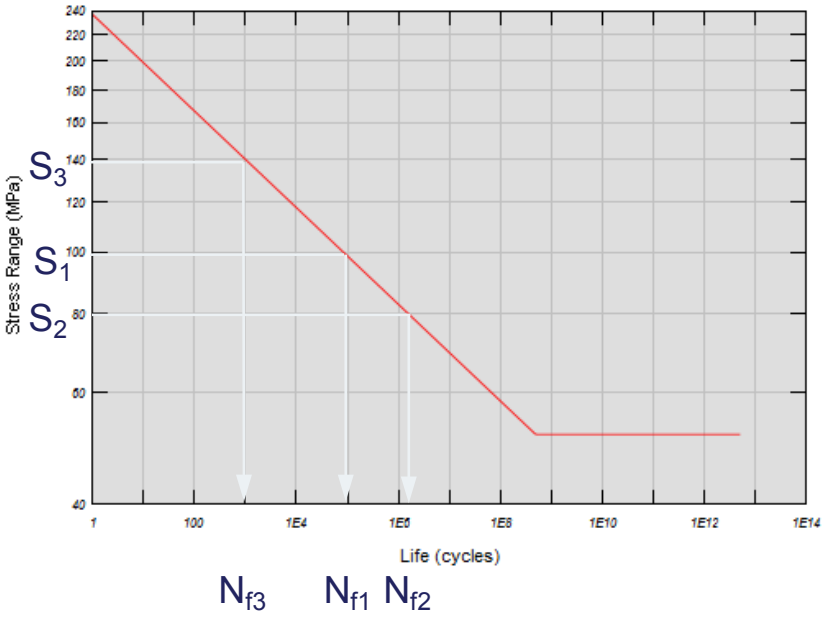
Historically Significant Fatigue Failures



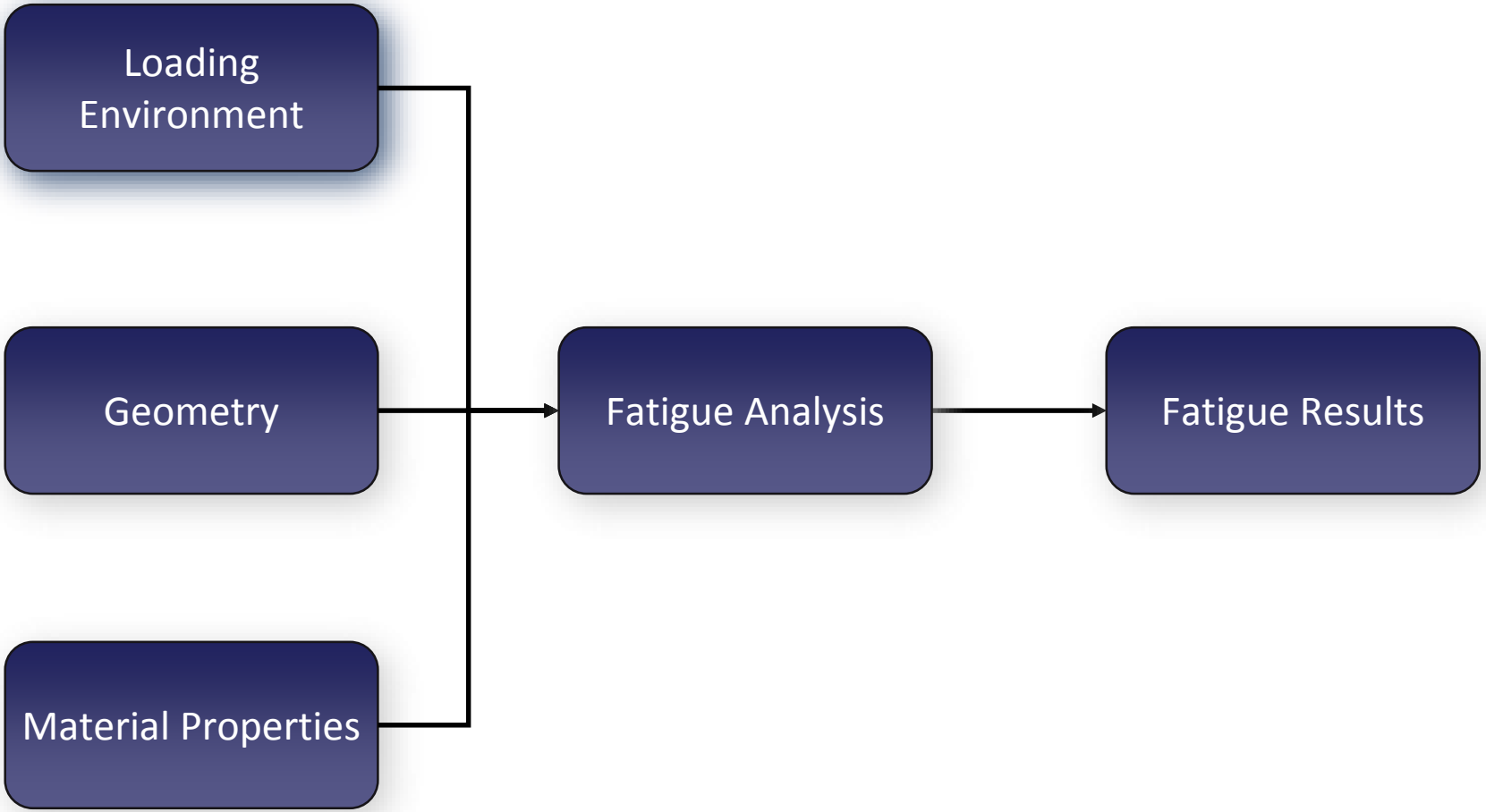
Design for Durability: Summary

- Fatigue is a progressive failure under repetitive stress cycling
- Fatigue has been investigated as a failure mode for over 150 years
- Fatigue failures still occur today
- A properly designed structure can resist fatigue failure

Calculating Fatigue

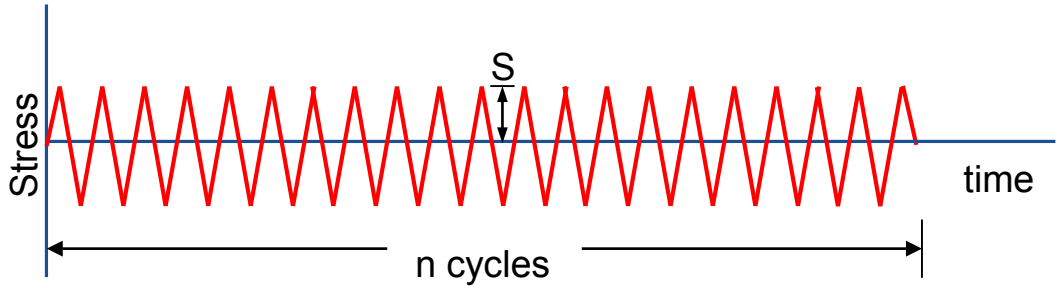


Fatigue Analysis Roadmap



Fatigue Analysis Roadmap

Loading Environment

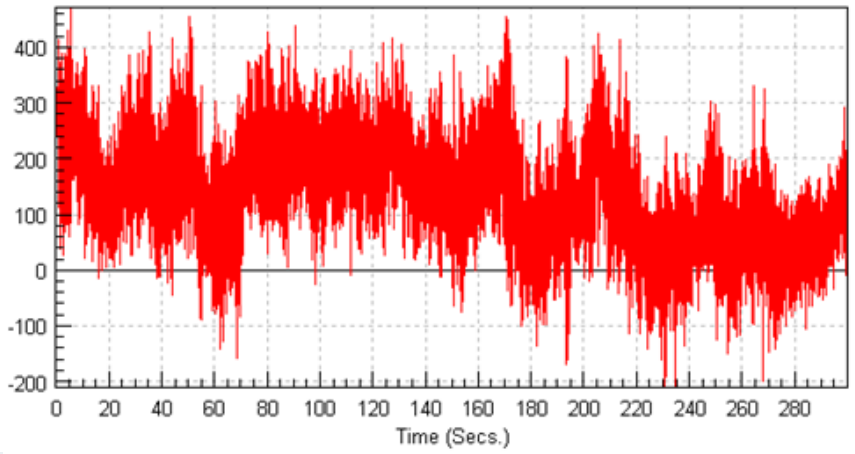


Geometry

Material Properties

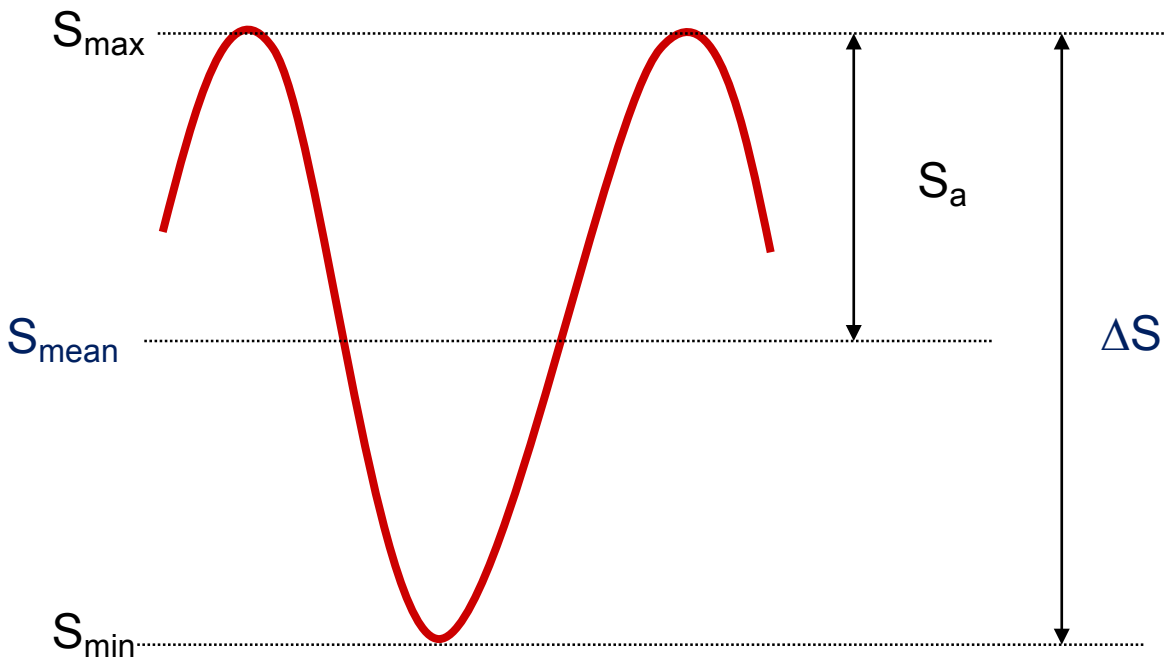
Fatigue Analysis

Fatigue Results



Loading Environment

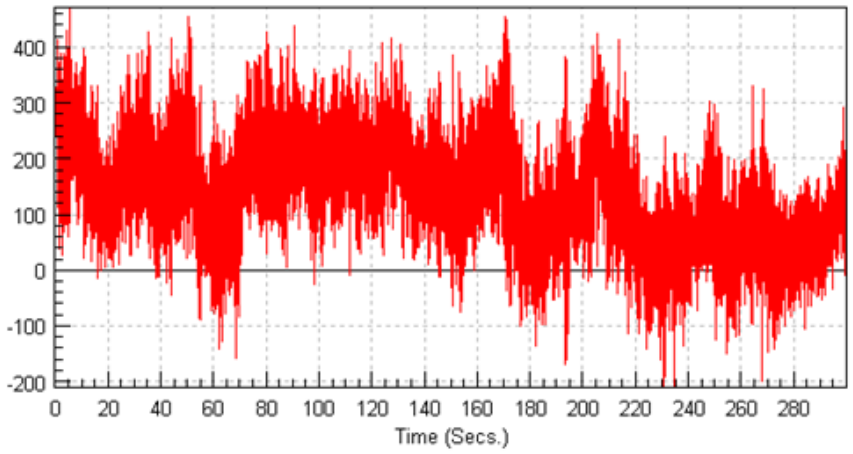
- Fatigue and crack growth are driven by cyclic loading
- Constant stress will not cause crack initiation or growth

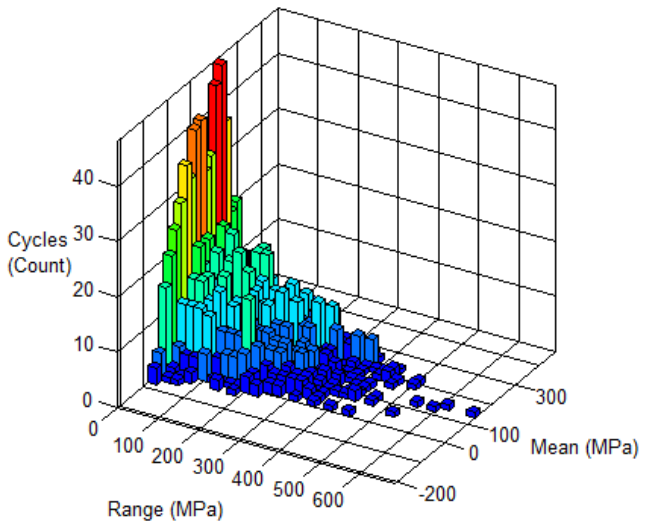


- Change of stress (ΔS or S_a) is really important – called *cyclic range*
  - Larger stress range = shorter life
- Mean stress (S_{mean}) is also important
  - Tensile mean stress = shorter life
  - Compressive mean stress = longer life

Loading Environment

- Real loading is often fairly random
- We need a method of finding fatigue cycles in a varying waveform
- **Rainflow** is the most common cycle counting method for fatigue analysis
  - Applicable to SN, EN and crack growth analysis





Rainflow Cycle Count

Fatigue Analysis Roadmap

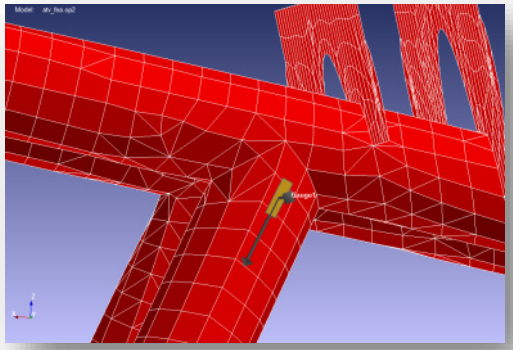
Loading Environment

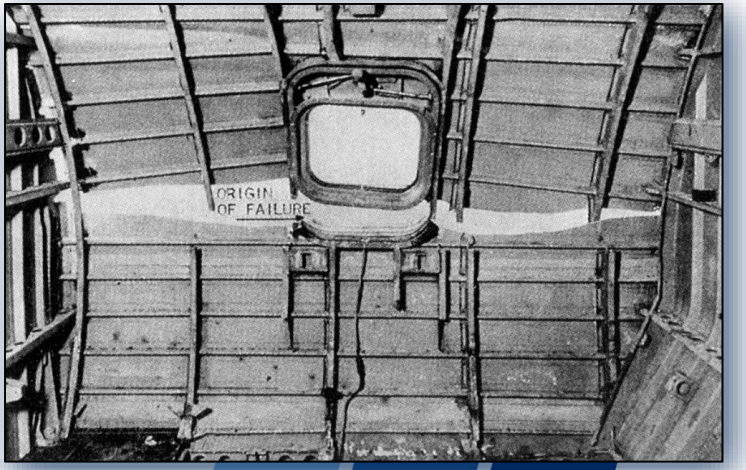
Geometry

Material Properties

Fatigue Analysis

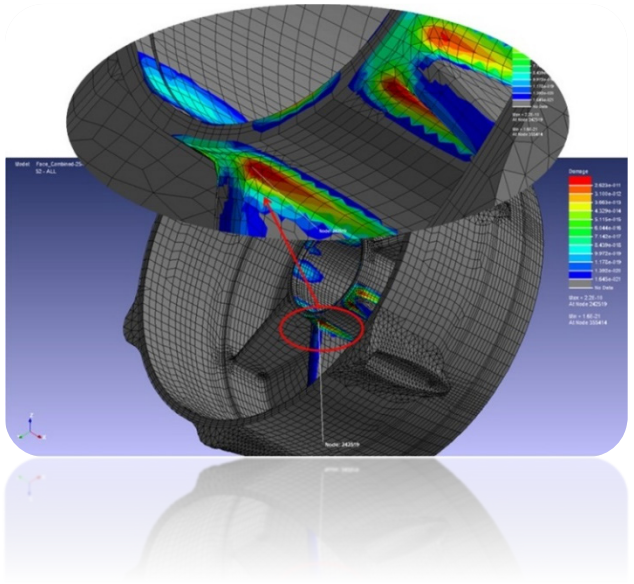
Fatigue Results





Local Stress from Geometry and Loading

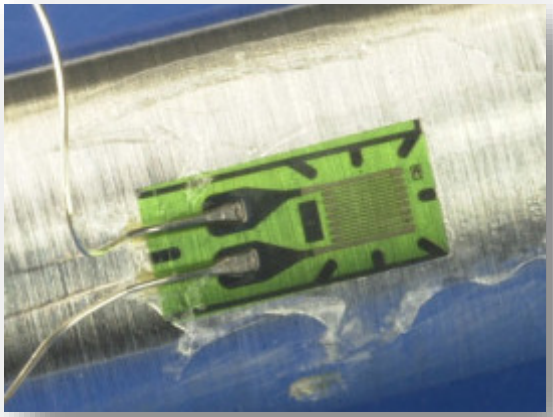
Geometry plus loading gives us the stress history of a component



Finite Element Analysis (FEA) results can be used in a CAE environment to perform a fatigue analysis

Measurements taken using a strain gauge can be used for fatigue analysis

- This “includes” geometric effects at the point where the measurement is taken
- A scale factor (K_t) may be required to compensate for strain gauge location near hot-spots



Fatigue Analysis Roadmap

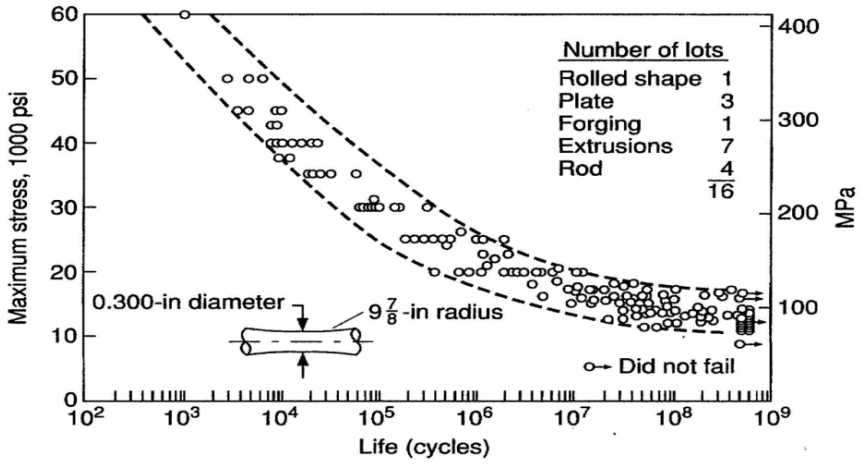
Loading Environment

Geometry

Material Properties

Fatigue Analysis

Fatigue Results



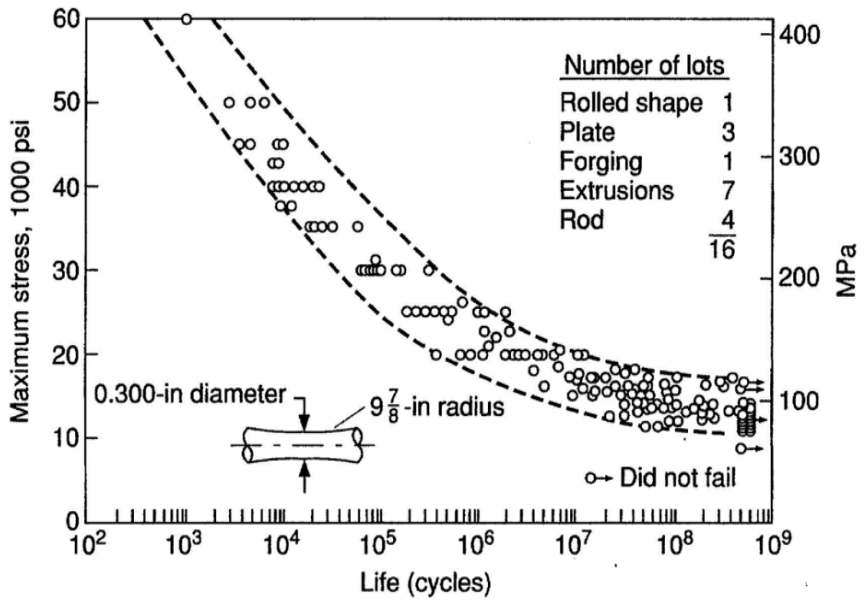
Material Properties

- Component durability is directly influenced by how the material responds to loading
- Thus, the accuracy of any fatigue calculation is dependent on the quality of the material properties
- Material fatigue properties are characterized experimentally

nCode AMCT Facility

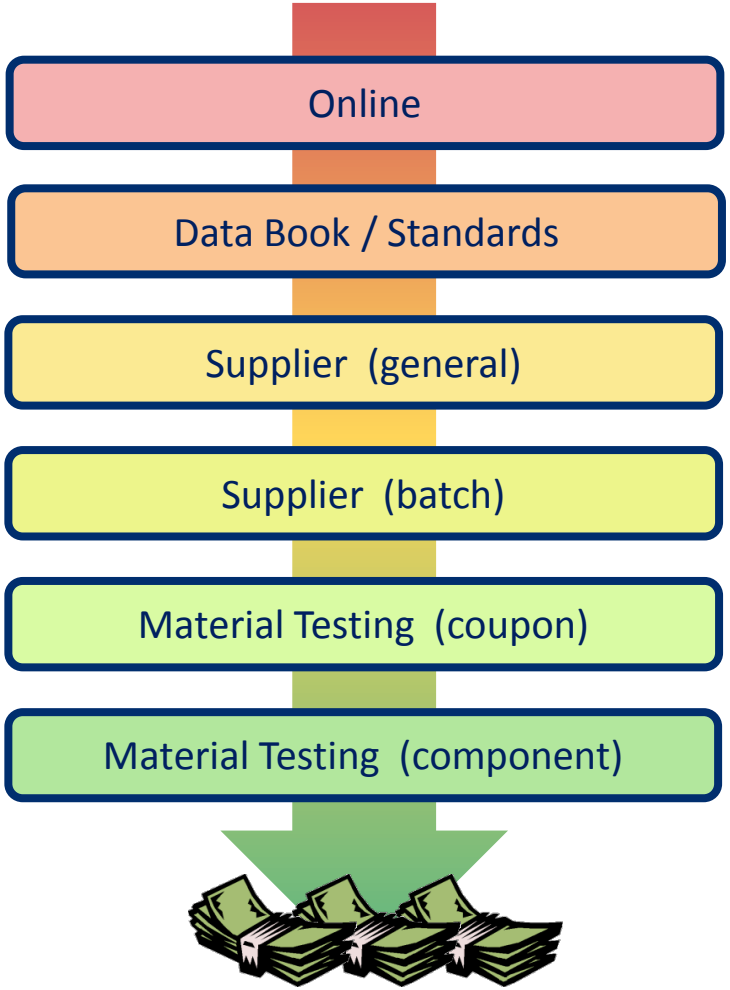
Material Properties

- Material characteristics
  - Test and break machined material coupons
  - Plot applied stress or strain versus life
  - Captures material effects
  - Generic to this material but needs corrections to model geometry etc.



Material Properties

Often overlooked and expensive to obtain; good materials data is vital for performing an accurate fatigue analysis…



Did you read off a pixelated image?

When was the data generated?

How consistent is their product?

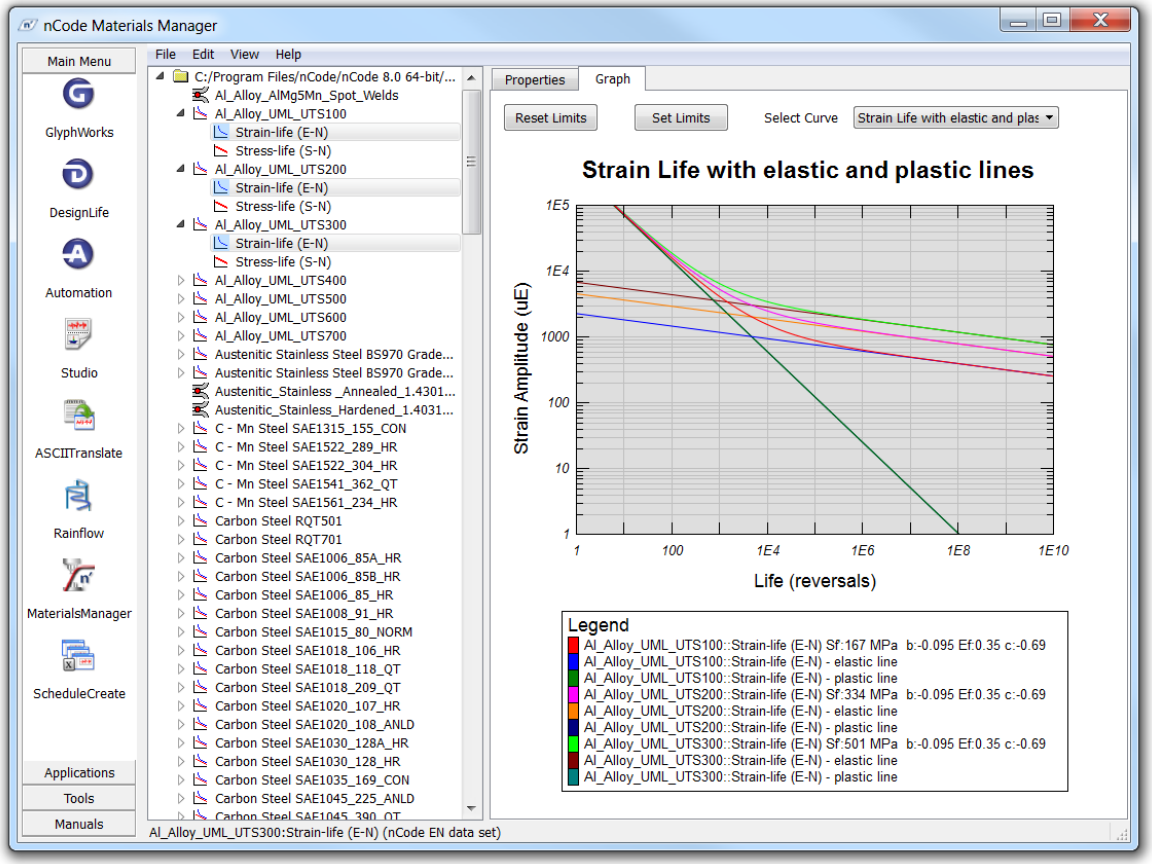
Do they have material test certification?

Pay for peace of mind!

Includes manufacturing stresses…

nCode Materials Manager

- Many different material types and compositions:
  - Steel, Aluminium, Titanium, Cast Iron, Welds (etc.)
- Many different international standards
  - MIL-HDBK-5, Eurocodes (etc.)



nCode Premium Materials Database

- All materials tested in-house by nCode AMCT engineers
- Fully certified testing facility ISO9001
- Over 100 materials!
- Corresponding International standards

Material	ISO	WNR	EN	UNS	BS	US	DIN	NF	JIS	Trade Name
100Cr6 Steel	ISO 4957 (12/1999) 102Cr8	1.2067	EN 10132-4 (02/2000 + AC 12/2002)	T61203	BS EN 10132-4 (02/2000 + AC 12/2002) 102Cr6		102Cr6 and 100Cr6	AFNOR NF EN 10132-4 (02/2000 + AC 12/2002) 102Cr6 and AFNOR NF A 35-590 (1992) 100Cr6	JIS G 4805 (2008) SUJ 2	
13-8 PH Stainless Steel				S13800		AMS 5629 & ASTM A564				
2024 - T851 Aluminium Alloy - Longl			AW-2024	A92024		AMS QQ-A-250/4A T851				
2024 - T851 Aluminium Alloy - Trans			AW-2024	A92024		AMS QQ-A-250/4A T851				
21CrMoV5-7 Steel		1.7709	EN 10269 (04/2006) 21CrMoV5-7	21CrMoV5-7	BS EN 10269 (04/2006) 21CrMoV5-7		DIN EN 10269 (04/2006) 21CrMoV5-7	AFNOR NF EN 10269 (04/2006) 21CrMoV5-7		56 TG, BGH 7709, DE 7709, Remy 1.7709
2205 Duplex Stainless Steel		1.4462	EN 10083:part3: 2005 1.4462	S32205	BS 970 318S13	ASTM S31803 or S32205	X2CrNiMoN 22 5 3	Z3 CND 22-05 Az		
40CrNiMo Steel	ISO 14737 (2003) G35CrNiMo6-6	1.6562*		G43370	BS970 817M40	ASTM E 4340			G4053:2003 Grade SNCM 439	

- Requires *Prenscia Access* licensing

Fatigue Analysis Roadmap

Loading Environment

Geometry

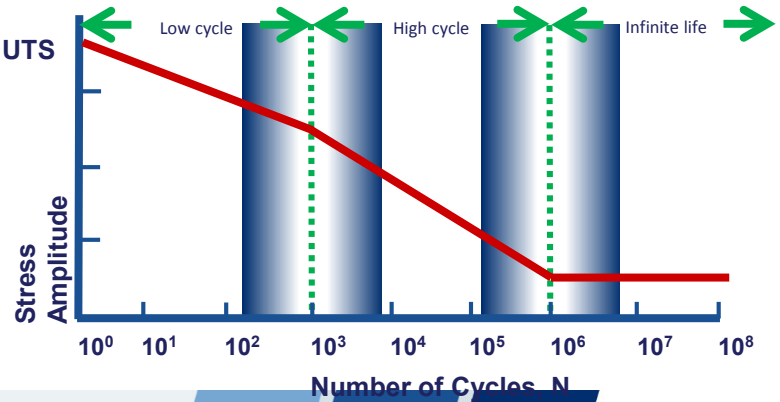
Material Properties

Fatigue Analysis

Fatigue Results

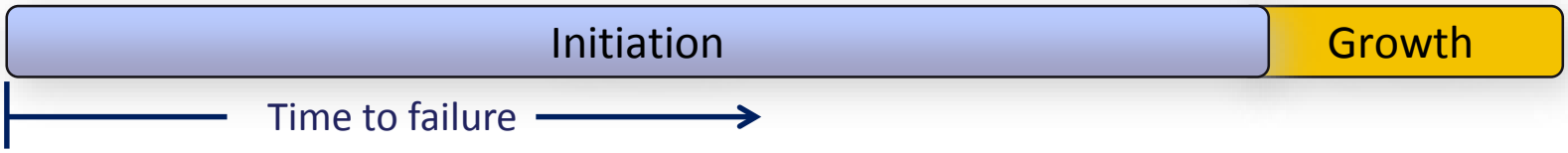
3 Main Approaches

- **Stress-Life** (SN Analysis)
- **Strain-Life** (EN or Crack Initiation)
- **Crack Growth** (LEFM)



Common Philosophies in Different Industries

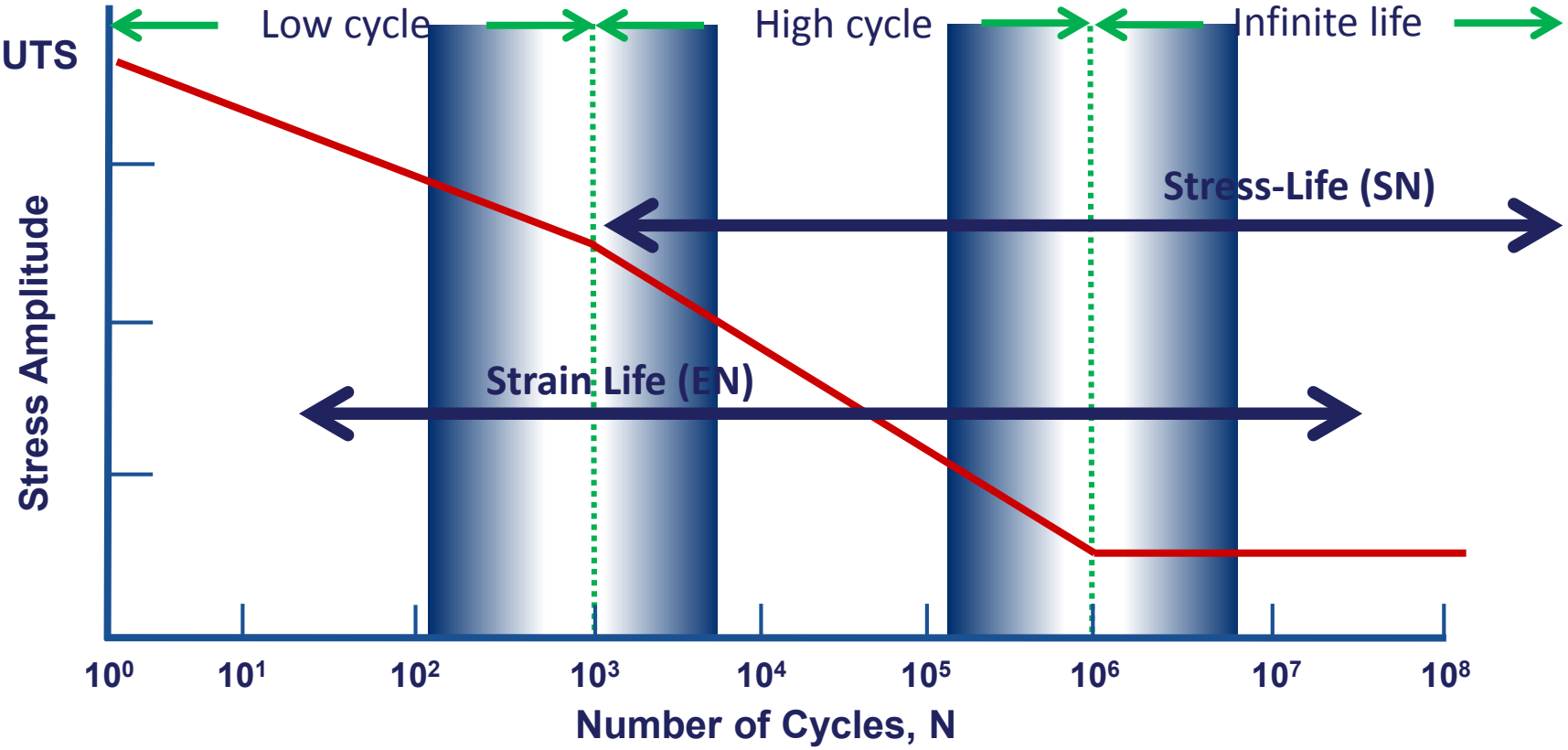
- Ground Vehicles
  - Considerable time is spent initiating a crack
  - Inspections are not economically viable
  - Crack growth, if allowed, can lead to surprises
  - Noticeable cracks are considered failure



- Aerospace
  - Many components use tough, crack tolerant materials
  - Industry conservatively assumes that cracks are present
  - Growth is designed to be slow and predictable
  - Frequent inspections are conducted

Fatigue Regimes

- Some parts are designed to last a long time
- Others are designed for shorter lives due to cost or weight
- The analysis type (EN/SN) depends on the application



Damage Accumulation with Palgrem-Miner's Rule

- Failure is said to occur when the sum of all partial damages equals one

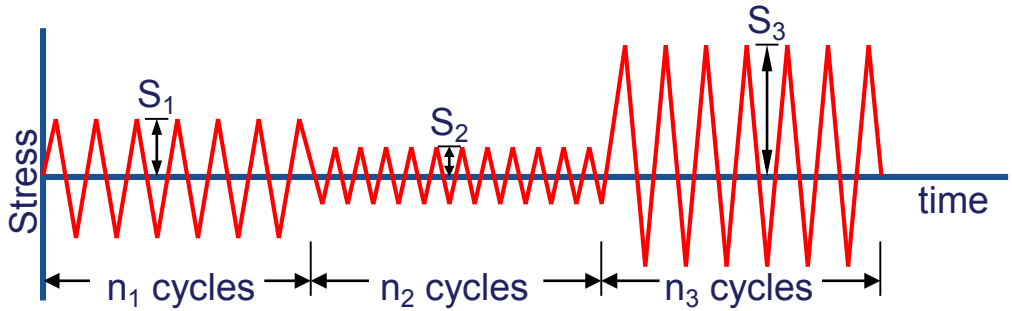
- Expect failure when:

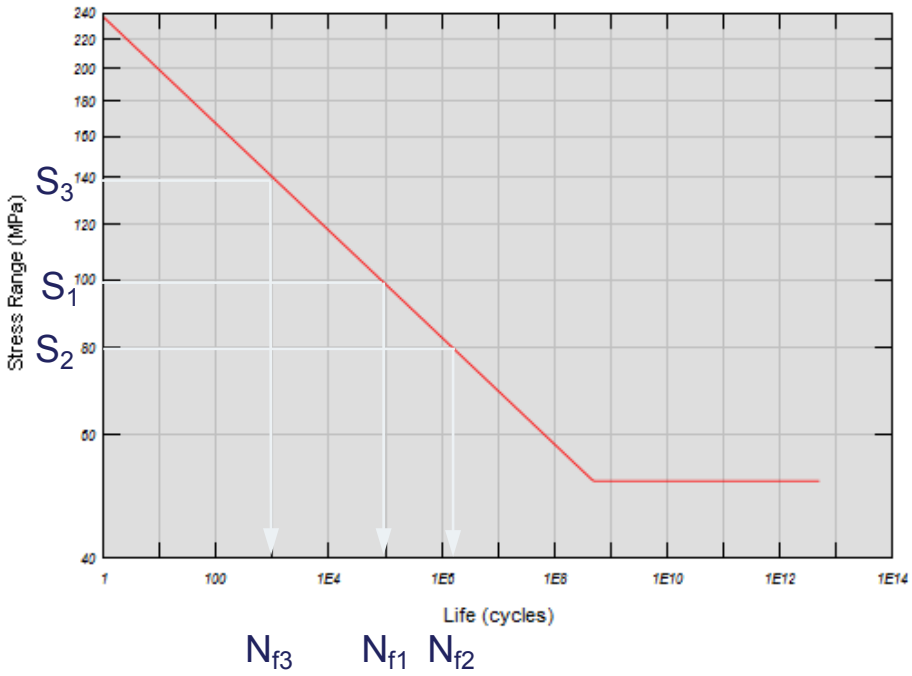
$$\sum_{i=1}^{m} \frac{n_i}{N_i} \geq 1$$

Miner's constant

Partial damage $= \frac{n_i}{N_i}$

$$\frac{n_1}{N_{f1}} + \frac{n_2}{N_{f2}} + \frac{n_3}{N_{f3}} + \cdots = 1$$





Fatigue Analysis Roadmap

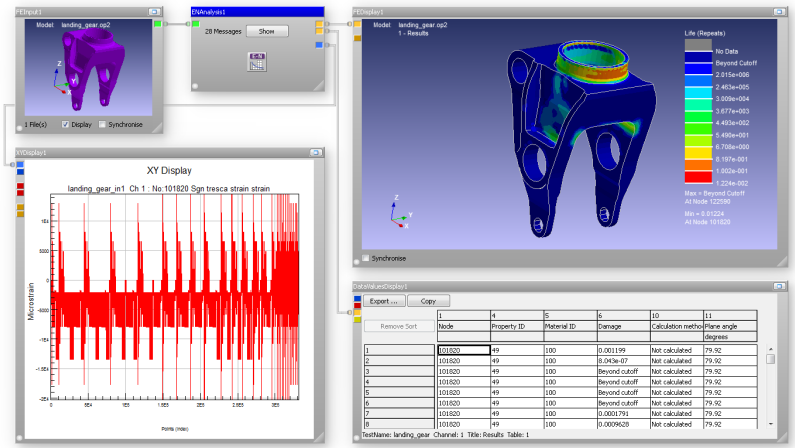
Loading Environment

Geometry

Material Properties

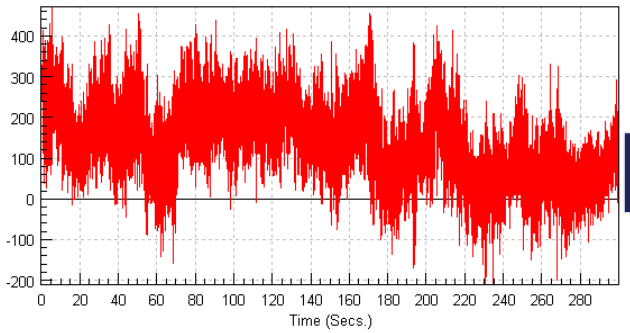
Fatigue Analysis

Fatigue Results

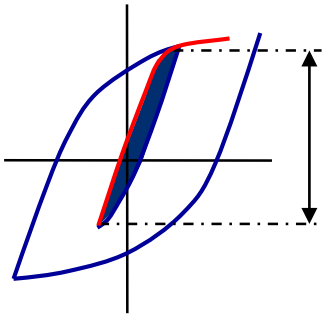


Fatigue Analysis Route – An Overview

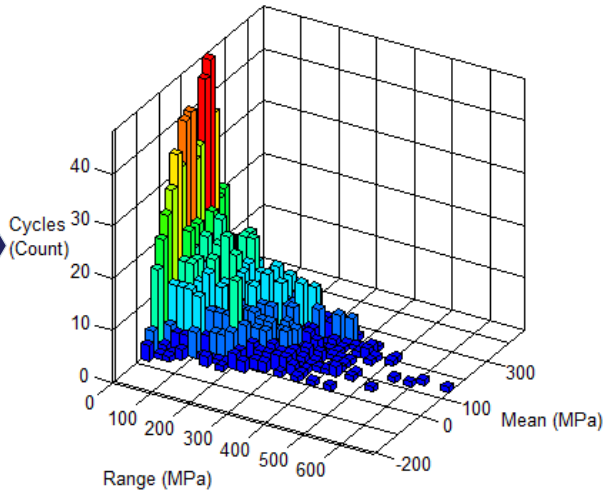
Time Signal



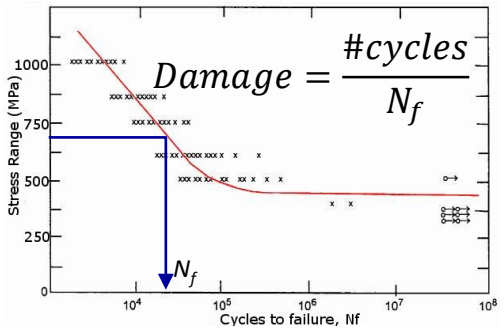
Rainflow Cycle Counting



Rainflow Histogram

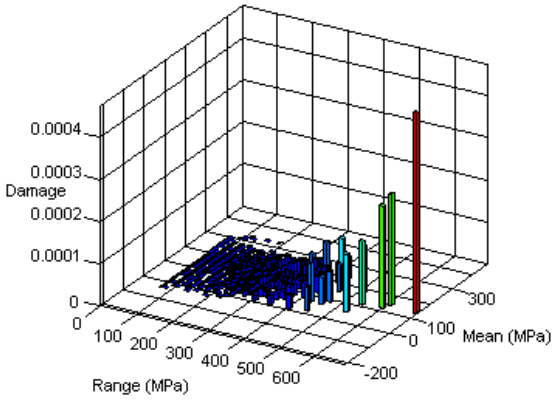


SN Analysis



$$Damage = \frac{\#cycles}{N_f}$$

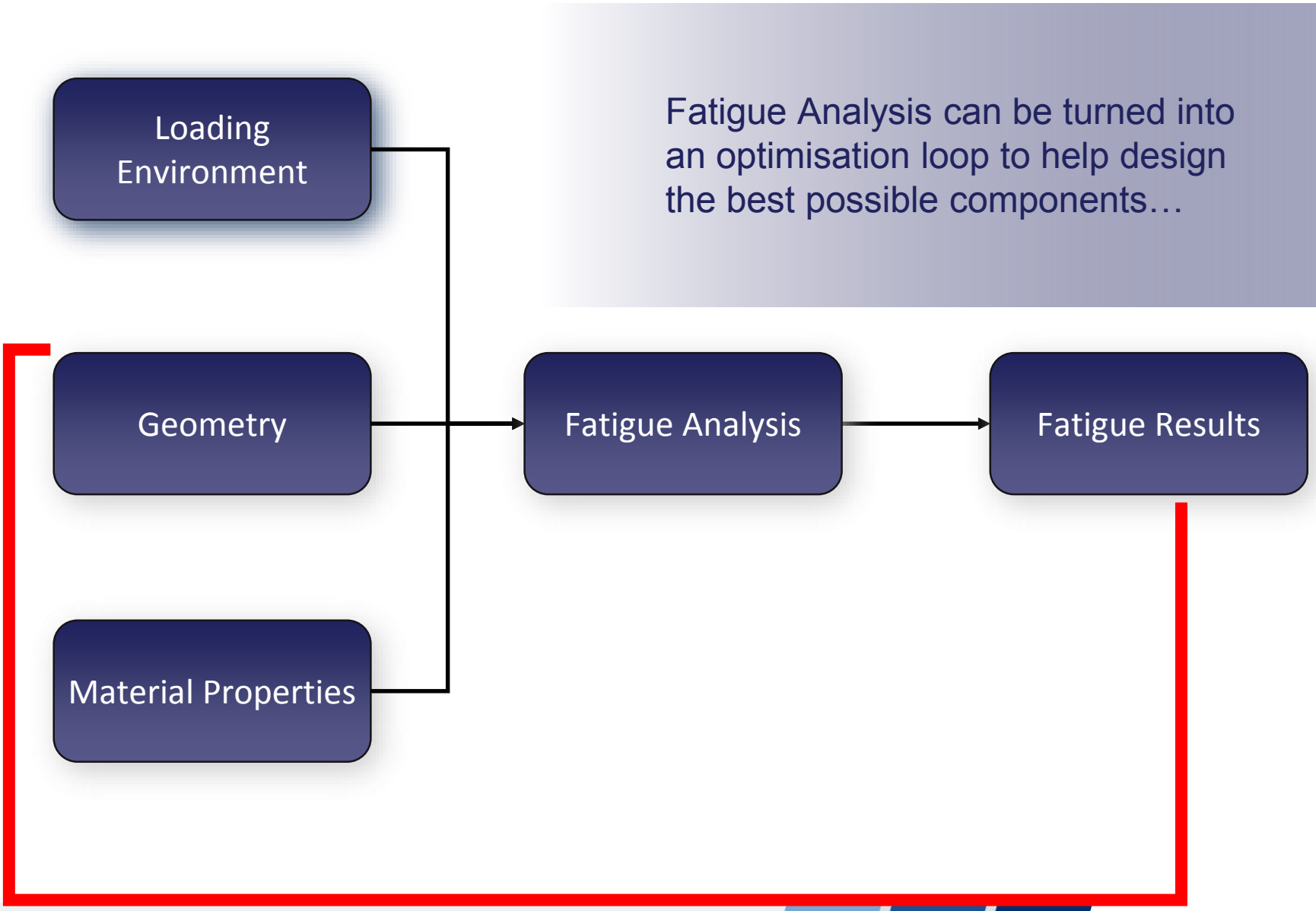
Damage Histogram



Palmgren-Miner's damage summation

$$Life = \frac{1}{\sum Damage}$$

Fatigue Analysis Roadmap

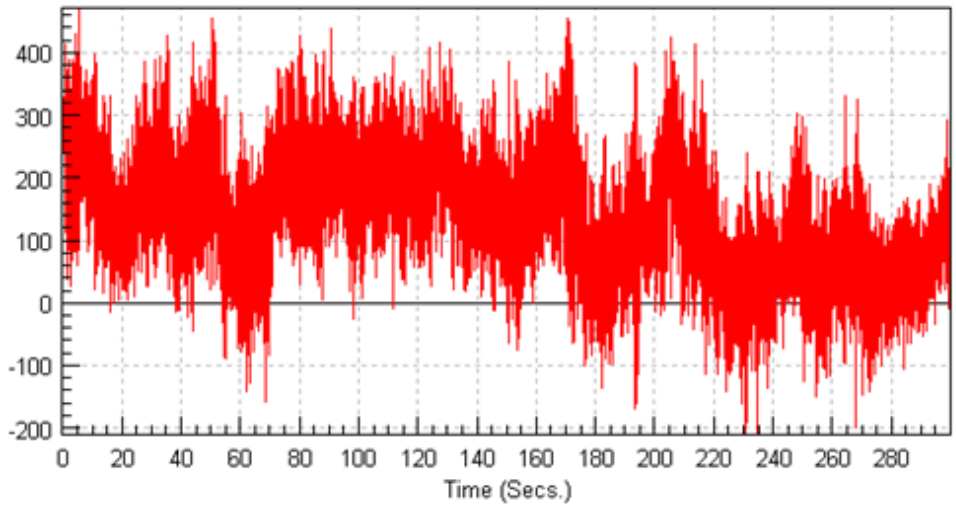


Fatigue from Measured Data

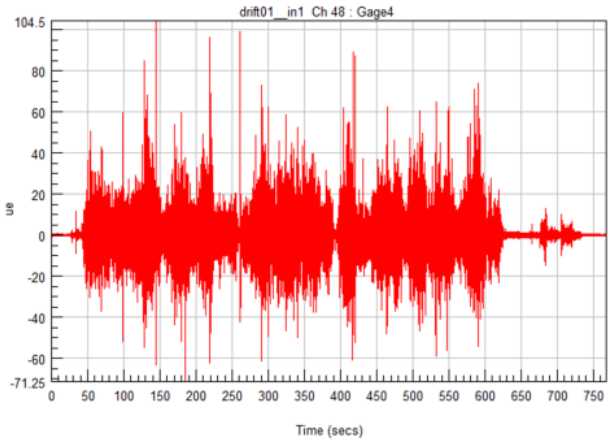
Fatigue from Measured Data

Measurements from a strain gauge can be used directly for fatigue analysis:

- Data needs to be cleaned and anomalies need to be removed
  - Spikes, Drift, Drop-out, Clipping, Flat-line, etc.
- A scale factor (Kt) may also be applied to compensate for strain gauge location near hot-spots
- Lots of additional factors need to be considered:
  - Material, Temperature, Mean Stress Correction



Fatigue Analysis Roadmap



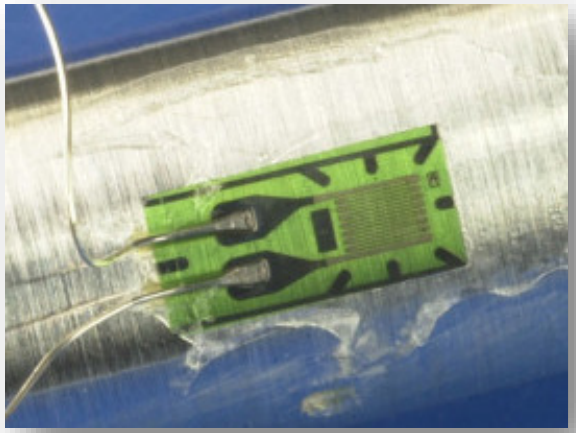
Measured Strain Data

Geometry

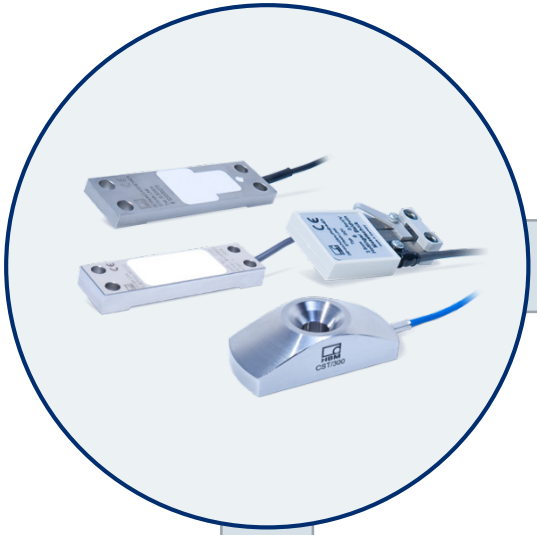
Material Properties

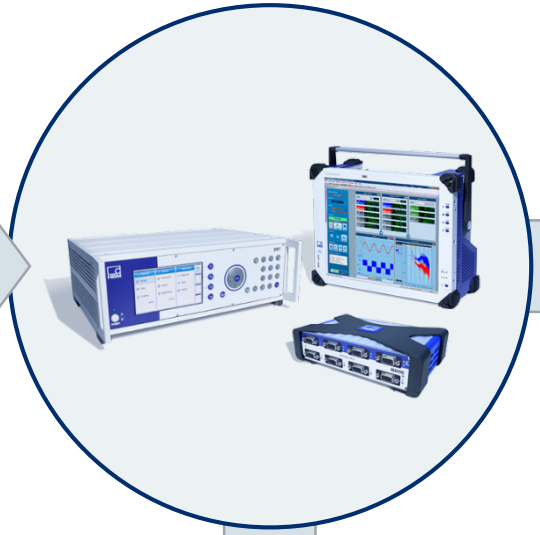
Fatigue Analysis

Fatigue Results



Measuring Test Data



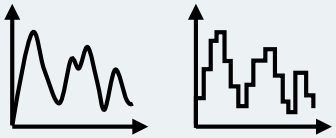


Sensor

Measurement of a physical phenomenon

DAQ Device

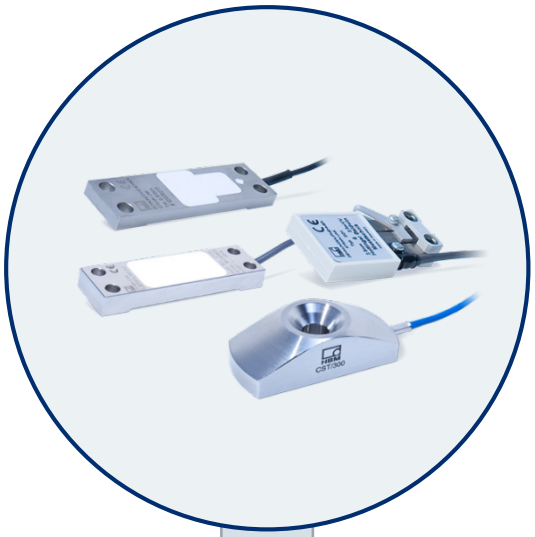
Conditioning and digitization of analogue signals



Computer

Software for storing, processing, analysing and visualizing data

Sensors



Sensor

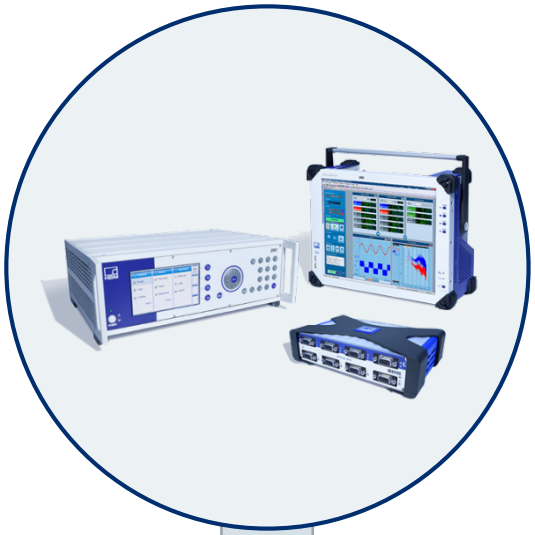
Measurement of a physical phenomenon

Choosing the correct sensor…

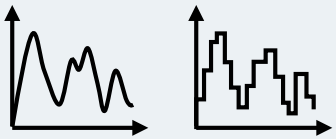
- What phenomenon is being measured?
- What range of values are expected?
- How sensitive does the sensor need to be?
- What environment will the sensor be exposed to?
- Where/how can the sensor be mounted?
- What are the electrical properties of the sensor?

Sensor	Units
Accelerometer	g
Strain Gauges	µe
Force Transducer	N
Temperature	K
Rotational Velocity	rpm
Sound	dB

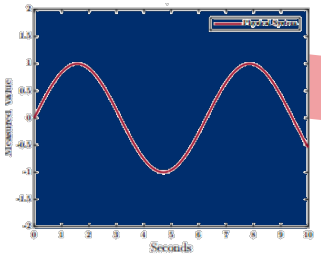
DAQ Device

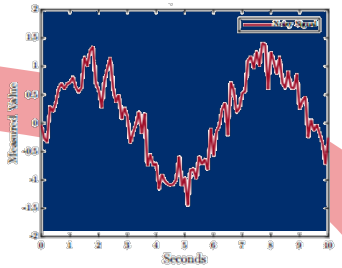


Conditioning and digitization of analogue signals

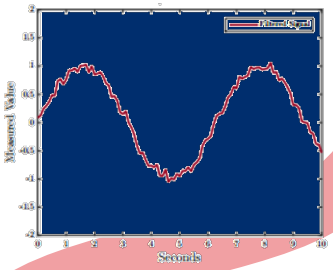


Physical Property



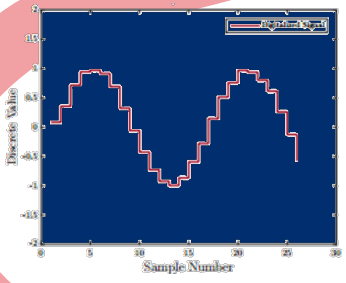


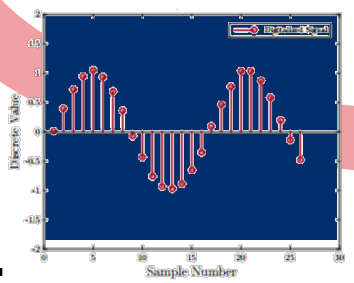
Noisy Electrical Signal



Conditioned Signal

Analogue-to-Digital Converter (ADC)

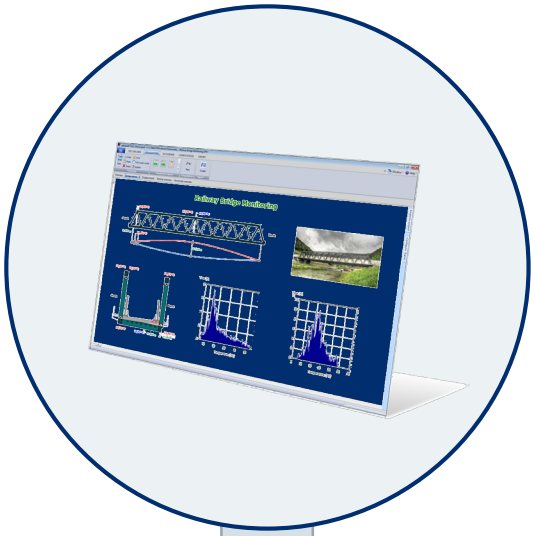




Binary Data

0	1	1	1
0	0	0	1
0	1	1	1
1	0	1	1
1	1	0	0
1	1	1	1
0	1	1	0
1	0	1	0
1	1	1	0
1	1	1	1
0	1	1	1

Computer

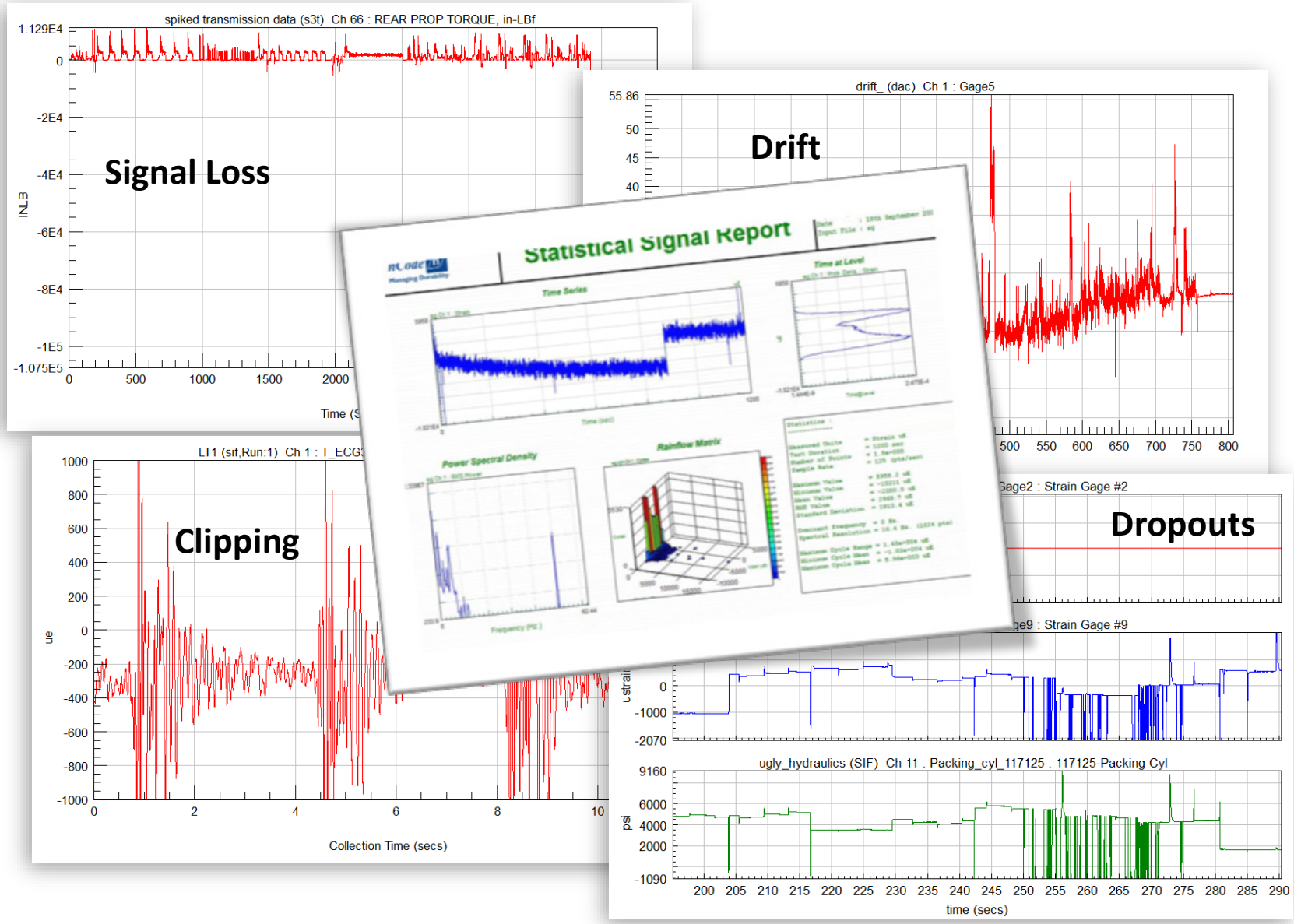


Software for storing, processing, analysing and visualising data

Raw data cannot achieve anything by itself…

Processing & Analysing	Computers can carry out automatic processes and operations on data, such as classification and organisation. Analysis of the collected data should reveal useful information in order to support decision-making.
Visualising	Data can be plotted and viewed in a variety of ways in order to gain new insights and support decisions.
Storage	It should be possible to efficiently search and retrieve archived data quickly and efficiently.

Measured Data Anomalies



55

GlyphWorks Demonstration

GlyphWorks has many tools for automatically identifying anomalies and removing them from measured test data…

1 - Input Glyph

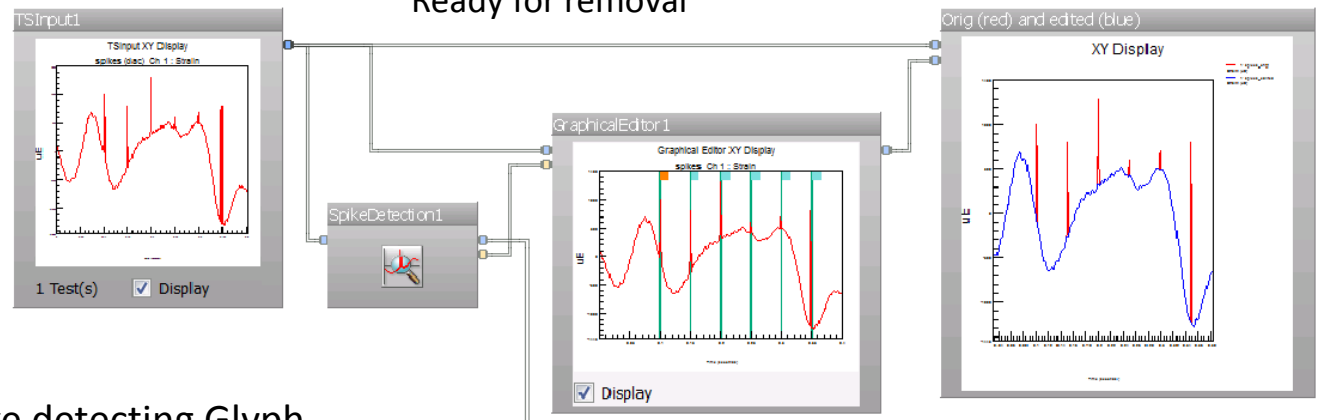
data with spikes

3 – Graphical Editor Glyph

Original data with spike location
Ready for removal

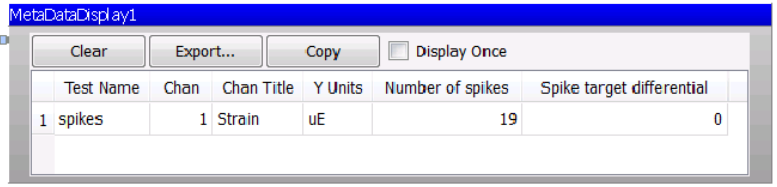
4 – Display Glyph

Original and ‘clean’ overlaid



2 – Spike detecting Glyph

Glyph uses a number of methods to detect spikes and identifies that start and end times



4 – Summary table of spike detection results

See GlyphWorks Worked Example #6

Fatigue Analysis Roadmap

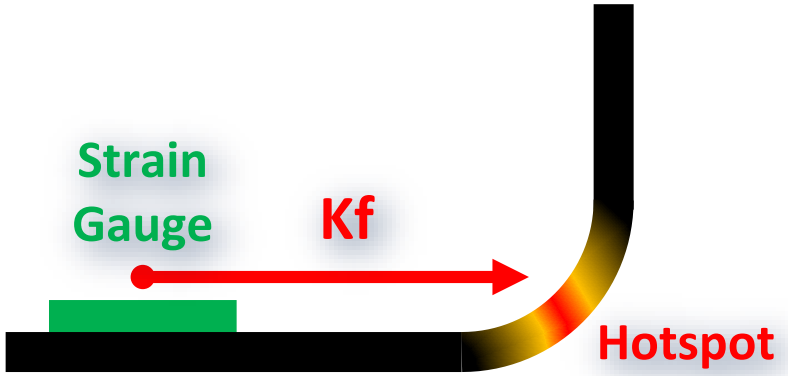
Loading Environment

Scale Factor (Kf)

Material Properties

Fatigue Analysis

Fatigue Results



Fatigue Analysis Roadmap

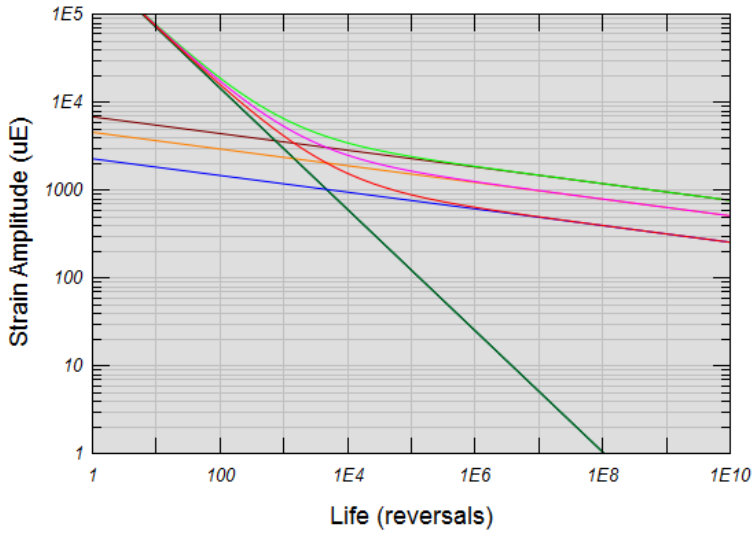
Loading Environment

Geometry

nCode Material Database

Fatigue Analysis

Fatigue Results



Fatigue Analysis Roadmap

Many different analysis properties…

- Mean stress correction
- Surface finish / treatment
- Certainty of survival

etc. …

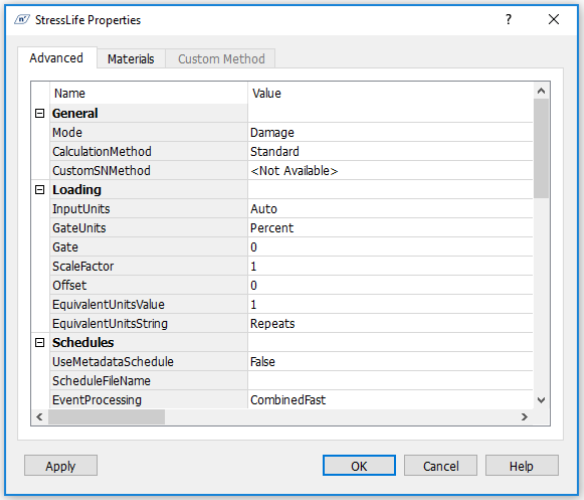
Loading Environment

Geometry

Material Properties

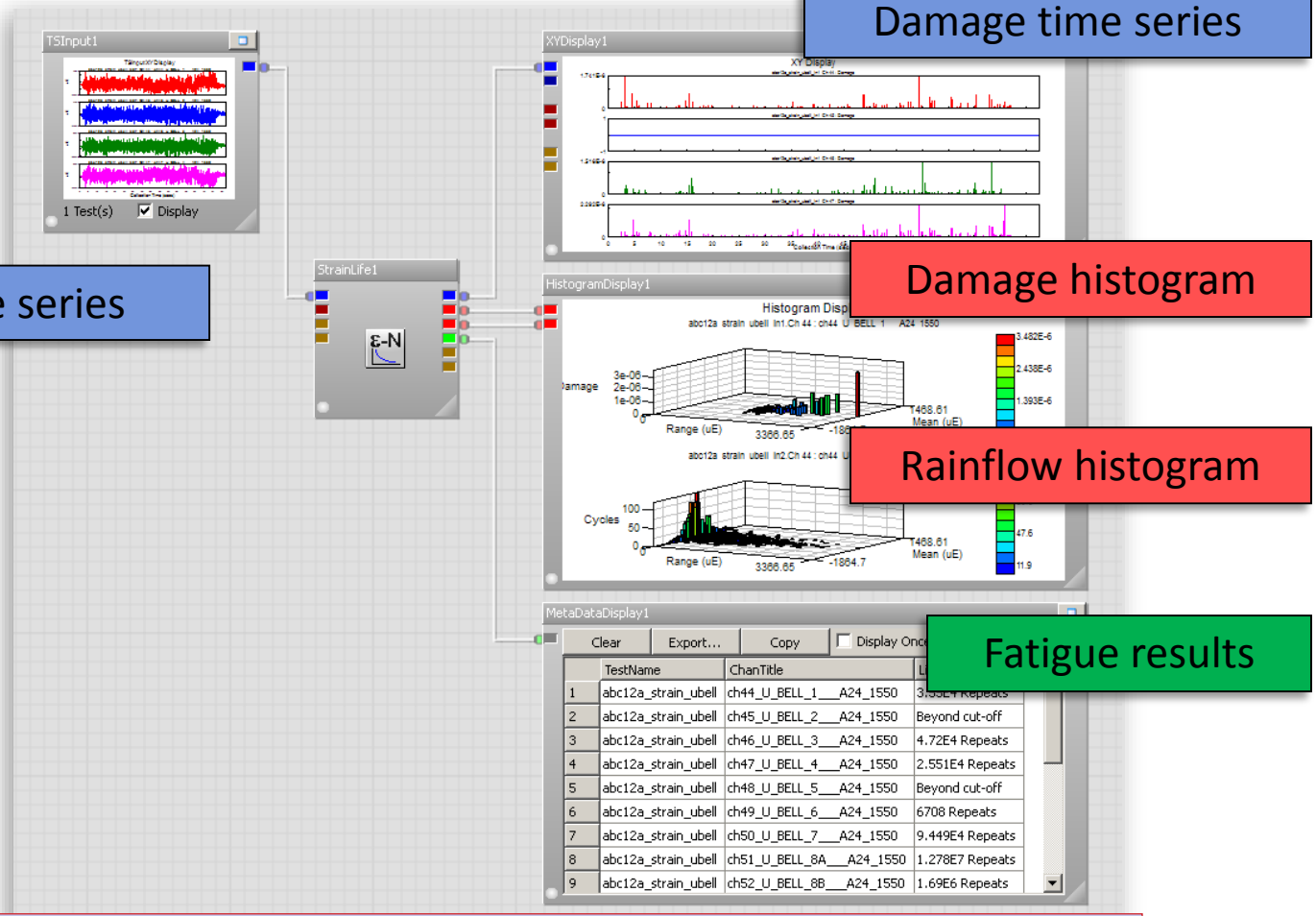
Fatigue Analysis Properties

Fatigue Results



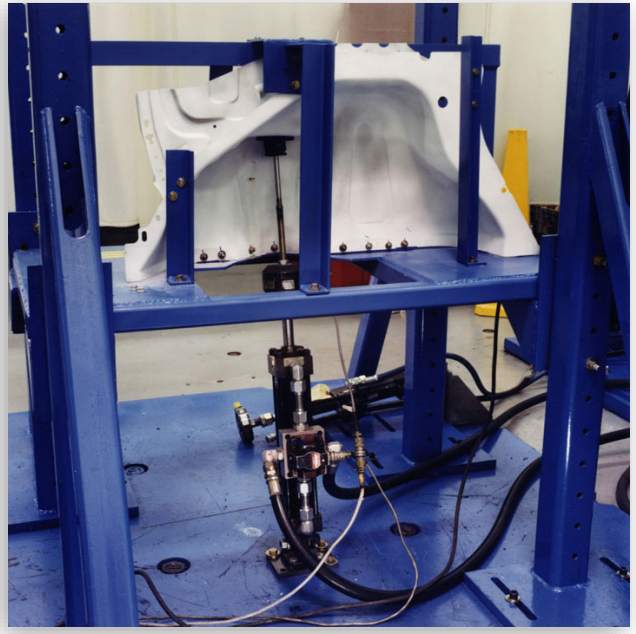
GlyphWorks Demonstration

GlyphWorks makes fatigue analysis from measured strain data simple



See GlyphWorks Worked Example #7

Accelerating Durability Tests



Is This Your Durability Test?

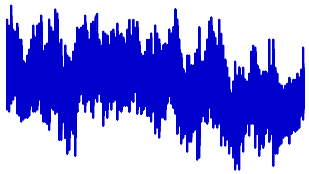
- A black box…
- We don’t have a test
- We have a test specification but no-one knows how/why it was derived
- We have used our test specification for >30 years and if it passes we never have any failures
- We use the test specification our customer tells us to use
- 1000 miles of pavé, 1000 miles of pot holes and 5000 miles of a high speed circuit
- 4 hours on the shaker with a specific random PSD

Customer Usage and the Duty Cycle

Duty Cycle

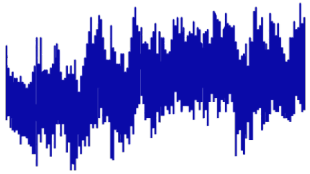
- Set of loading events representative of the real usage environment
- Also known as mission profile, durability schedule or composite
- Critical to understanding durability

Duty Cycle



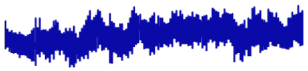
Belgian block
x 1000 repeats

+



Cross country
x 2000 repeats

+

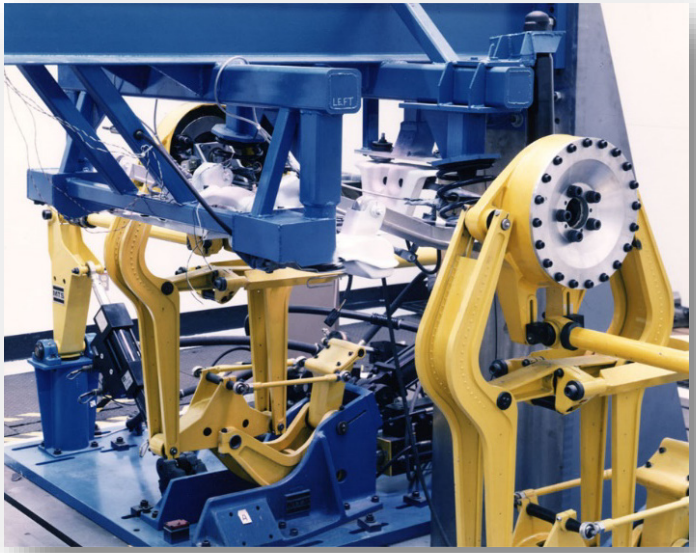


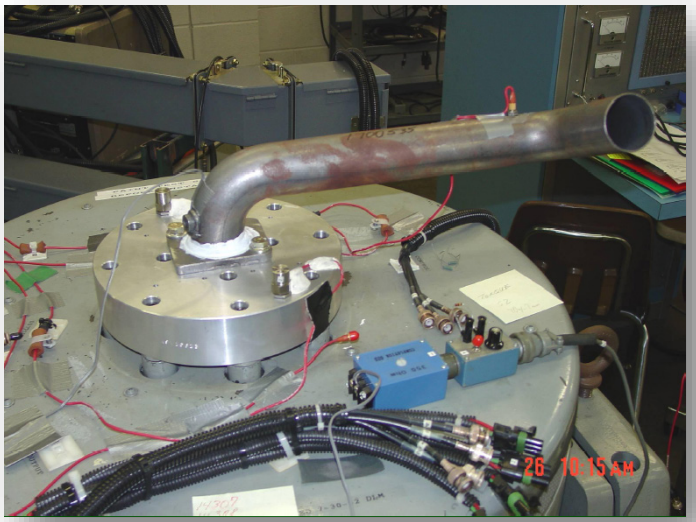
Engine vibration
x 10,000 hrs

etc. …

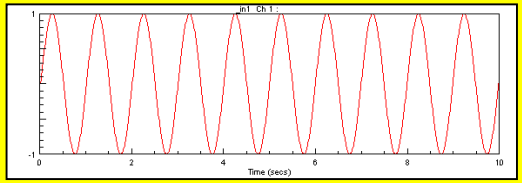
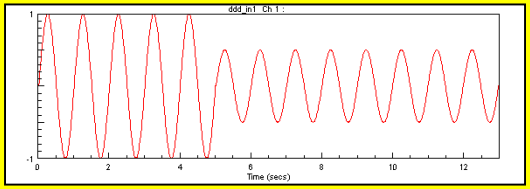
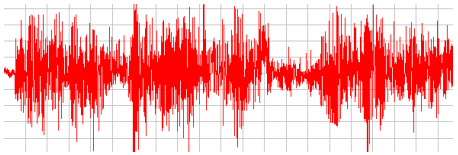
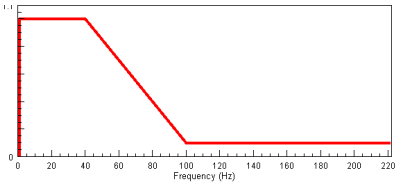
Constraints on a Durability Test

- Test must be suitable for:
  - component
  - sub-assembly
  - whole vehicle
- Test must replicate real failure mechanisms
- Test should be representative of real loading environment
- Test should be accelerated to reduce duration
- Different parts are tested in different ways
  - time domain
  - frequency domain





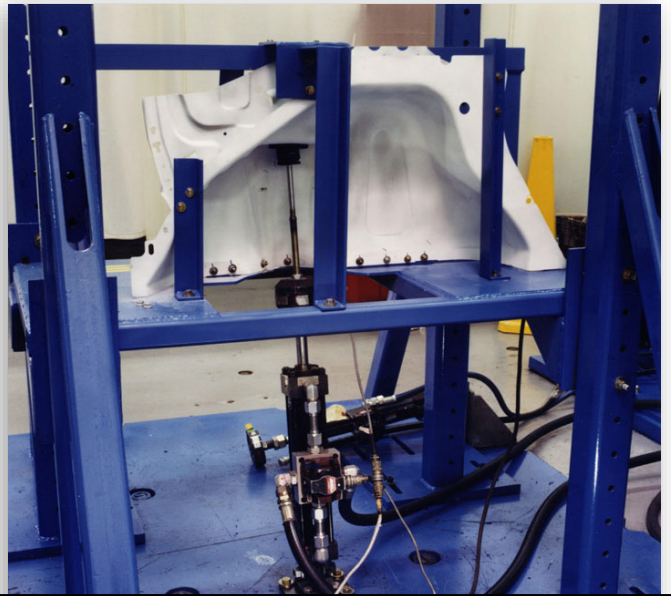
Ways to Accelerate a Durability Test

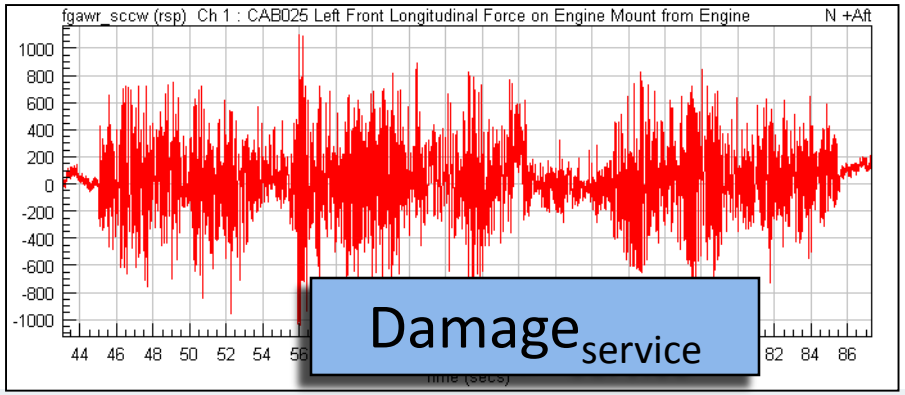
Test Rig Input		nCode Software
Constant amplitude		GlyphWorks
Block cycle		GlyphWorks
Time domain (RPC)		GlyphWorks Fatigue Edit
Frequency domain (PSD)		GlyphWorks Accelerated Testing

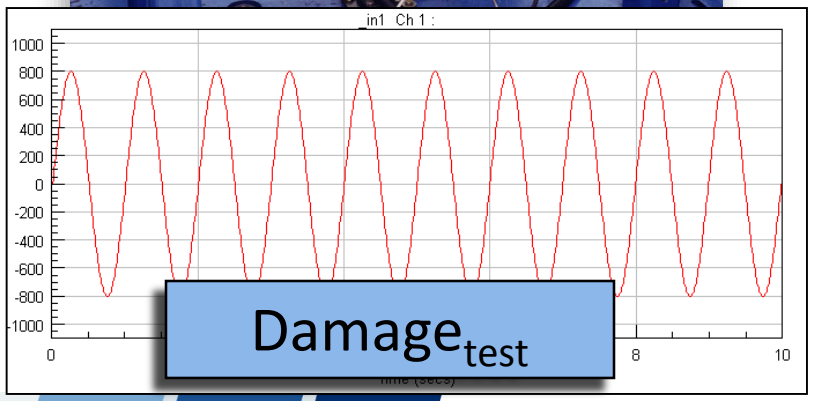
Constant Amplitude and Block Cycle Tests

Cyclic component tests….

- Are simple, quick, inexpensive and used everywhere
- Requires **damage correlation**

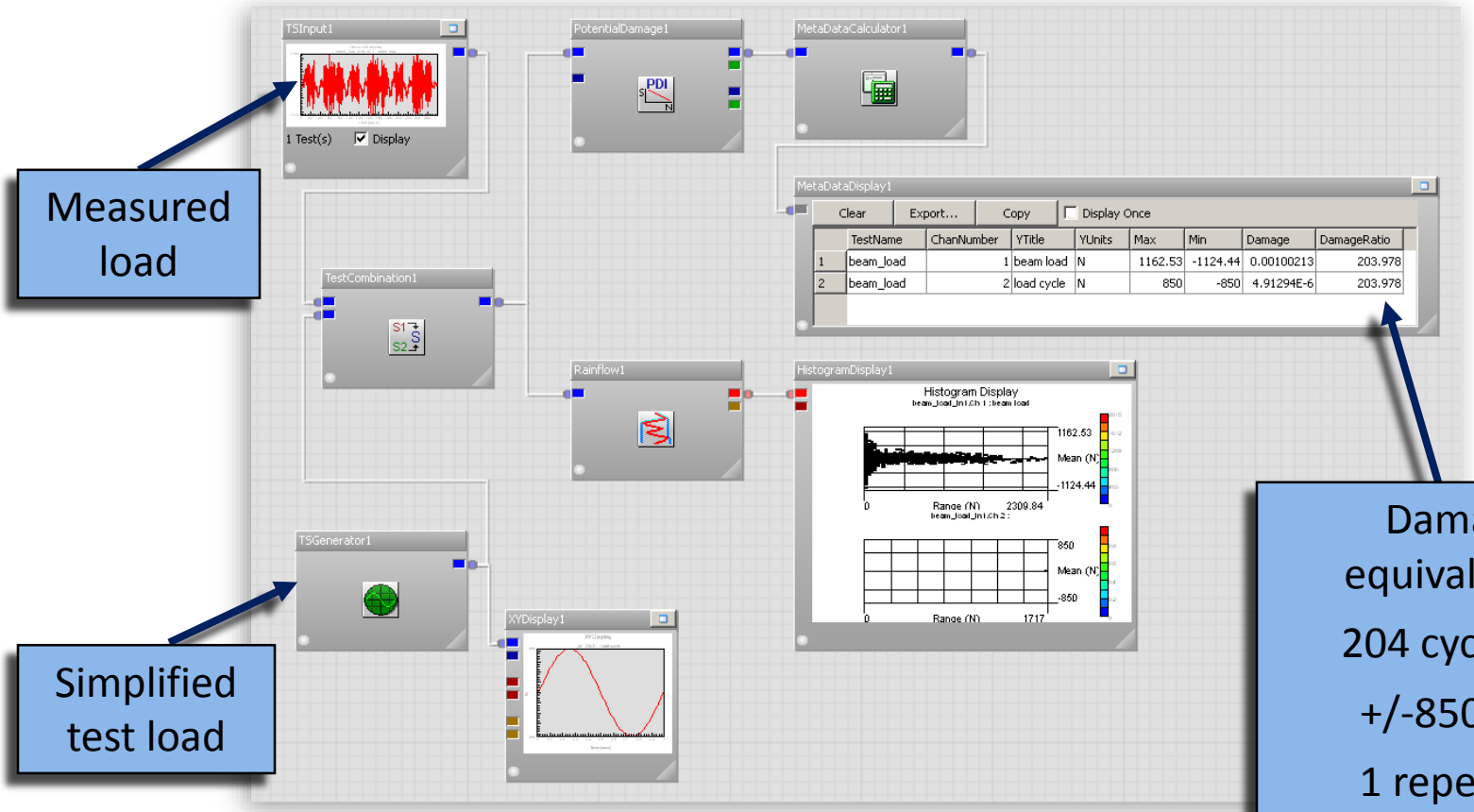






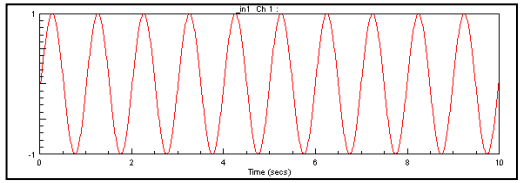
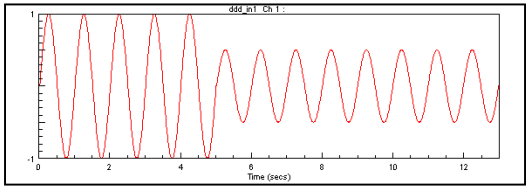
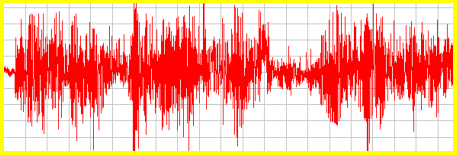
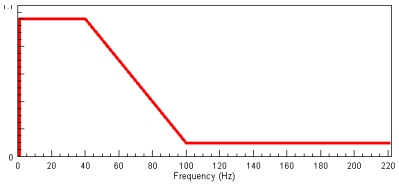
GlyphWorks Demonstration

GlyphWorks makes **Potential Damage Correlation** a simple process...



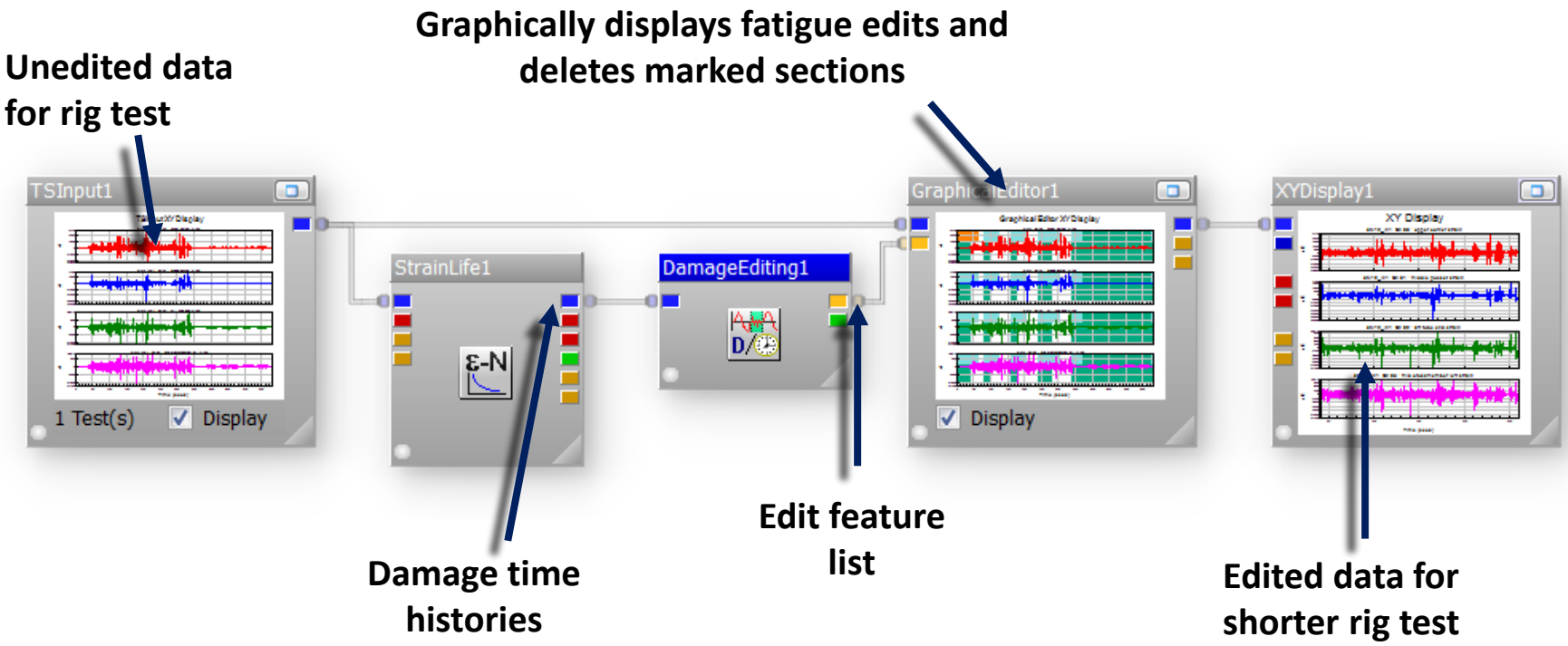
See GlyphWorks Worked Example #21

Ways to Accelerate a Durability Test

Test Rig Input	nCode Software
Constant amplitude 	GlyphWorks
Block cycle 	GlyphWorks
Time domain (RPC) 	GlyphWorks Fatigue Edit
Frequency domain (PSD) 	GlyphWorks Accelerated Testing

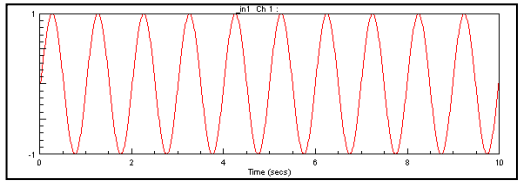
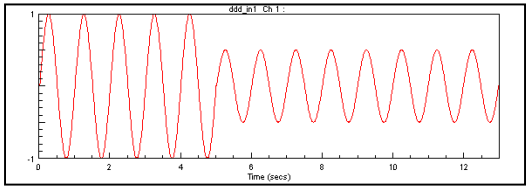
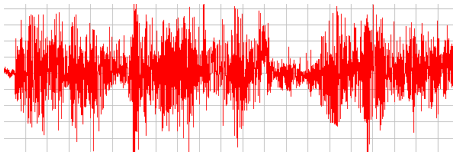
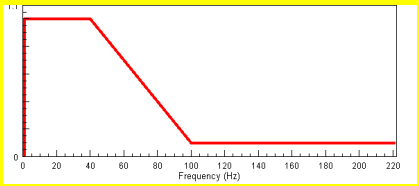
GlyphWorks Demonstration

GlyphWorks' **Damage Editing** glyph identifies non-damaging sections of time that can be removed for time-domain accelerated test profiles



See GlyphWorks Worked Example #7

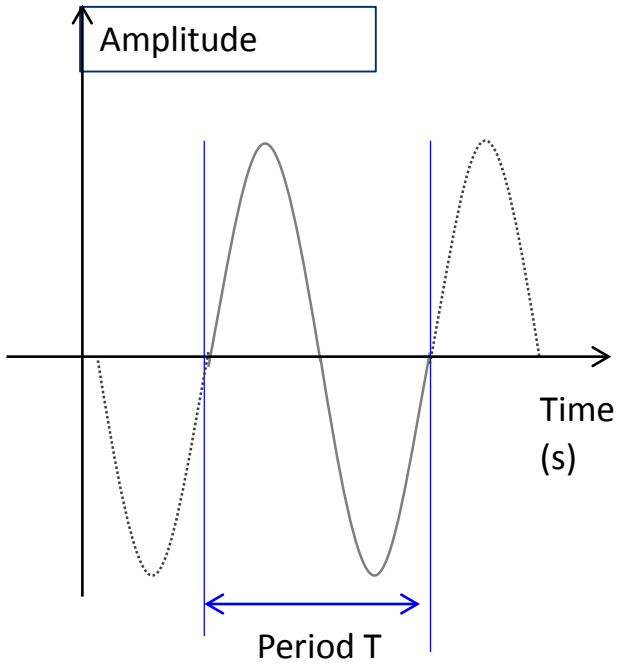
Ways to Accelerate a Durability Test

Test Rig Input		nCode Software
Constant amplitude		GlyphWorks
Block cycle		GlyphWorks
Time domain (RPC)		GlyphWorks Fatigue Edit
Frequency domain (PSD)		GlyphWorks Accelerated Testing

Why working in the frequency domain?

We are surrounded by periodic phenomena:

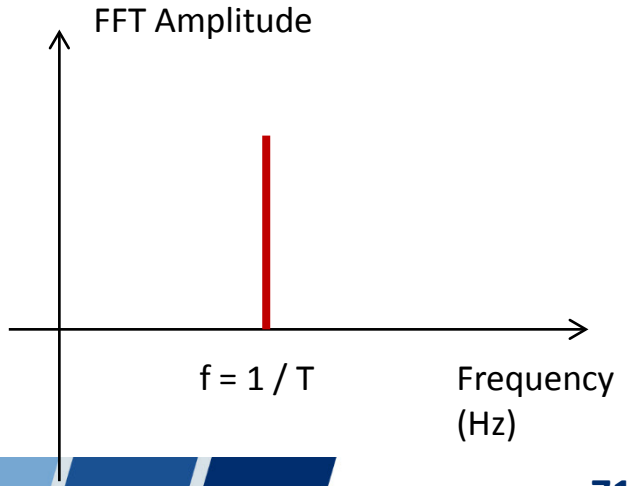
- Movement of planets
- Music/ rhythm,
- Alternating current,
- Our sleeping cycles
- Seasons
- etc. …



Vibration is defined as:

the oscillating motion of a rigid or elastic body or medium forced from a position or state of equilibrium.

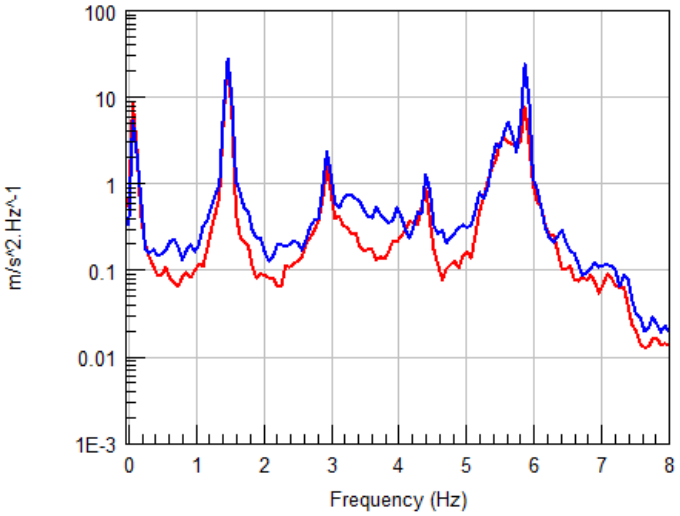
If a phenomenon is periodic, one is interested in the frequency of its occurrence.



Accelerated Testing in the Frequency Domain

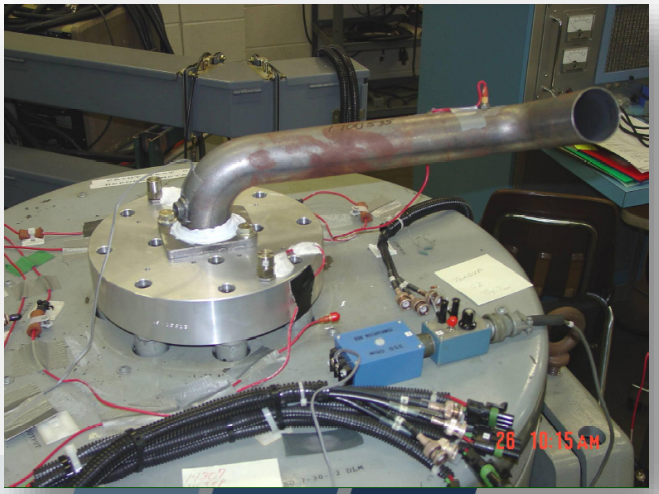
Some components and durability tests are best analysed using the *Frequency Domain* to quantify the vibration experienced:

- Random vibration
- Engine-mounted
- Vehicle-mounted
- Electrical components
- Wind & Wave loading



These are often tested using an Electrodynamic Shaker Table:

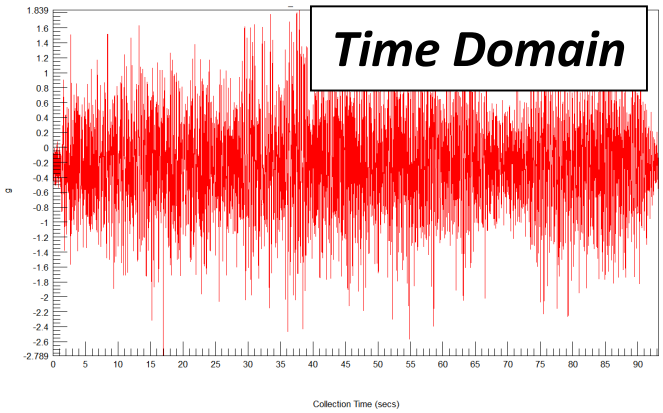
- PSD
- Swept Sine
- Sine-on-Random



What is the Fourier Transform?

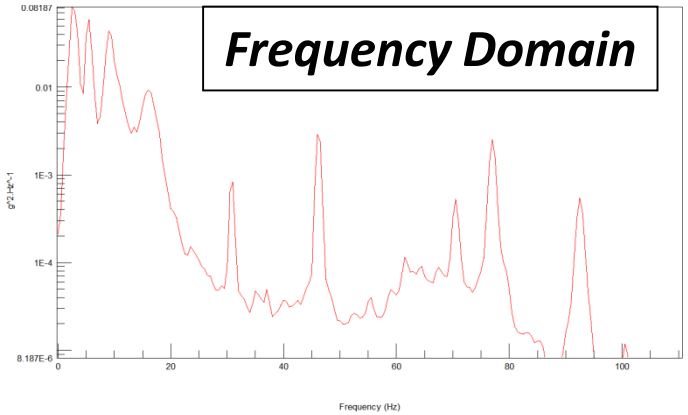
The Fourier transform is a way of converting from time domain to frequency domain

VibeSys uses the Fast Fourier Transform (FFT) to algorithm to compute the Discrete Fourier Transform (DFT)



Fourier Transform

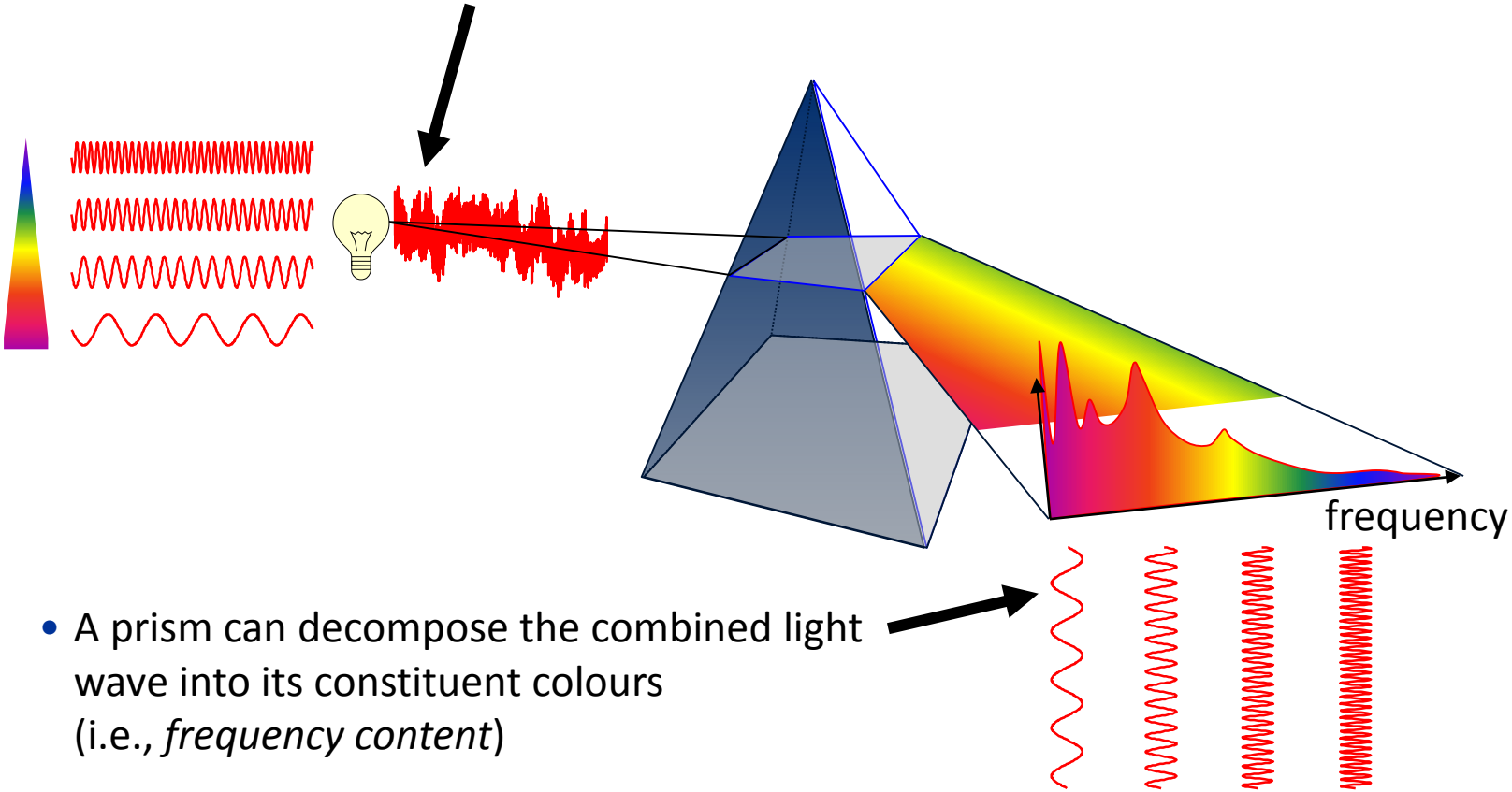
Inverse Fourier Transform



Introduction to the Frequency Domain

Nature's Frequency Analysis

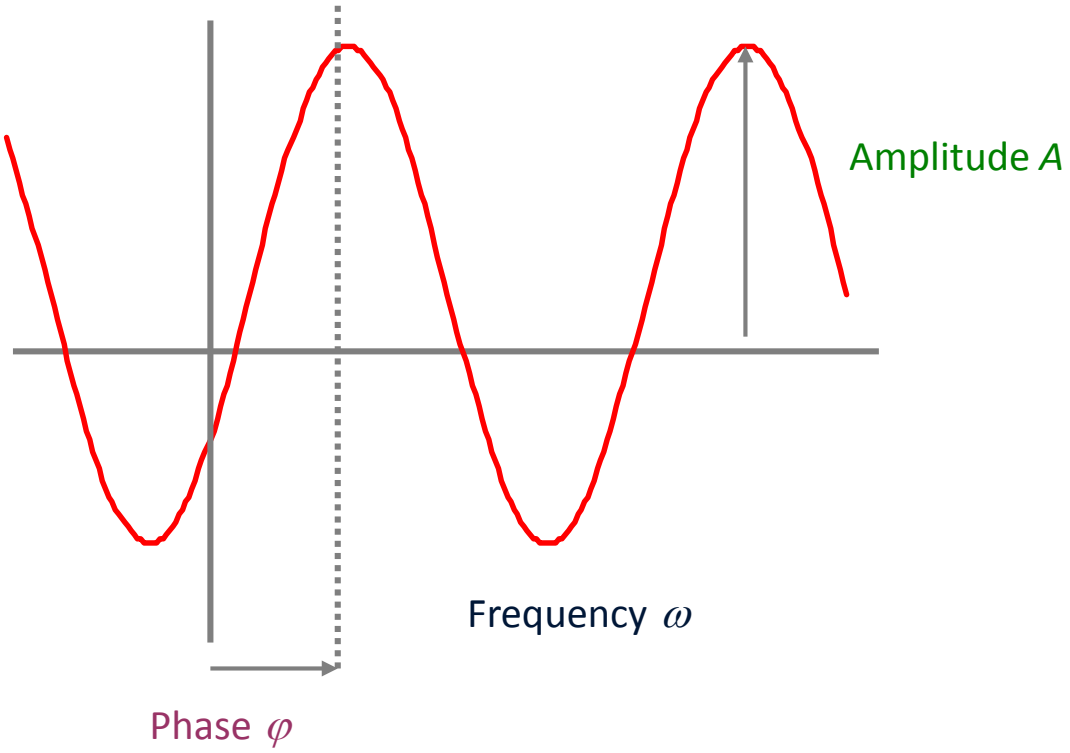
- Light source consisting of a number of colours.
- Each colour has its own frequency (*or wavelength*).
- Individual colours added together to produce the light wave.



- A prism can decompose the combined light wave into its constituent colours (i.e., *frequency content*)

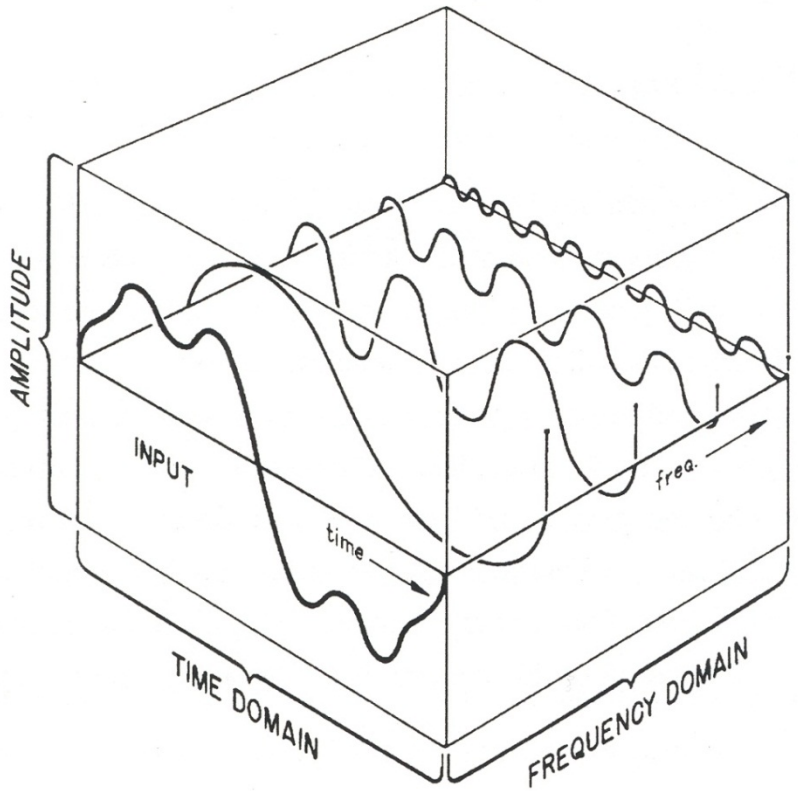
The Fourier Transform and the Frequency Domain

- The Fourier transform decomposes a signal into individual sinusoidal waves
- Each sinusoidal wave is described by 3 properties:
  - Amplitude
  - Frequency
  - Phase

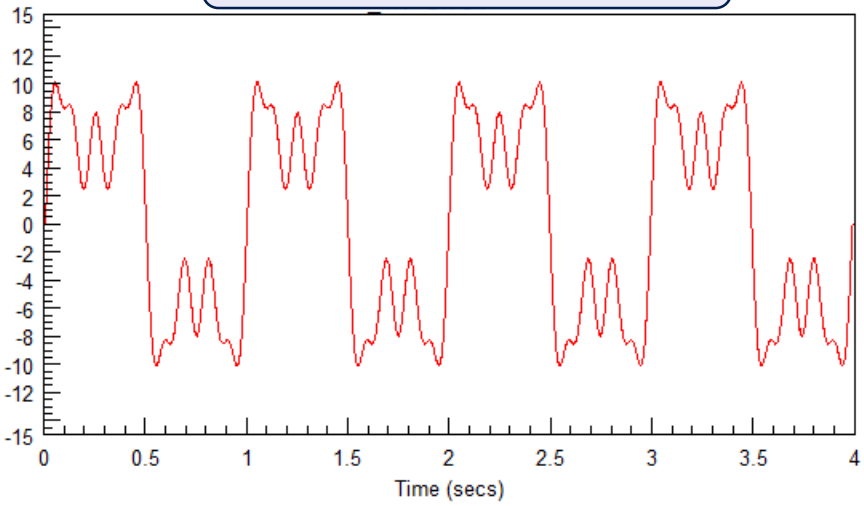


Fourier Transform

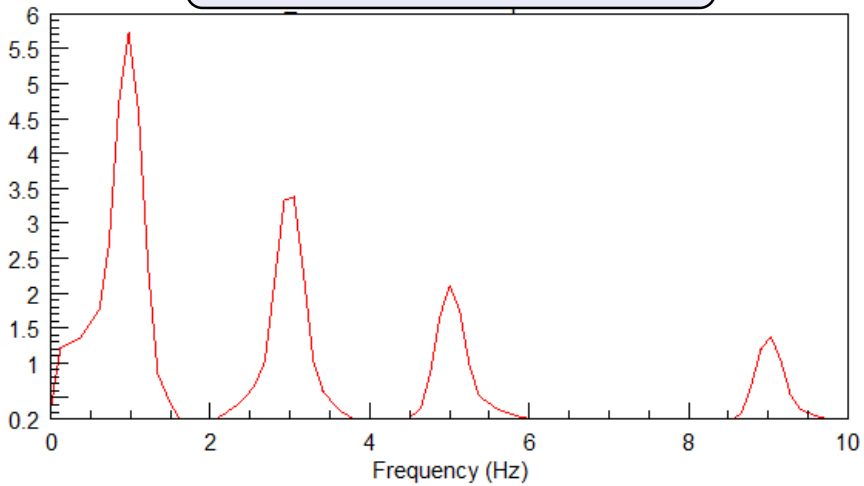
$$X(t) = \sum_k a_k \left[\cos(k\omega t) + i\sin(k\omega t)\right] = \sum_k a_k e^{ik\omega t}$$



Time Domain



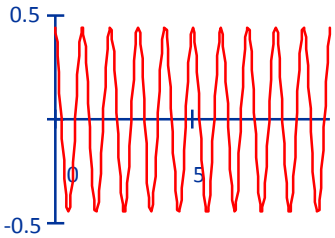
Frequency Domain



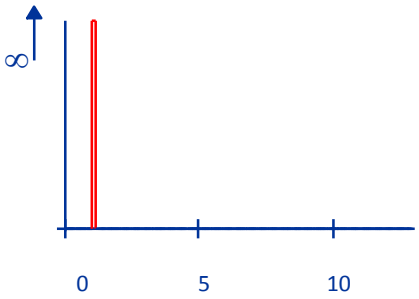
Power Spectral Density (PSD)

Sine wave

Time history

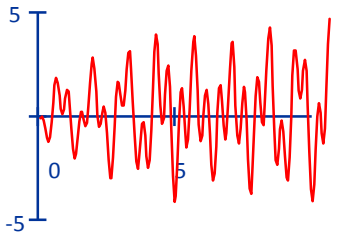


PSD

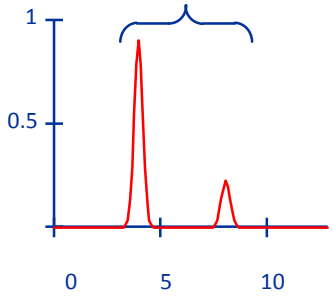


Broad band process

Time history

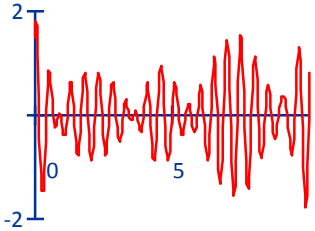


PSD

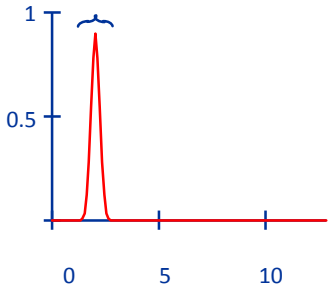


Narrow band process

Time history

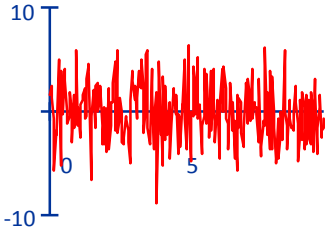


PSD

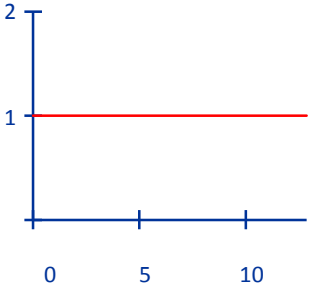


White noise process

Time history

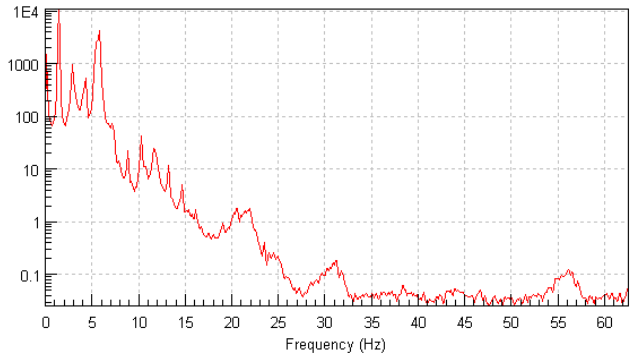


PSD



Fatigue Analysis from PSD

PSD

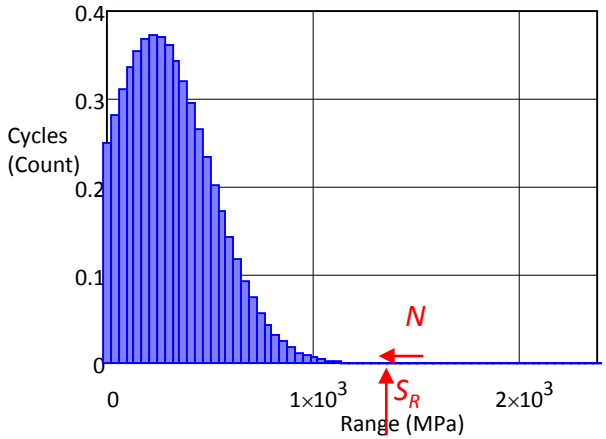


Rainflow Cycle Counting

Number of cycles
- Rice

Cycle ranges
- Bendat/Rice
- Steinberg
- Dirlik
- Lalanne/Rice

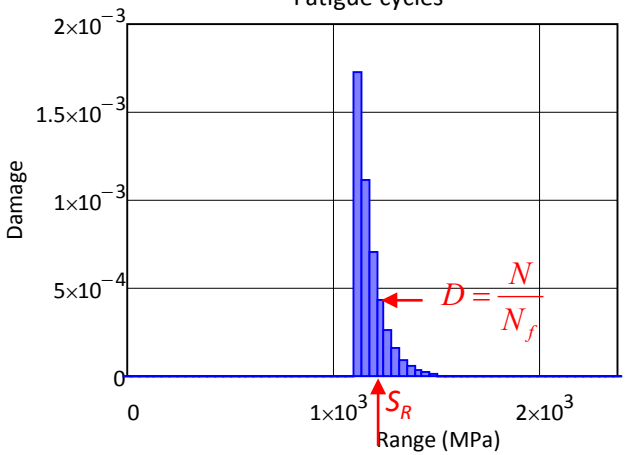
Rainflow Histogram

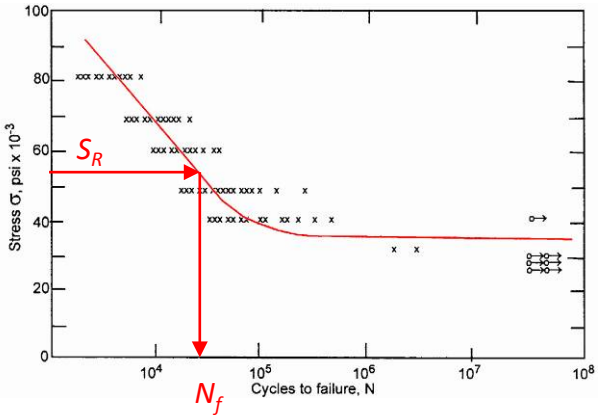


LIFE

Palmgren-Miner's damage summation

Fatigue cycles





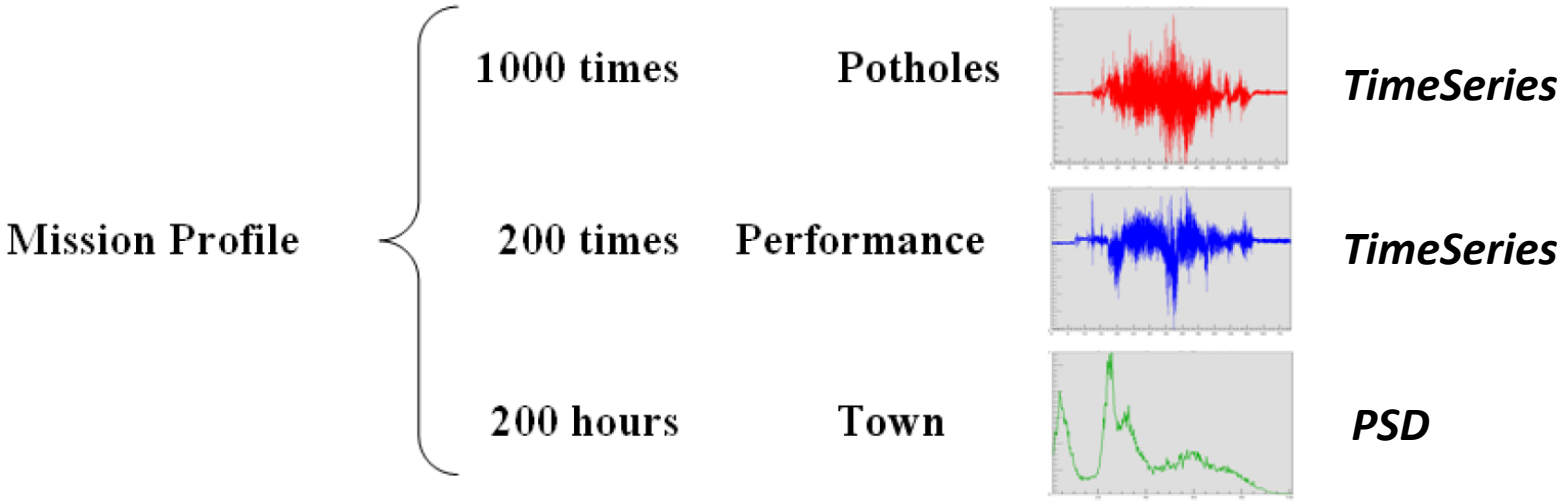
Damage Histogram

SN Analysis

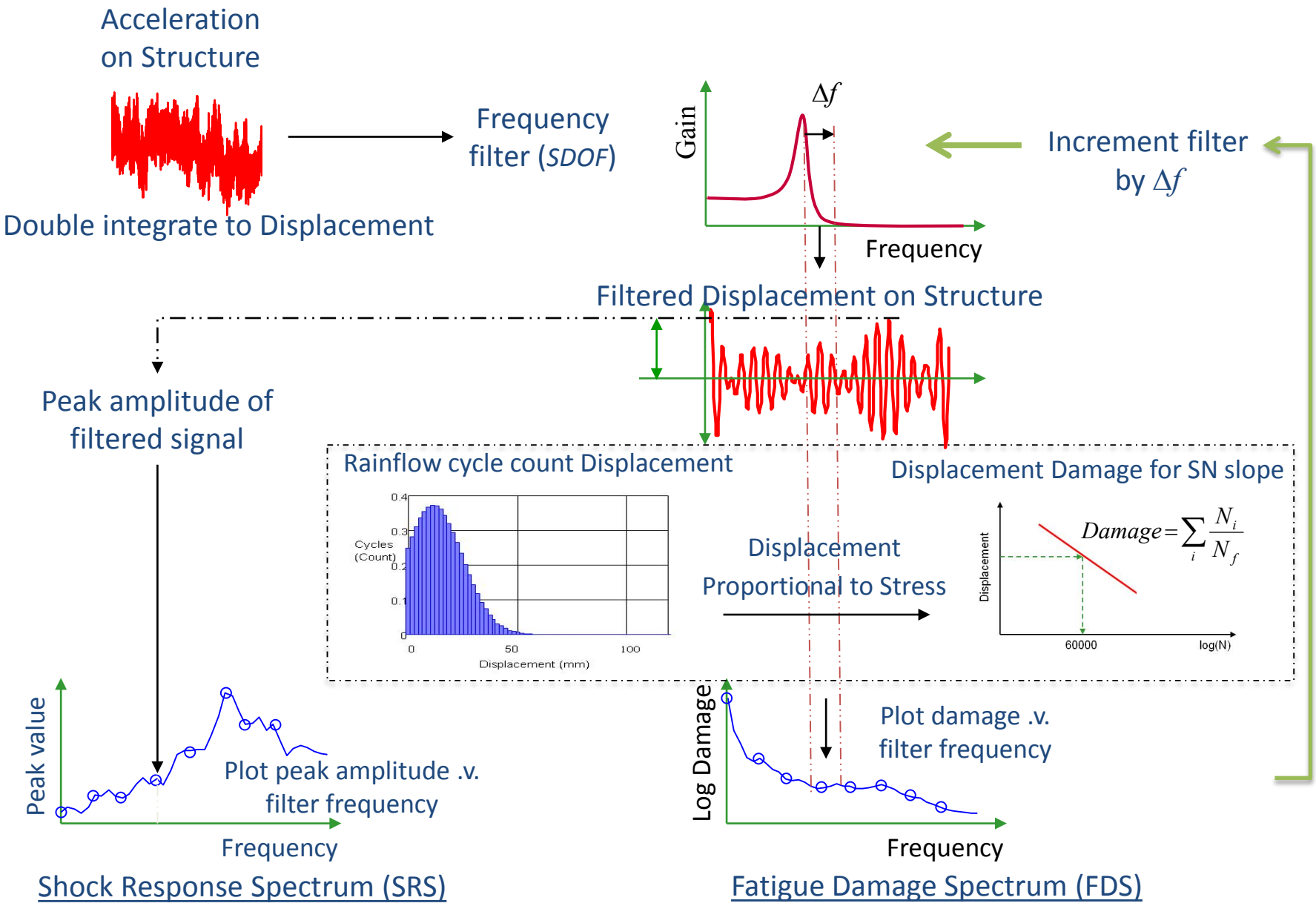
Accelerated Testing

The GlyphWorks Accelerated Testing module allows you to generate a mission profile for your ED shaker table.

- Multiple profiles can be combined
- PSDs and TimeSeries data can be used
- Number of repeats (or duration) can be specified

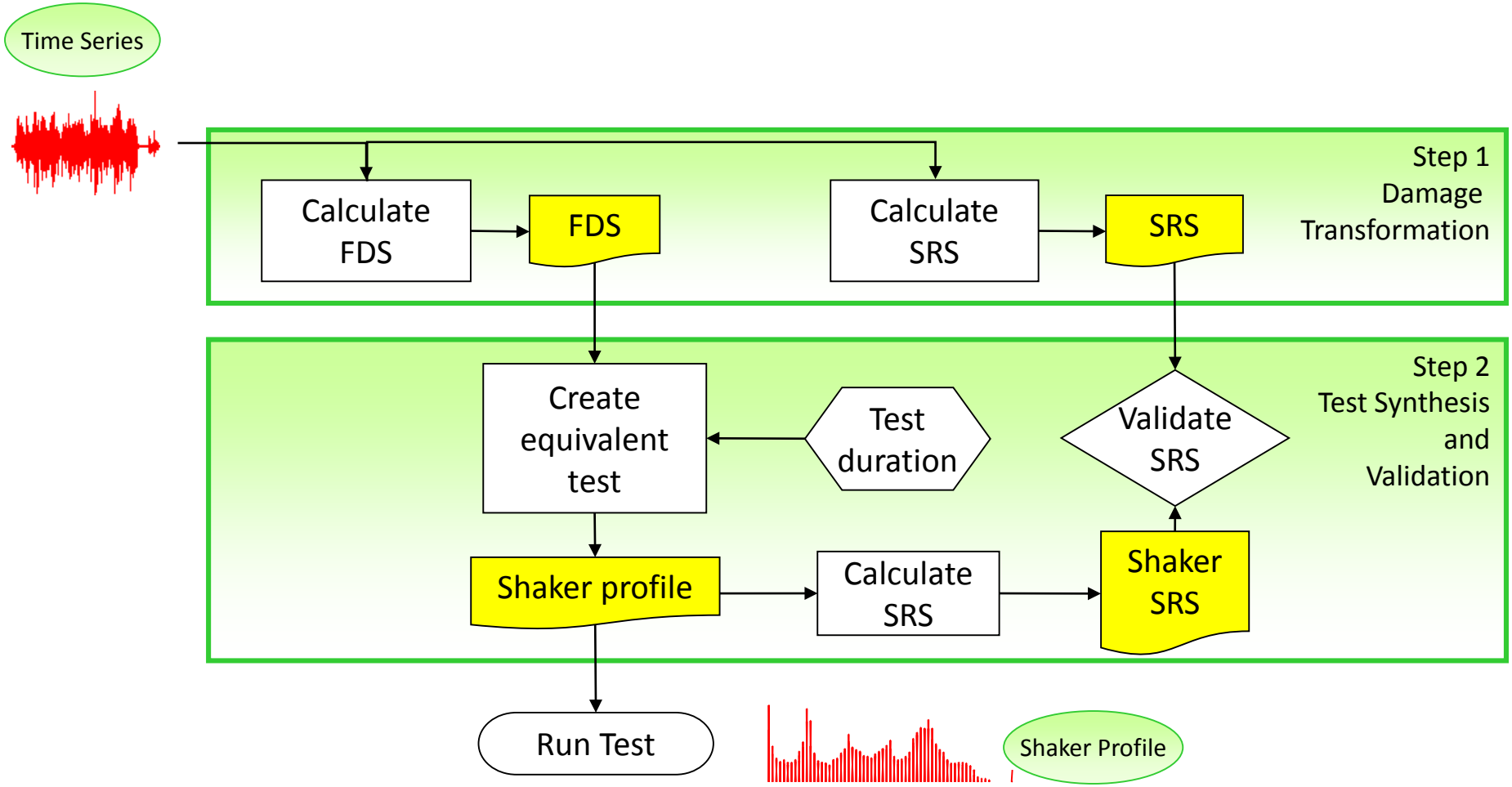


Shock Response Spectrum and Fatigue Damage Spectrum



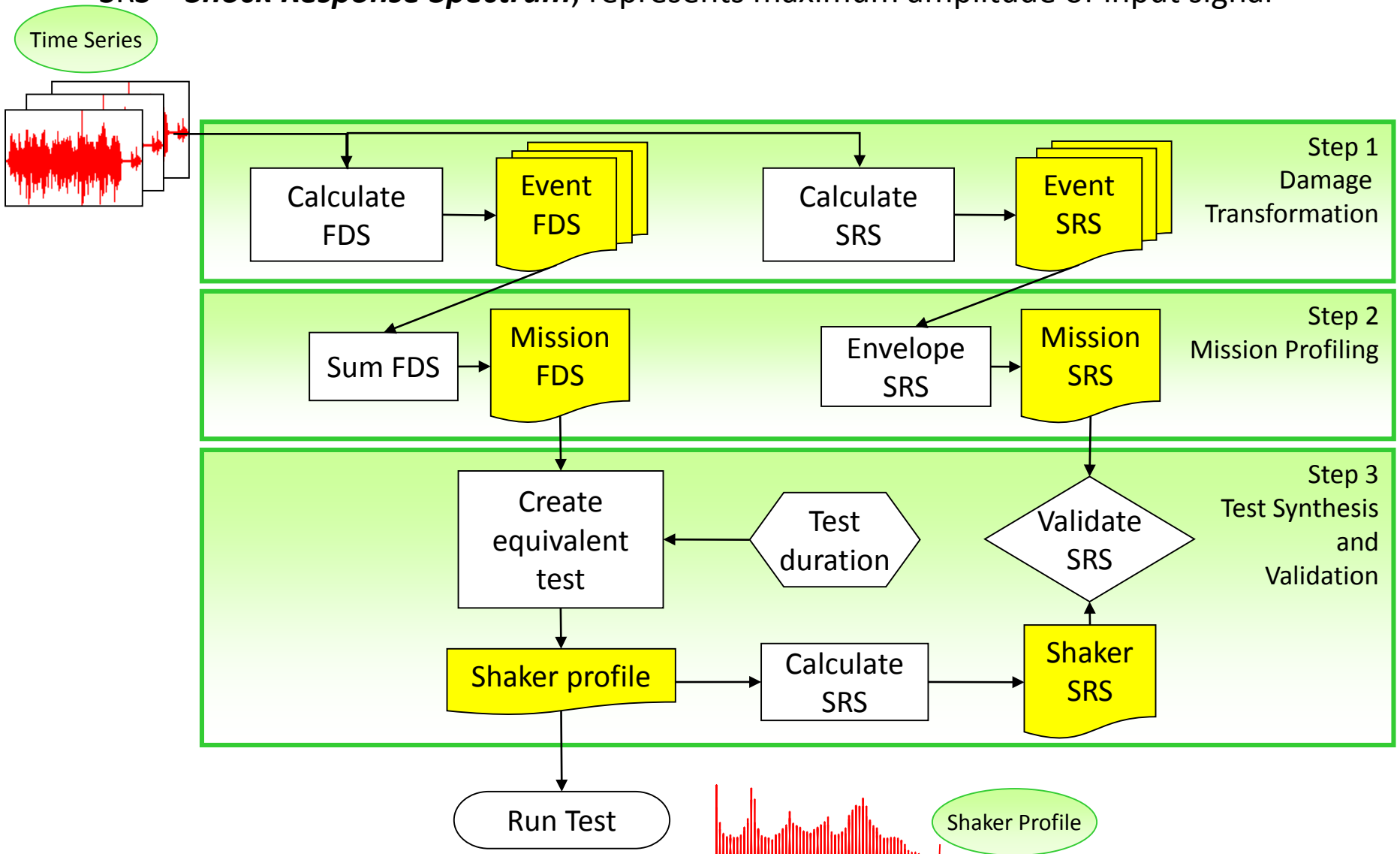
Analysis Roadmap: Single Time Series Event

FDS = ***Fatigue Damage Spectrum***, represents fatigue damage content of input signal
SRS = ***Shock Response Spectrum***, represents maximum amplitude of input signal



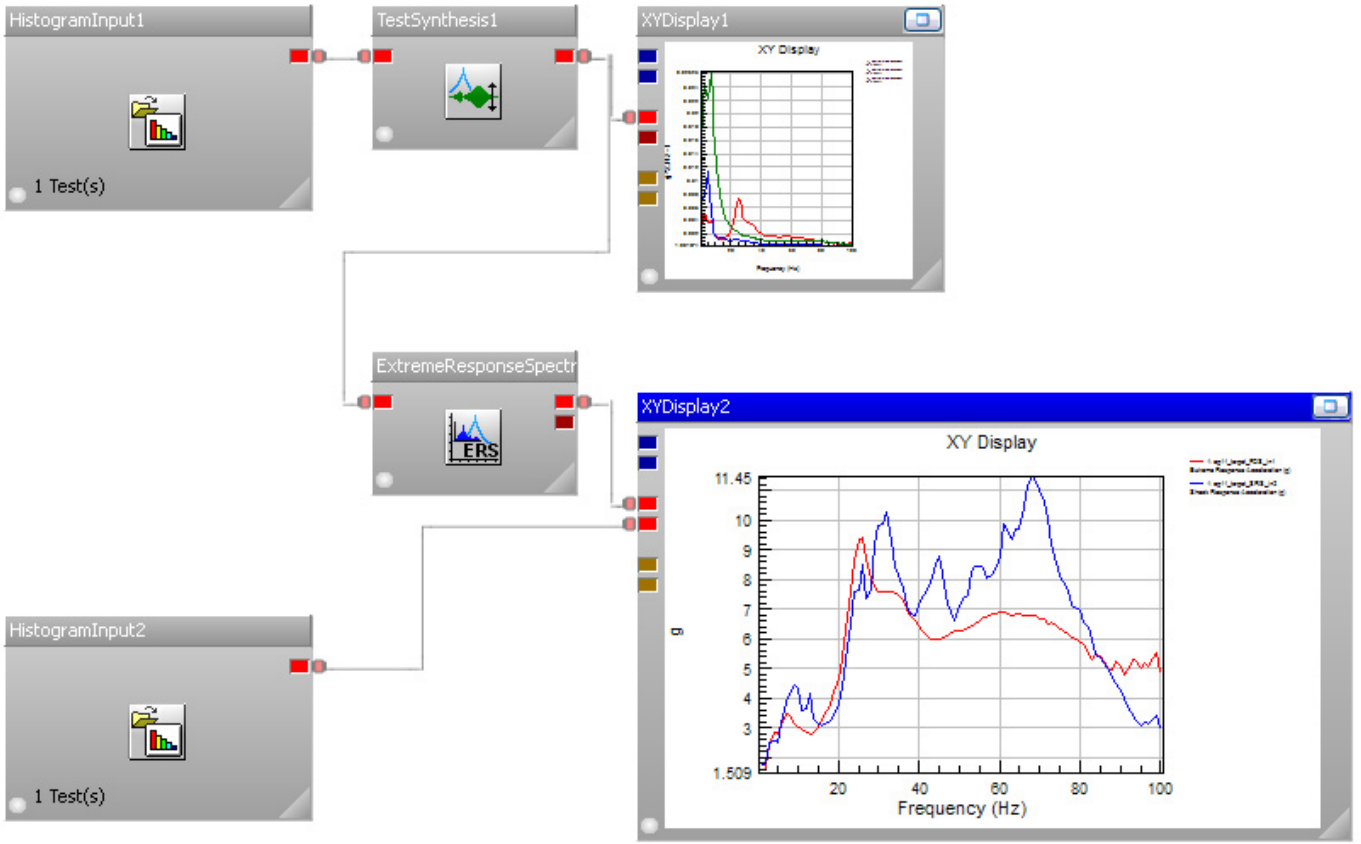
Analysis Roadmap: Multiple Time Series Events

FDS = ***Fatigue Damage Spectrum***, represents fatigue damage content of input signal
SRS = ***Shock Response Spectrum***, represents maximum amplitude of input signal



GlyphWorks Demonstration

GlyphWorks Accelerated Testing module allows efficient PSD profiles to be generated for vibration testing and durability analysis

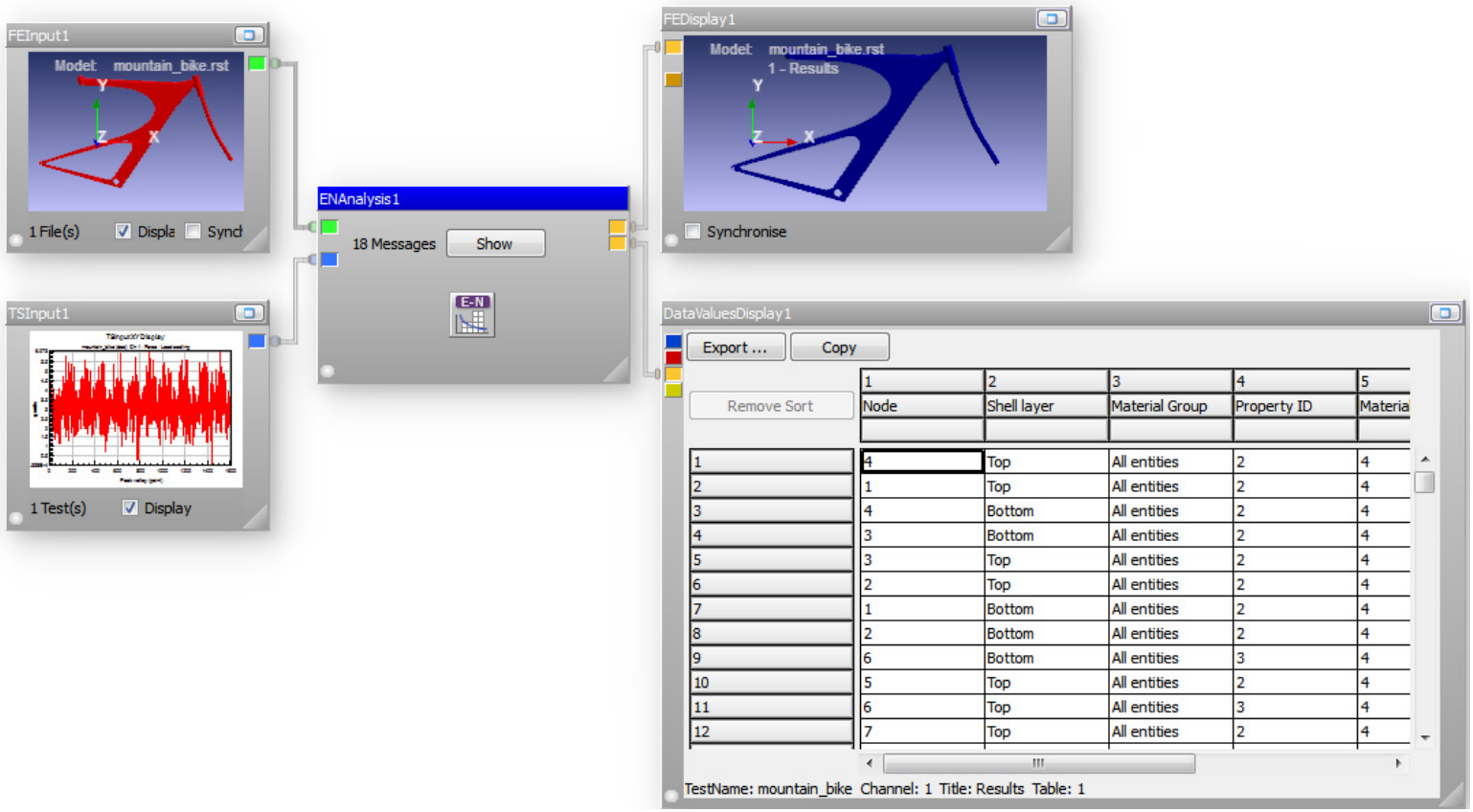


See GlyphWorks Worked Example #11

Fatigue from CAE

DesignLife Demonstration

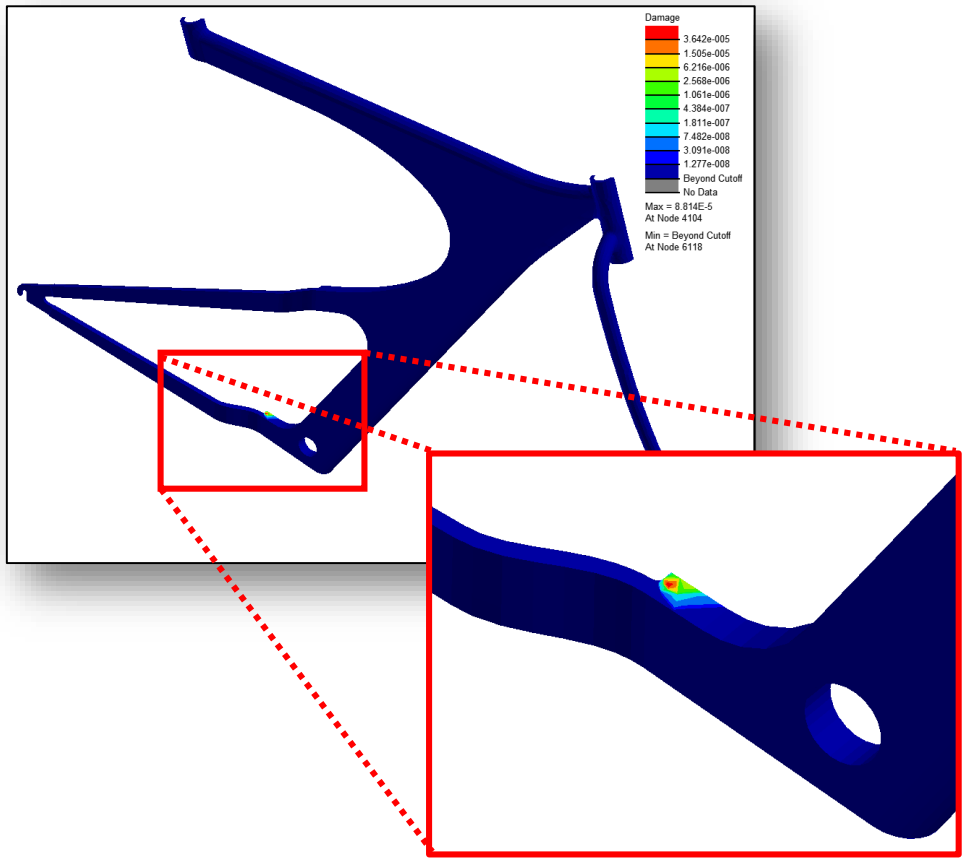
DesignLife fatigue analysis of a mountain bike can be used to demonstrate these principles



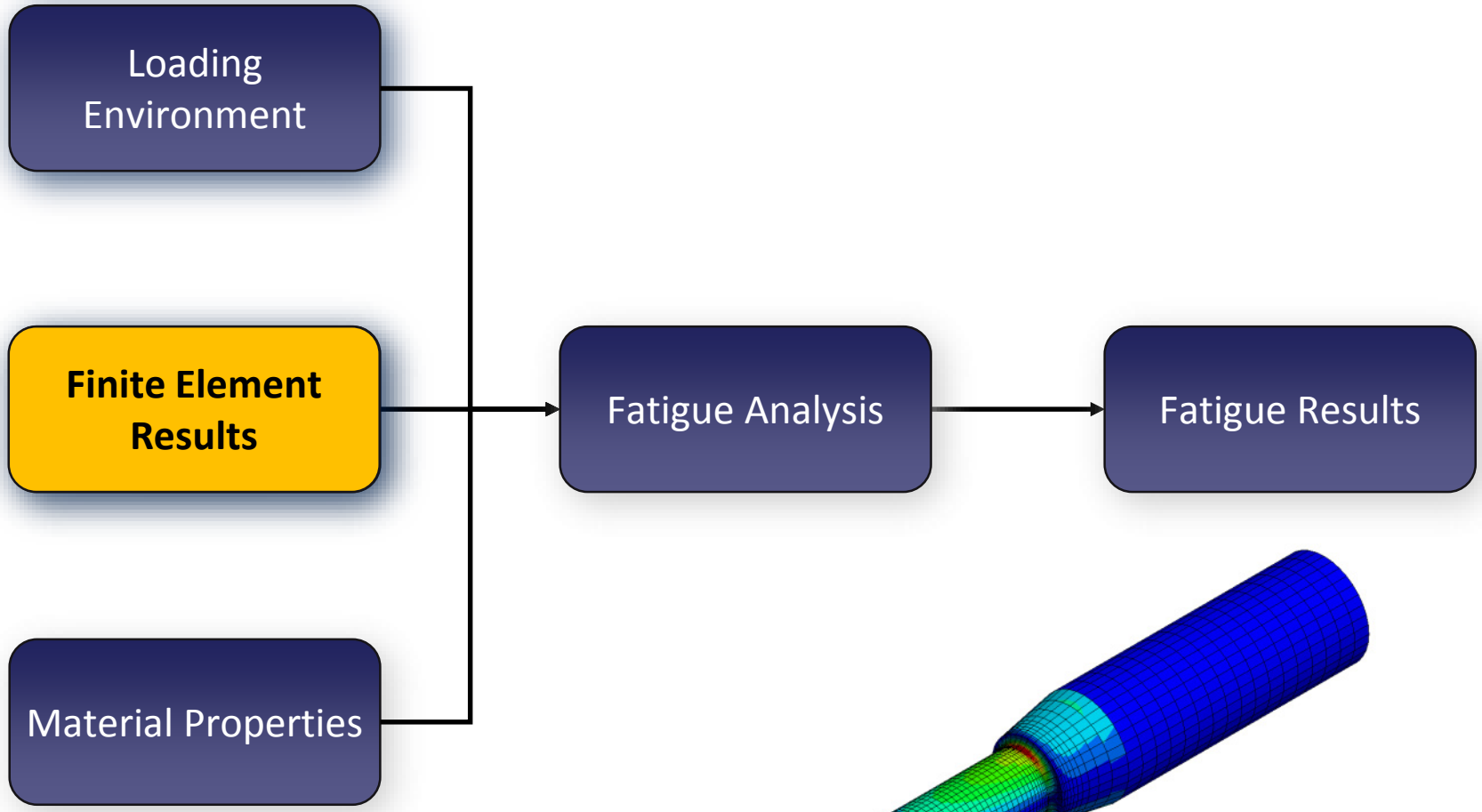
See GlyphWorks Worked Example #11

Comparison with Reality

Although the DesignLife example is a simplified FE model,
the location of the hotspot corresponds with real-life failures!

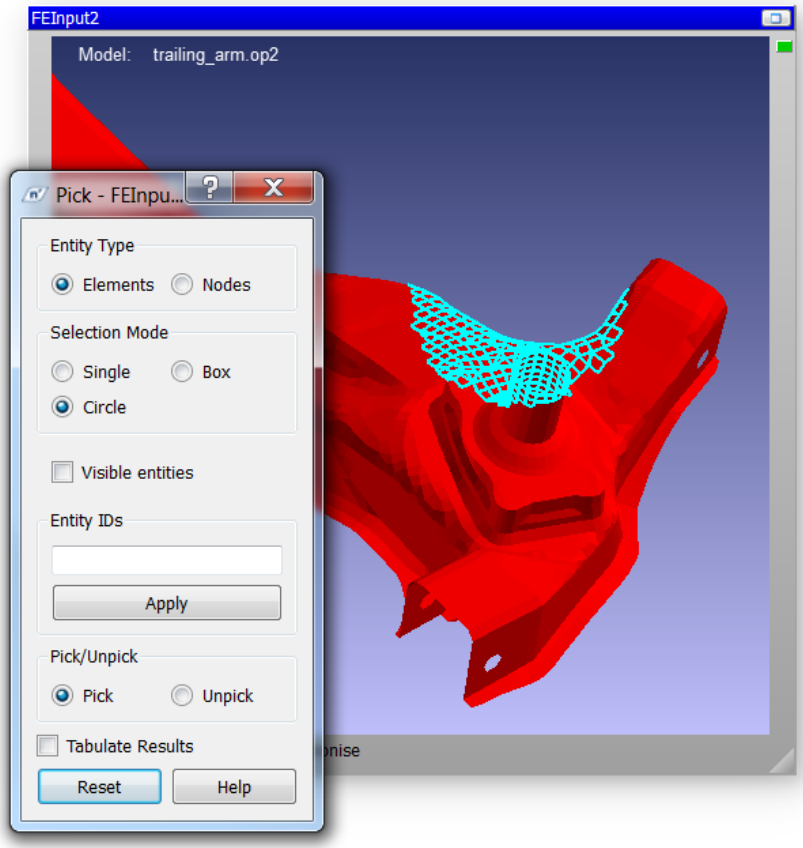


Fatigue Analysis Roadmap



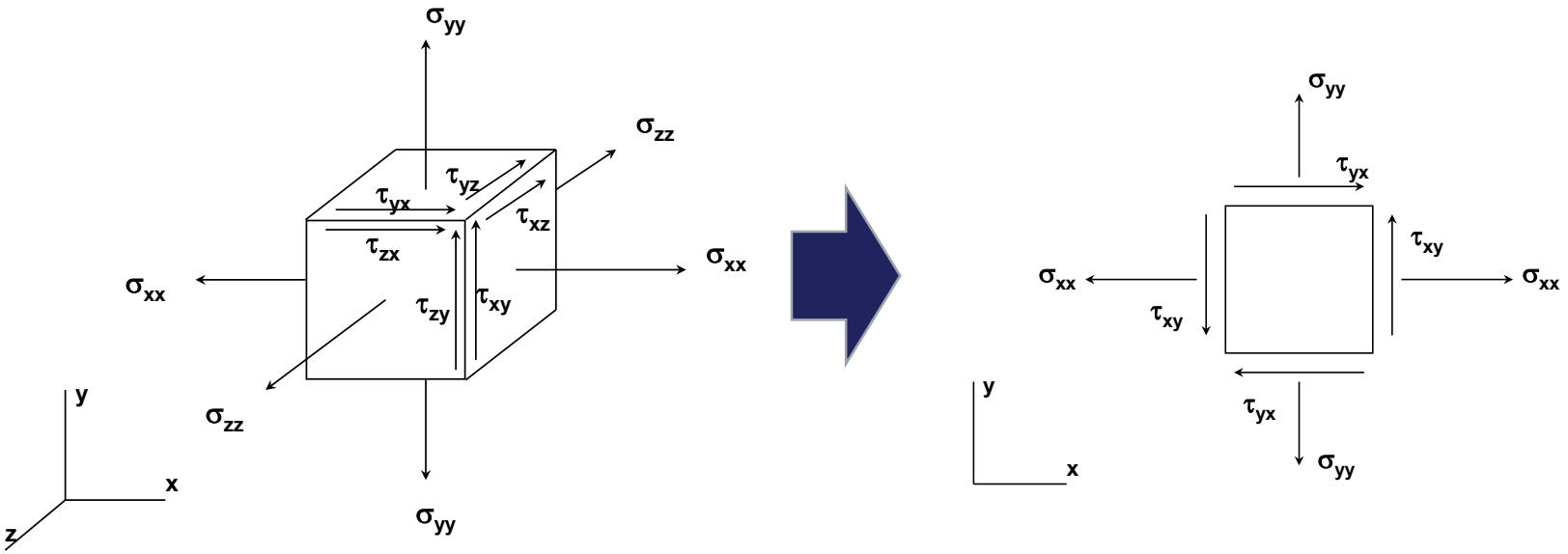
FEInput – File Formats

- The following file types are supported in the FEInput glyph
  - MSC.NASTRAN *.bdf, .dat* and *.op2*
  - NX NASTRAN *.bdf and .op2*
  - ABAQUS *.odb* and *.fil*
  - ANSYS *.rst* and *.rth*
  - LS-Dyna *.d3plot*
  - IDEAS *.unv*
  - Mechanica/Creo *.neu*
- The FEInput glyph can be configured to display a subset of the model in the following ways:
  - Element Type
  - Property
  - Material
  - Element Set
  - User defined groups



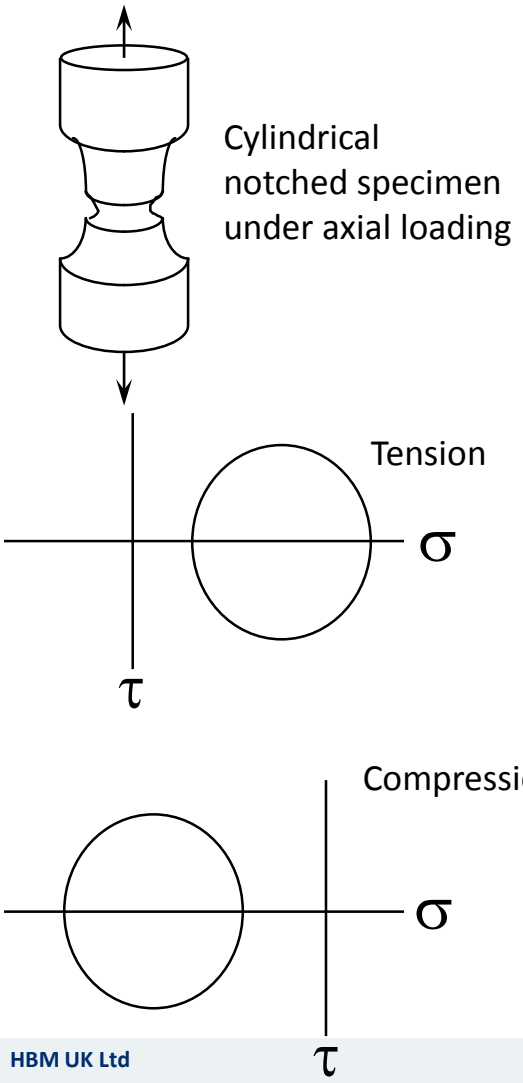
Stress State

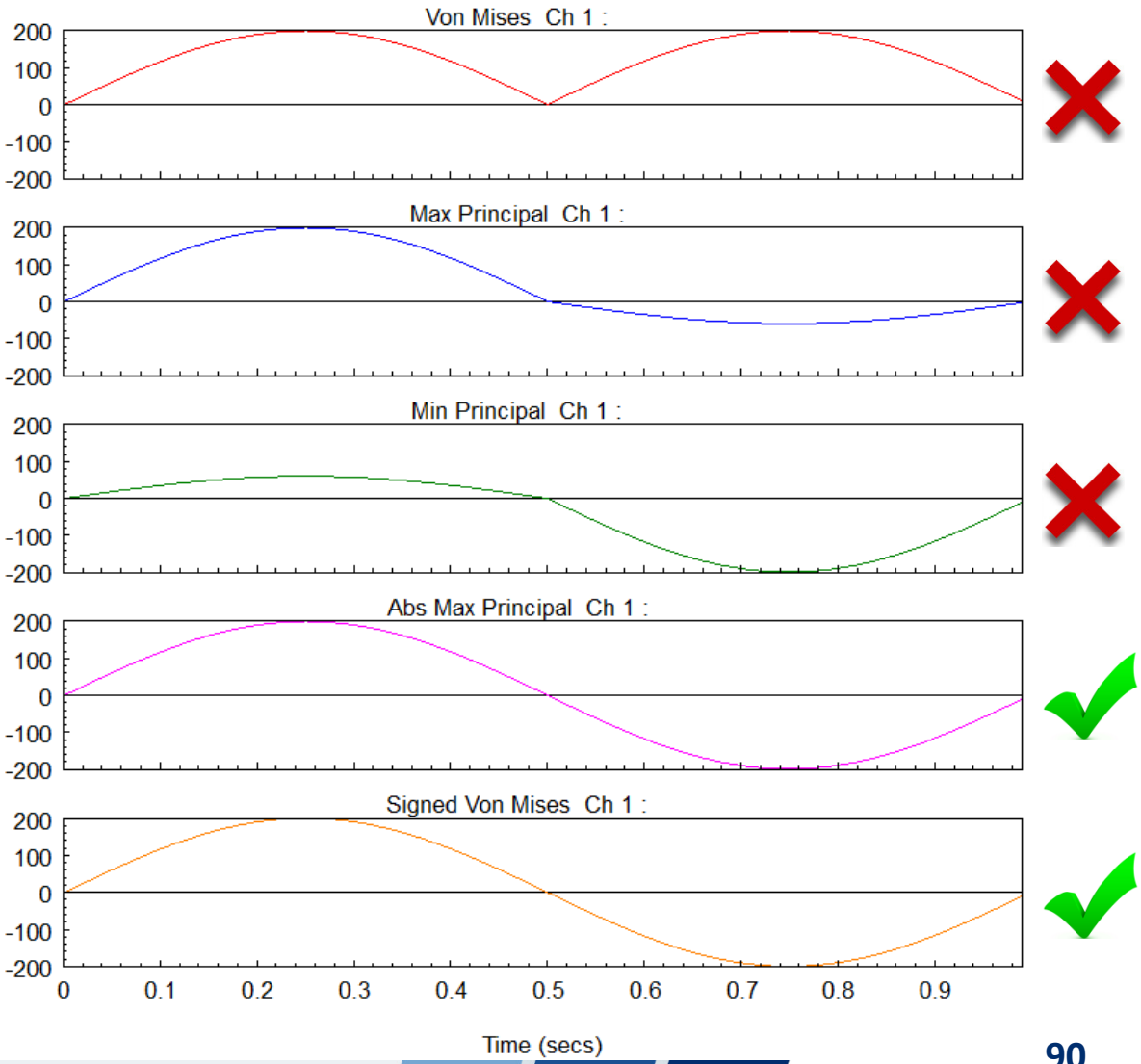
- In general, FE stresses are tensors
- Stress tensors have 9 components
- This can be reduced to 6 components through symmetry
- Assuming cracks only initiate on the surface allows reduction to 3 components
- This allows for efficient fatigue calculations using 2D stress states on the surface of the FE model



Fatigue Needs Signed Stresses

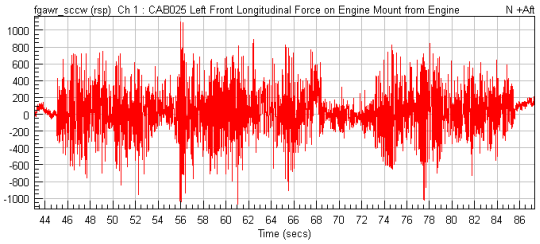
- Fatigue cycles are driven by ***changes of stress***
- Von Mises stress cannot describe the full tension-compression cycle

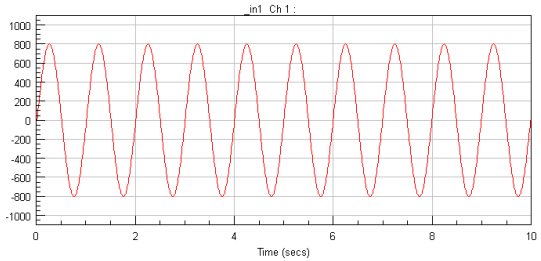




Fatigue Analysis Roadmap

Load Mapping



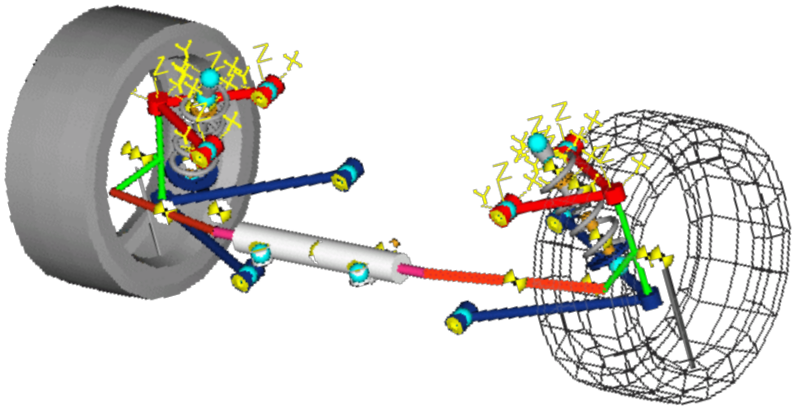


Geometry

Material Properties

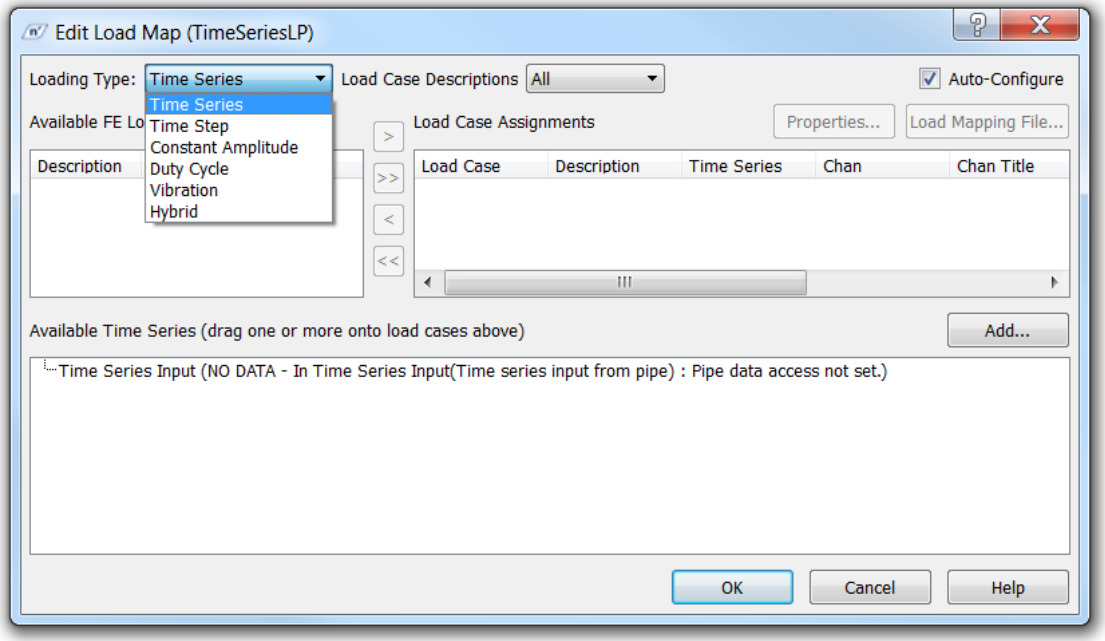
Fatigue Analysis

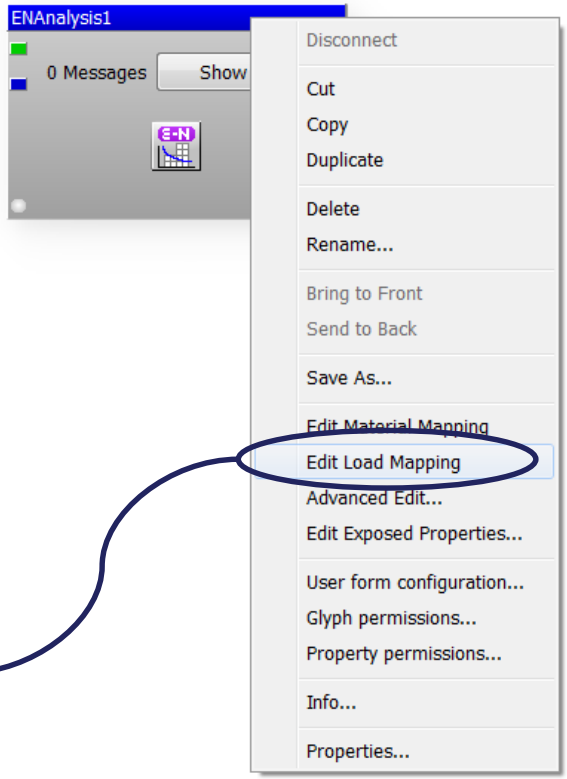
Fatigue Results



Load Mapping

- The Load Mapping interface allows the user to define the type of loading that will be used in the fatigue calculations





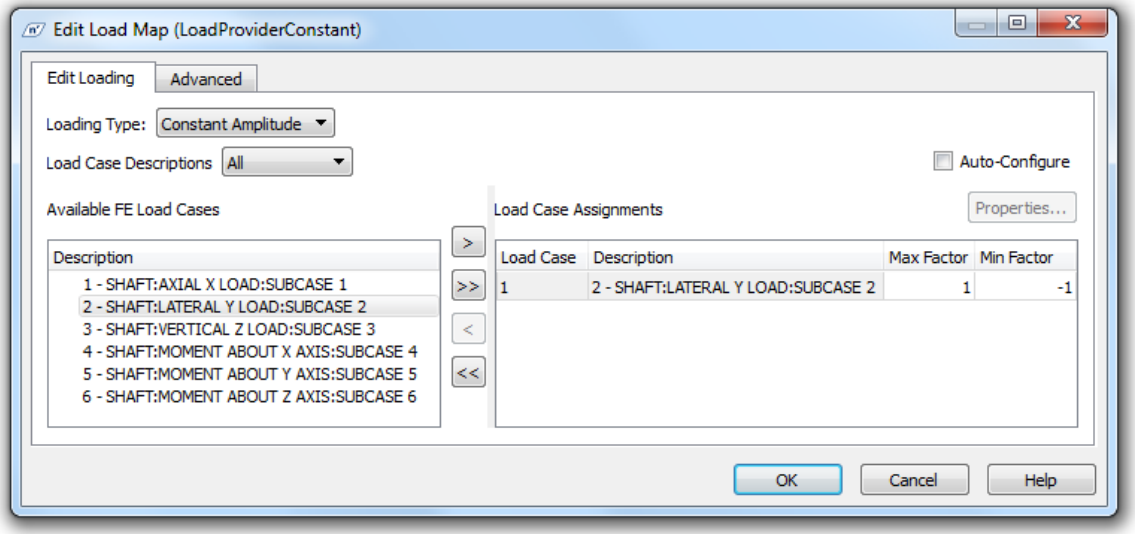
Types of Loads

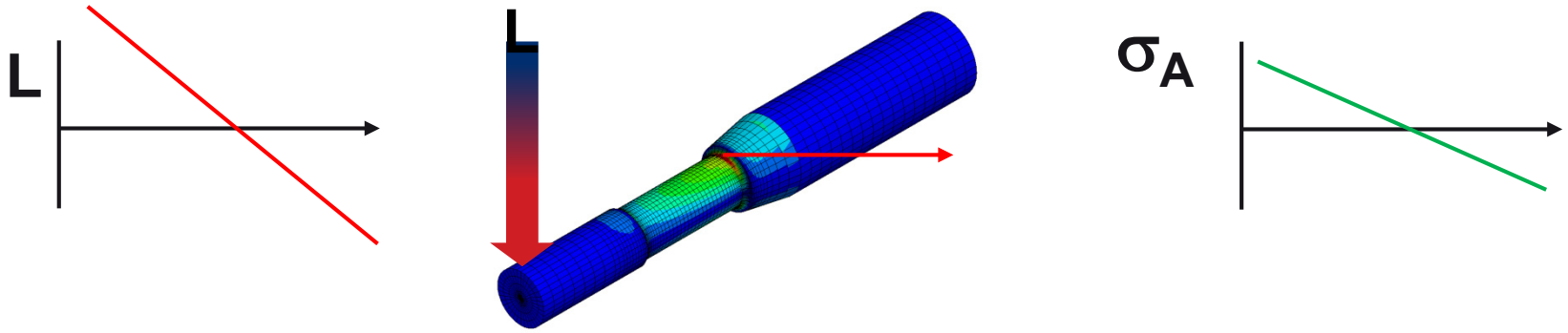
- The following Loading Types are available:

• Constant Amplitude • Time Series	Calculates stress histories by linear superposition of loadcase(s)
• Time Step	Uses stress histories solved for in the FE Model
• Duty Cycle	Constructs sequences and repeats of other Loading Types
• Vibration	Simulates vibration shaker table test
• Hybrid	Calculates stress histories through a combination of Loading Types

Loading Type: Constant Amplitude

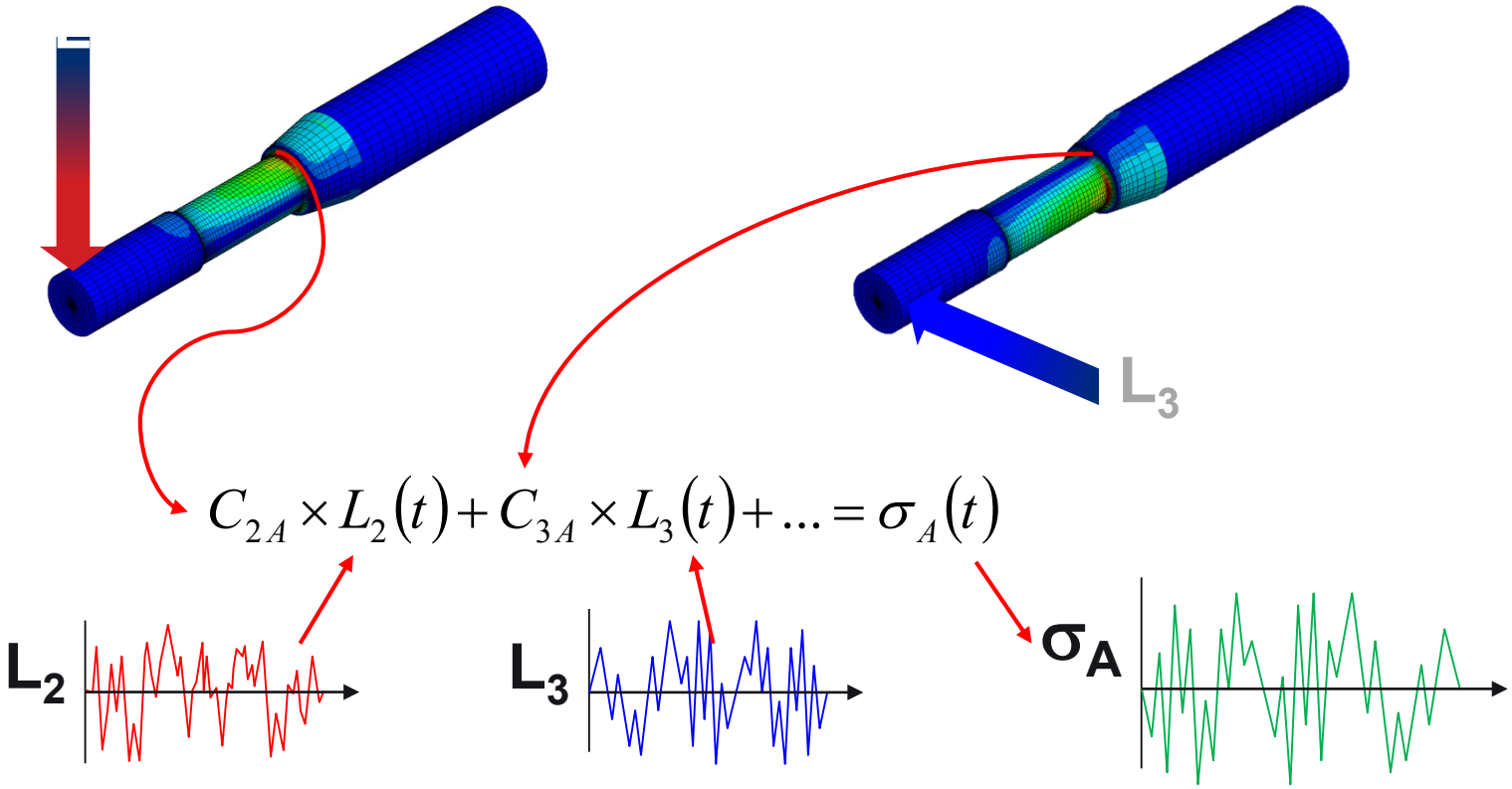
- Available FE load cases are scaled in sequence to create simple loading cycles
  - Max and min factors can be controlled independently
  - The selected load case is scaled by these factors





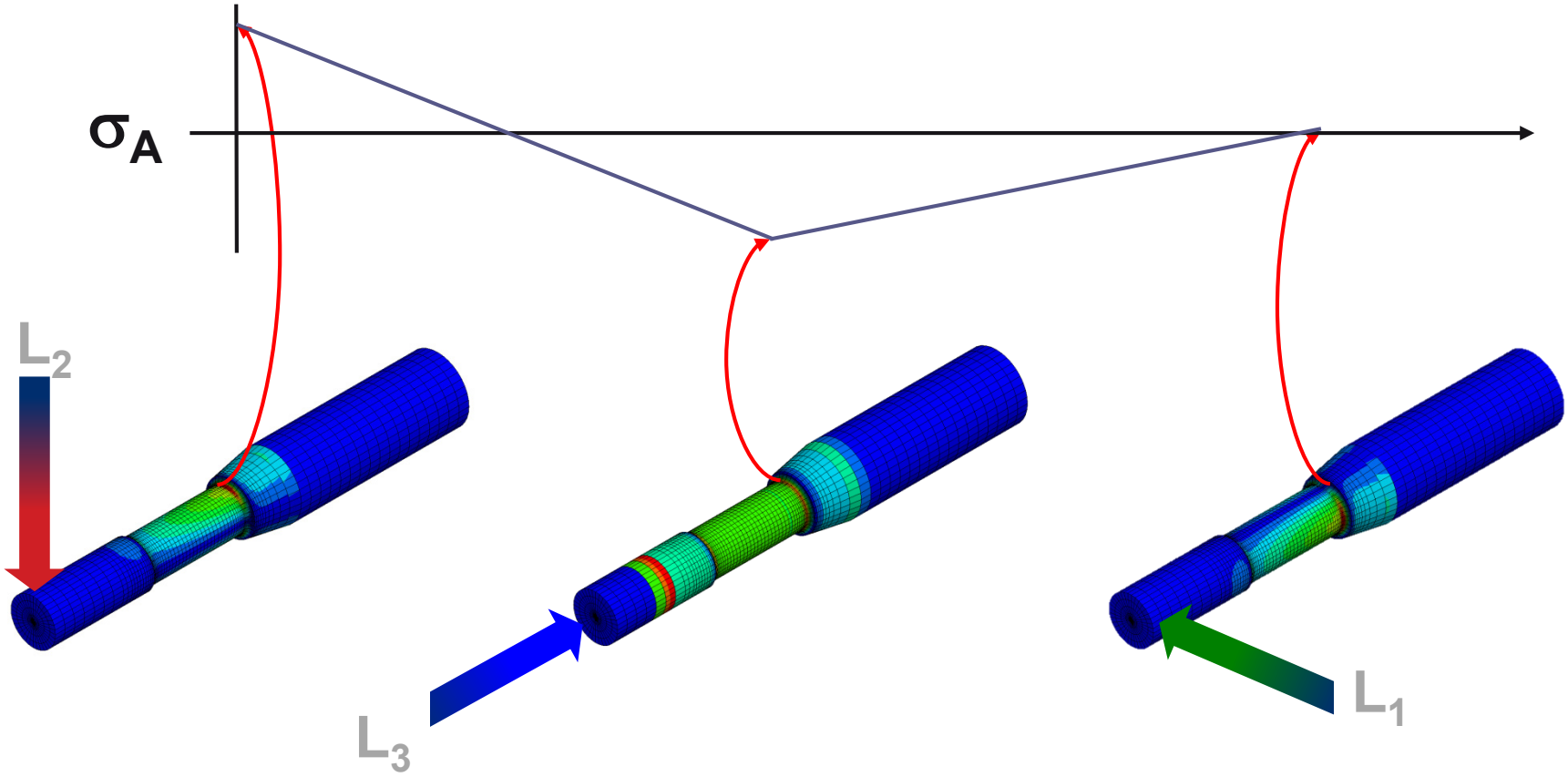
Loading Type: Time Series

- Use time domain loading data to drive fatigue cycles
- Individual FE load cases for each DOF can be paired with measured time series load channels to generate stress or strain histories
- Uses linear superposition of stress tensors for multiple load cases



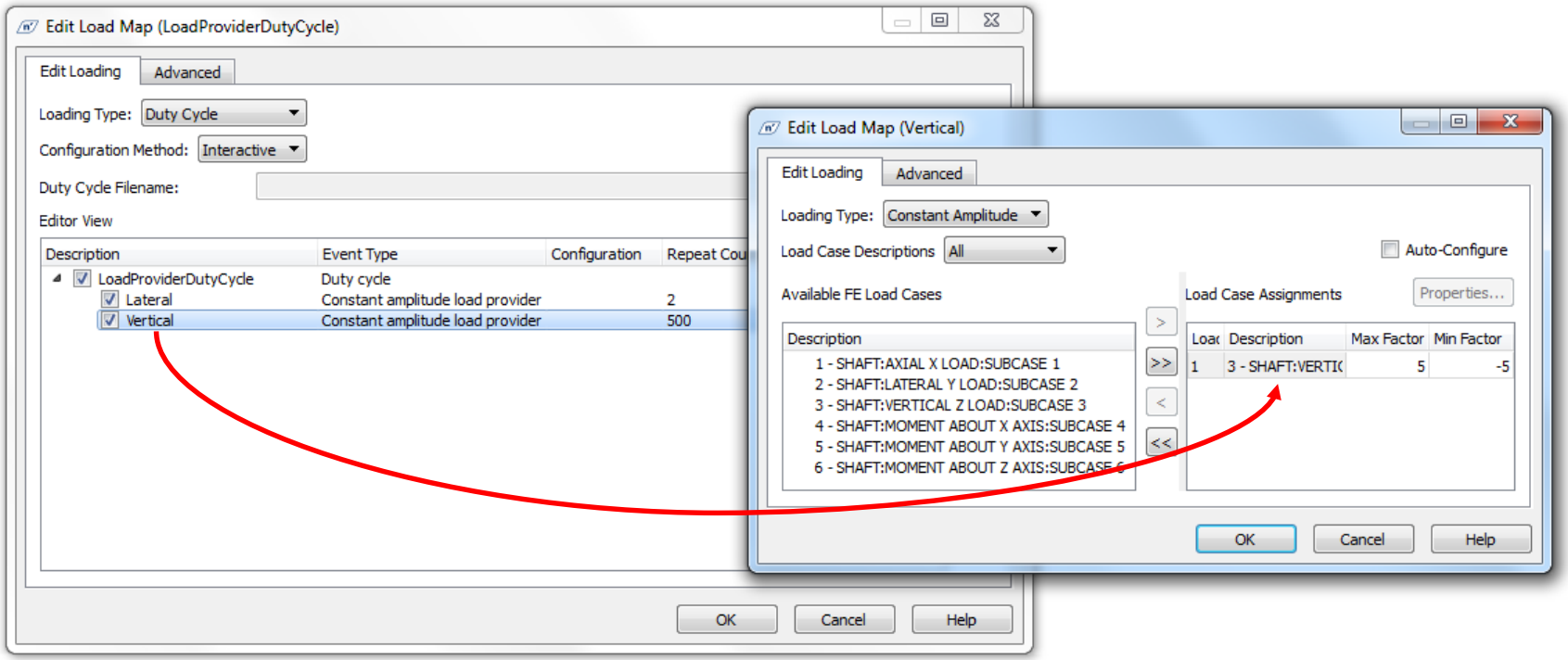
Loading Type: Time Step

- Time step can also be used to sequence separate load cases into cycles
  - Example cycle = Vertical, (L1) → Axial, (L2) → Lateral, (L3)
  - The sequential order can be user defined



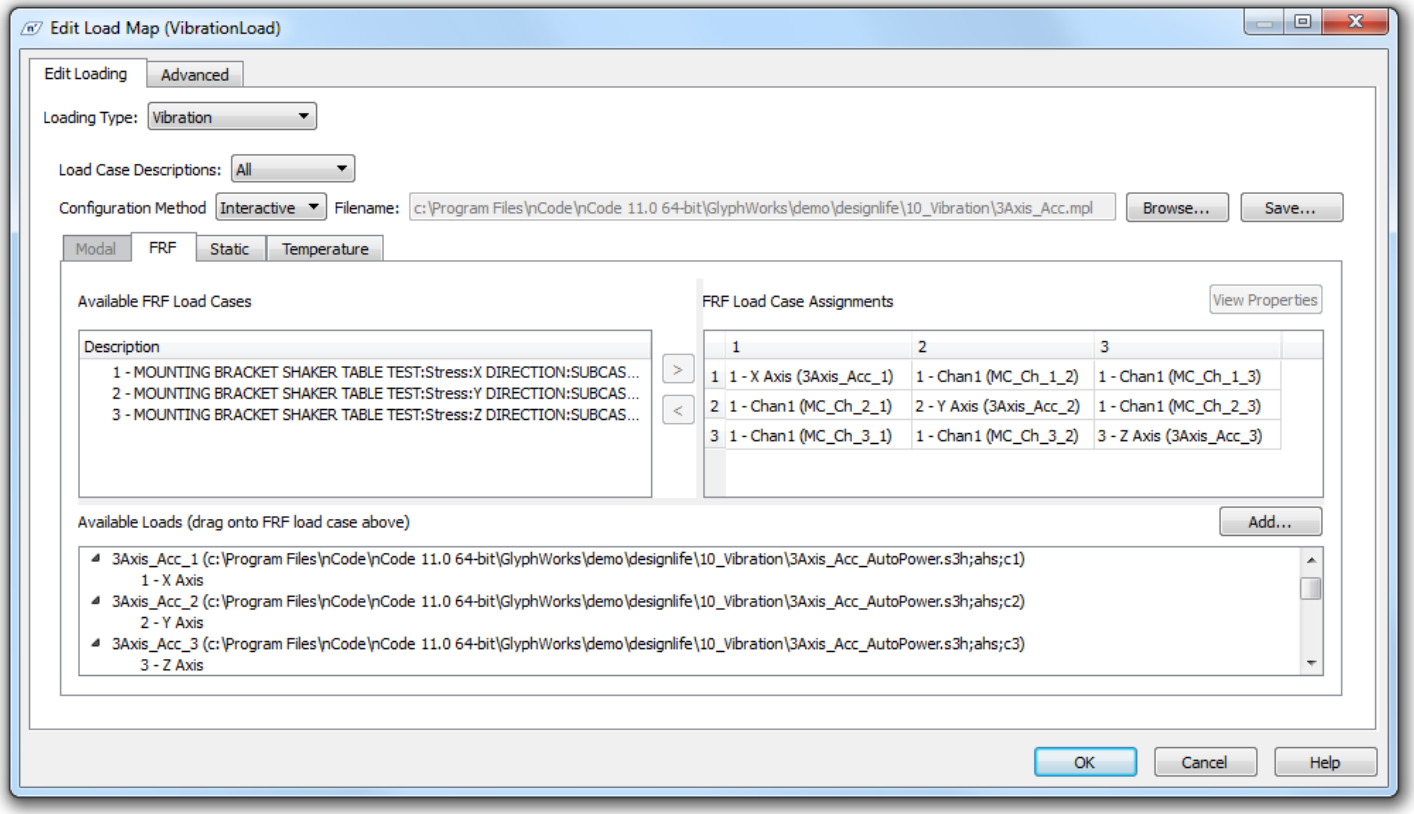
Loading Type: Duty Cycle

- Duty cycles allow sequences and repeats of other loading types
  - Damage is calculated per event
  - User provides repeats for each event in the duty cycle
  - Damage is added cumulatively per Miner's Rule
  - Events in a duty cycle can be a variety of loading types



Loading Type: Vibration

- Algorithms are used to count cycles in the frequency domain
- The FE stress solution is scaled by loading described as a PSD, sine sweep, sine dwell or sine on random loading profile



Fatigue Analysis Roadmap

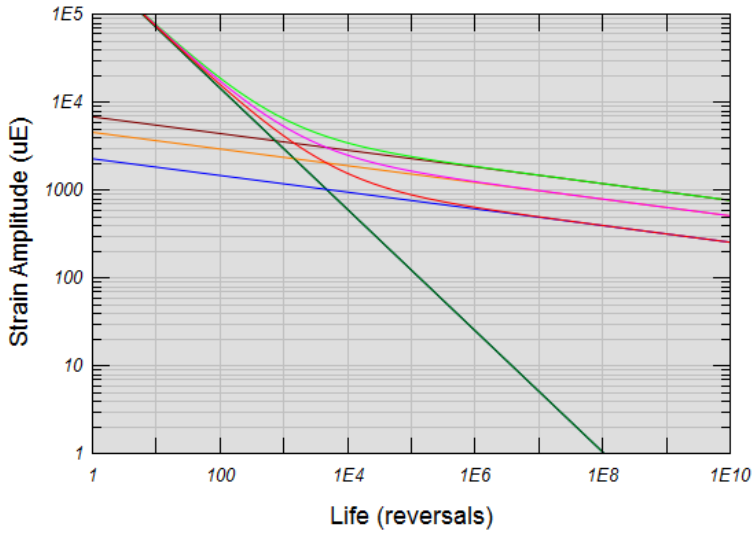
Loading Environment

Geometry

nCode Material Database

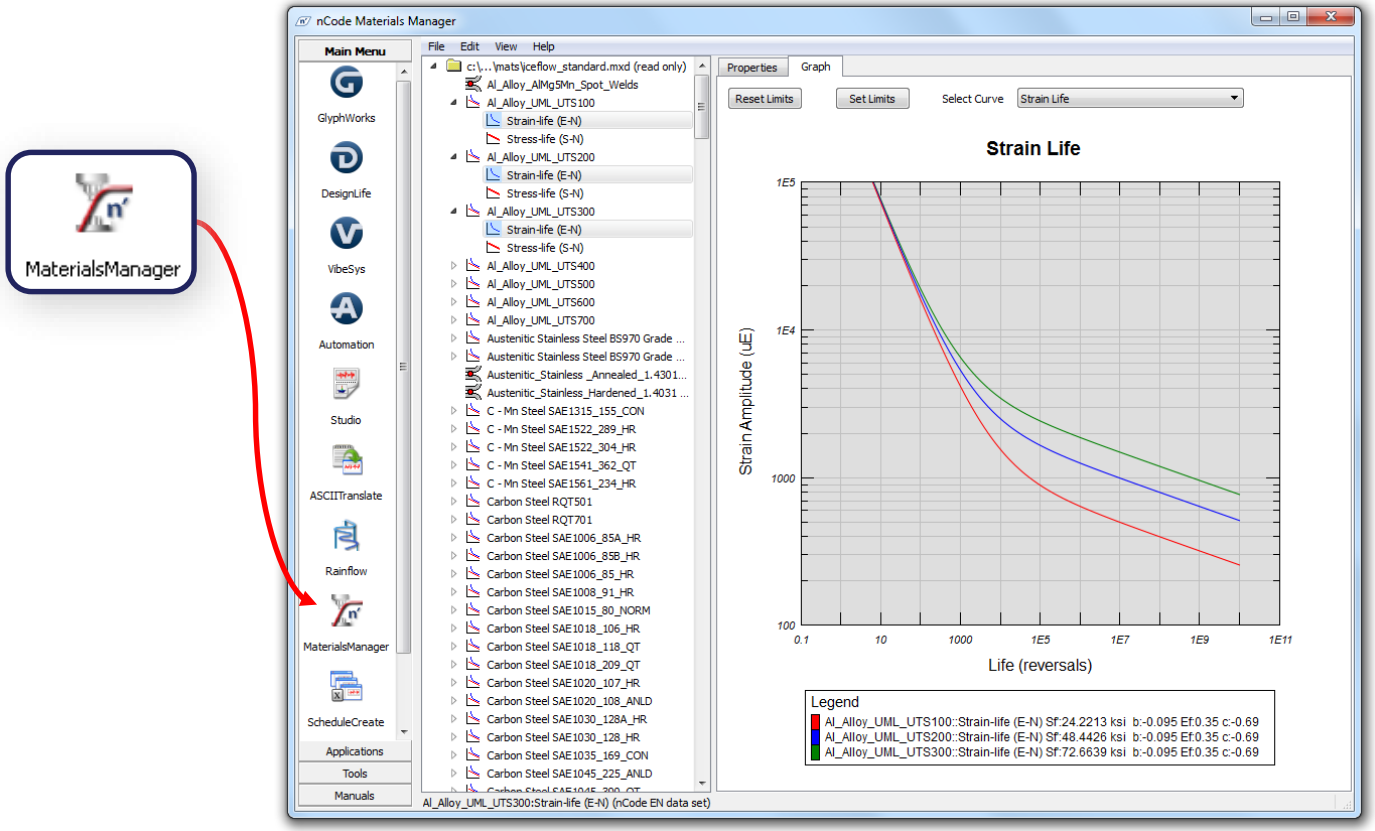
Fatigue Analysis

Fatigue Results



Material Manager

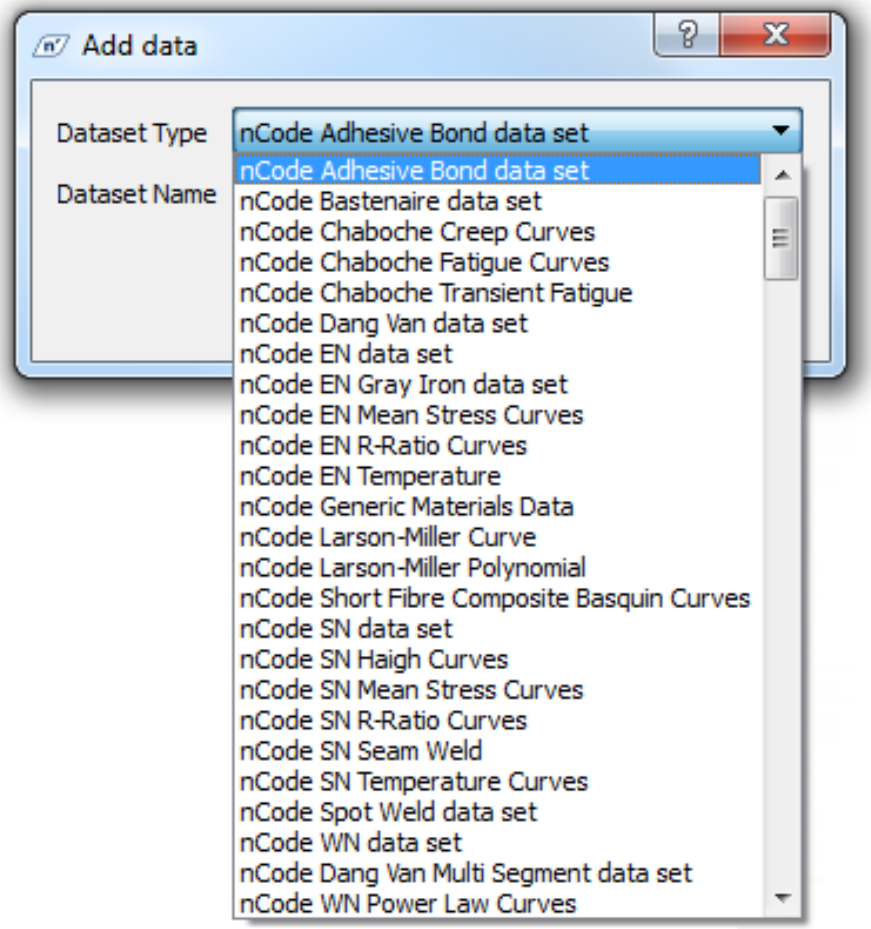
- nCode includes a standard library of material fatigue curves which can be accessed through the *MaterialsManager*



- nCode **Premium Materials Database** requires *Prenscia Access* licensing

Fatigue Curve Formulations

- Standard SN and EN data sets describe fatigue properties with coefficients
  - SN: UTS, E, sf, b, etc.
  - EN: UTS, E, sf, b, c, ef, n', K', etc.
- Other common data sets include
  - SN Mean Stress Curves
    - Family of SN curves separated by mean stress values
  - SN R-Ratio Curves
    - Family of SN curves separated by R ratios
  - SN Temperature Curves
    - Family of SN curves characterized at different temperatures
  - EN Mean Stress Curves
    - Family of EN curves separated by mean stress values
  - EN R-Ratio Curves
    - Family of EN curves separated by R ratios

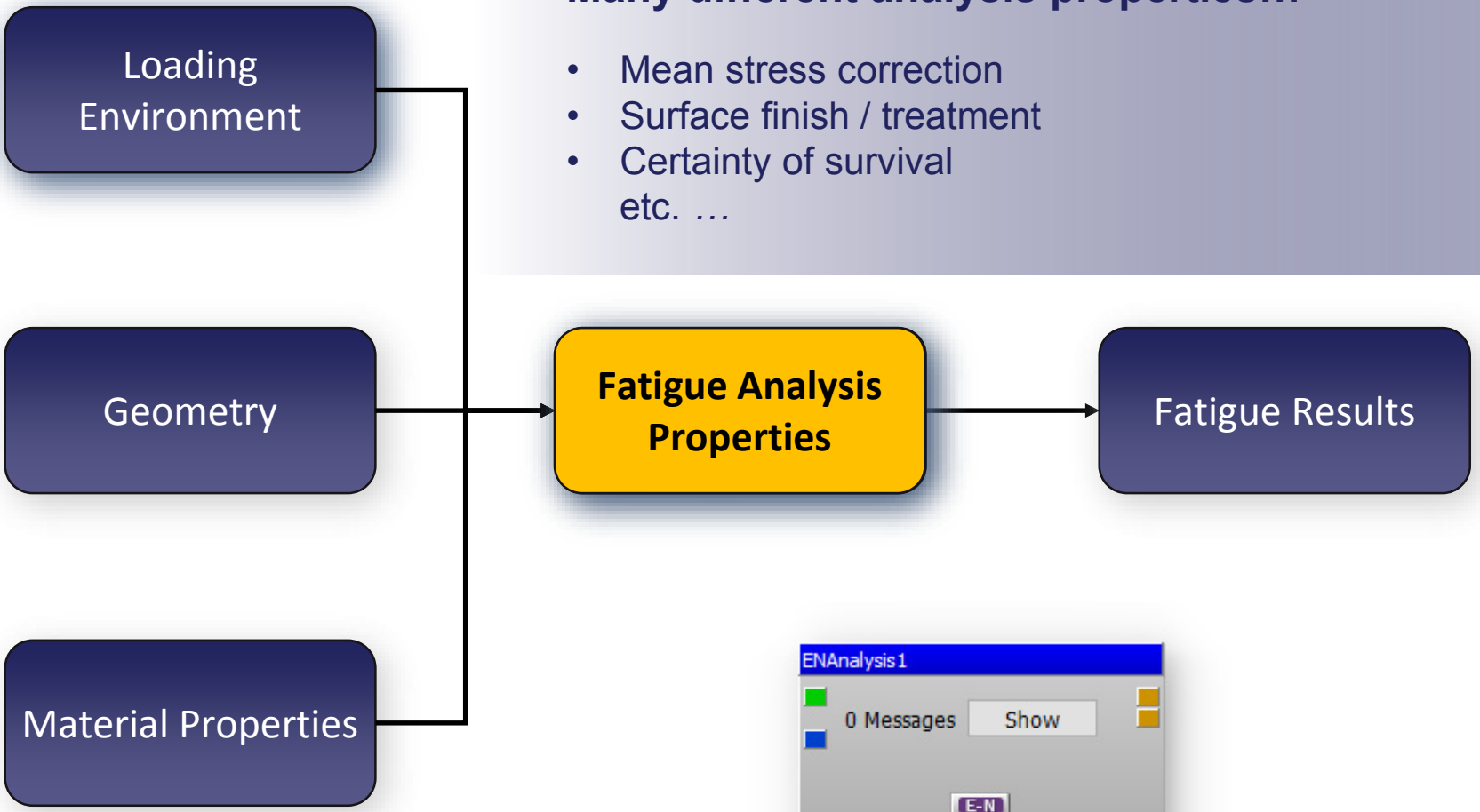


Fatigue Analysis Roadmap

Many different analysis properties…

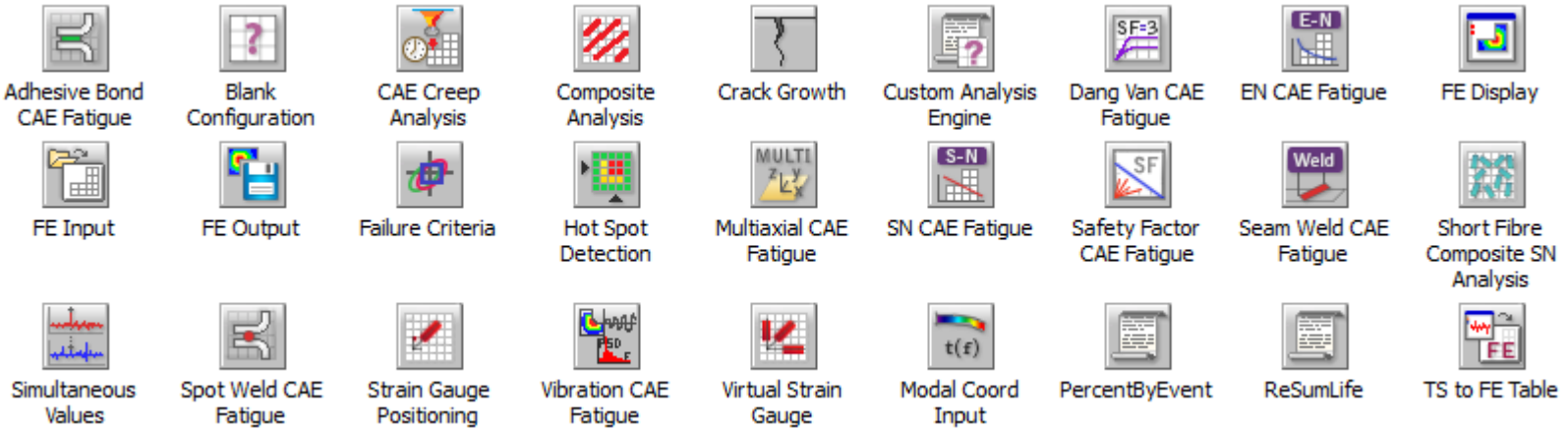
- Mean stress correction
- Surface finish / treatment
- Certainty of survival

etc. …



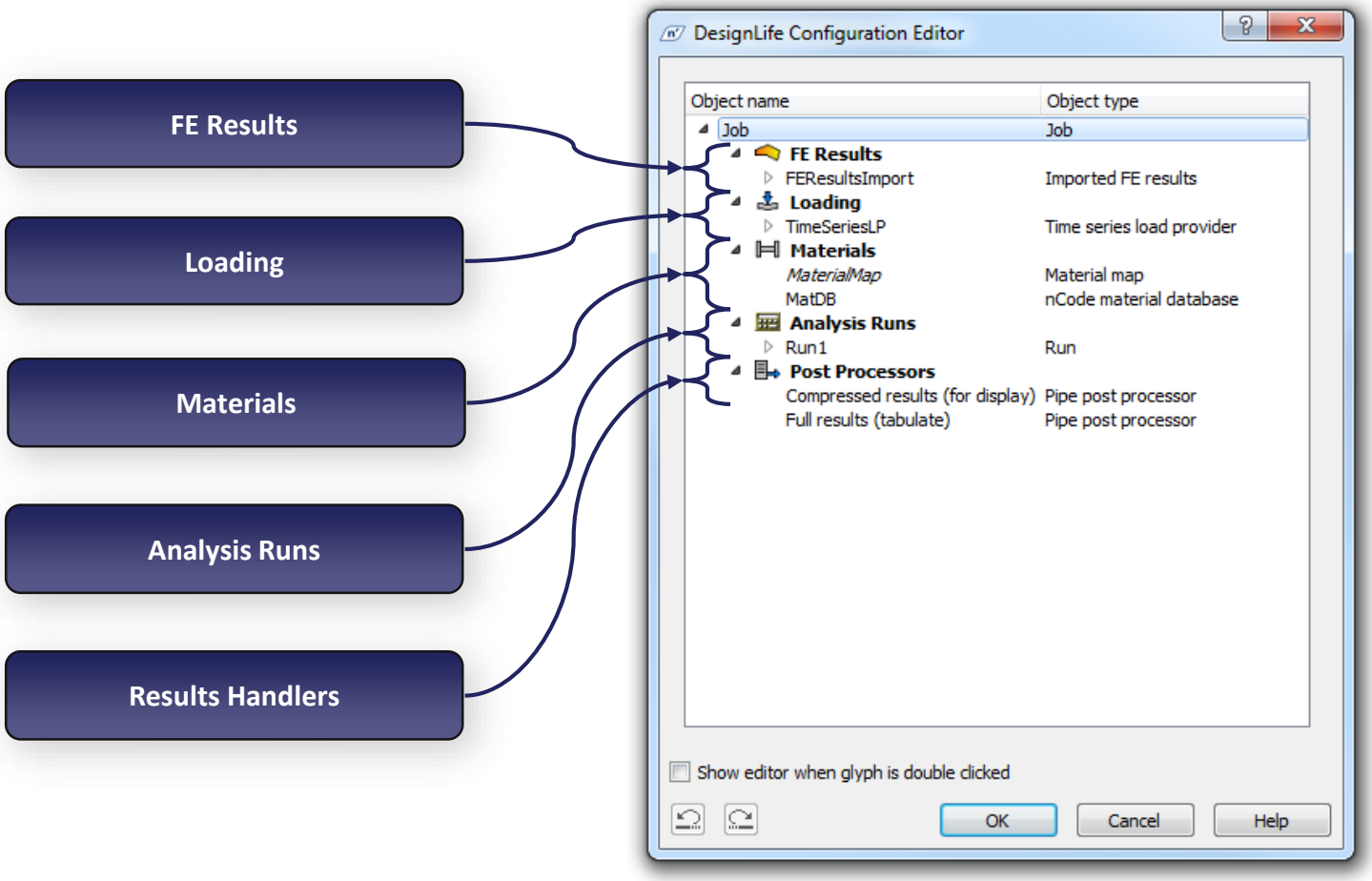
DesignLife Glyph Palette

- Below is a list of notable pre-configured analysis glyphs that can be found on the DesignLife Glyph Palette
  - SN CAE Fatigue
  - EN CAE Fatigue
  - Spot Weld CAE Fatigue
  - Seam Weld CAE Fatigue
  - Virtual Strain Gauge
  - Vibration CAE Fatigue

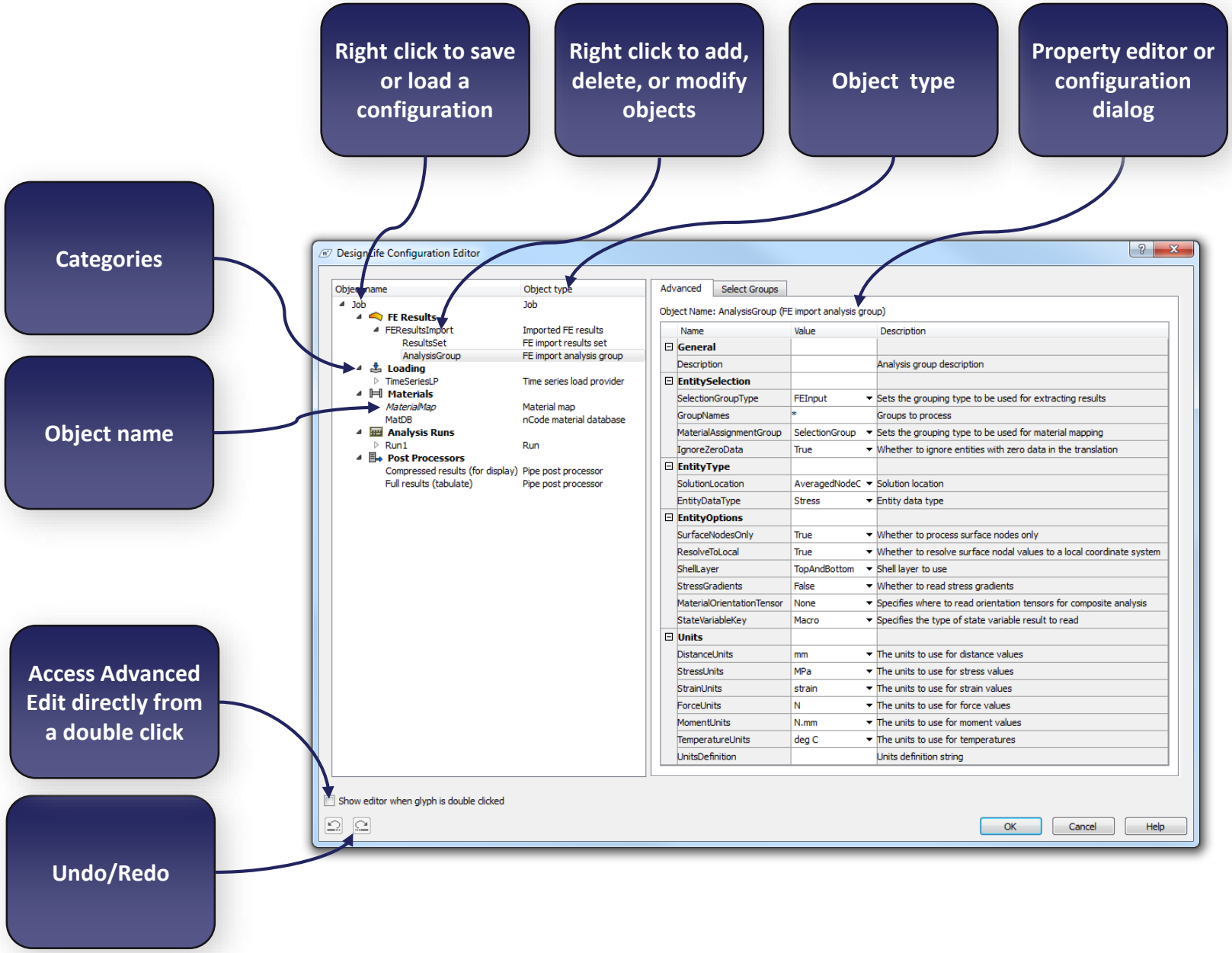


Advanced Edit Structure

- A CAE Analysis glyph requires at least one of each item below:



Advanced Edit Structure



Advanced Edit Benefits

Completely customise your fatigue analysis, such as…

- Analyse sub-groups and individual parts of a component without having to display the FE model
- Output node/element load histories and responses as TimeSeries data
- Perform an optimised analysis using the "***Auto-Elimination***" tool

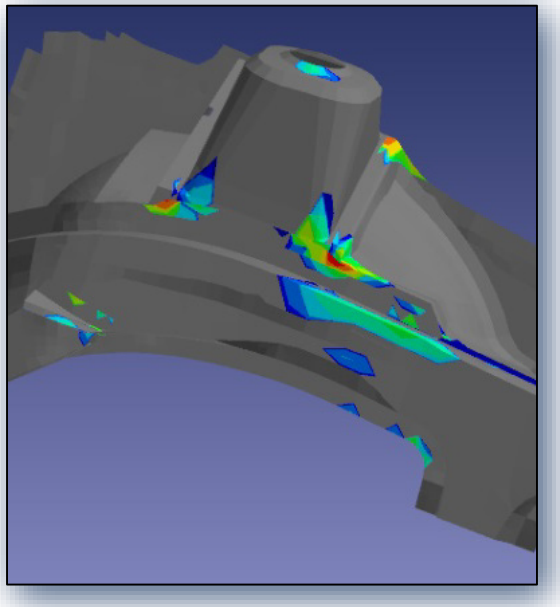
Run 1 = coarse analysis, full FE model

↓

Auto-Elimination identifies the most damaged areas

↓

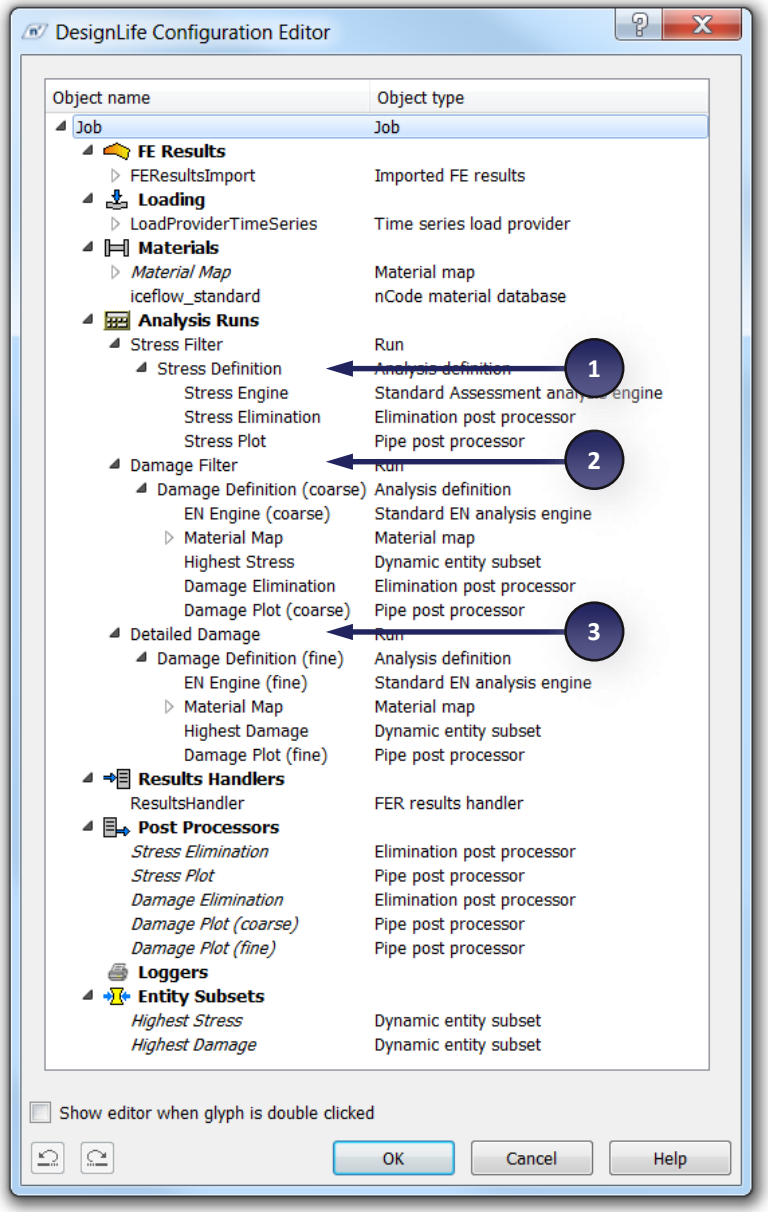
Run 2 = detailed analysis, areas of interest



Multiple Run with 3 Passes

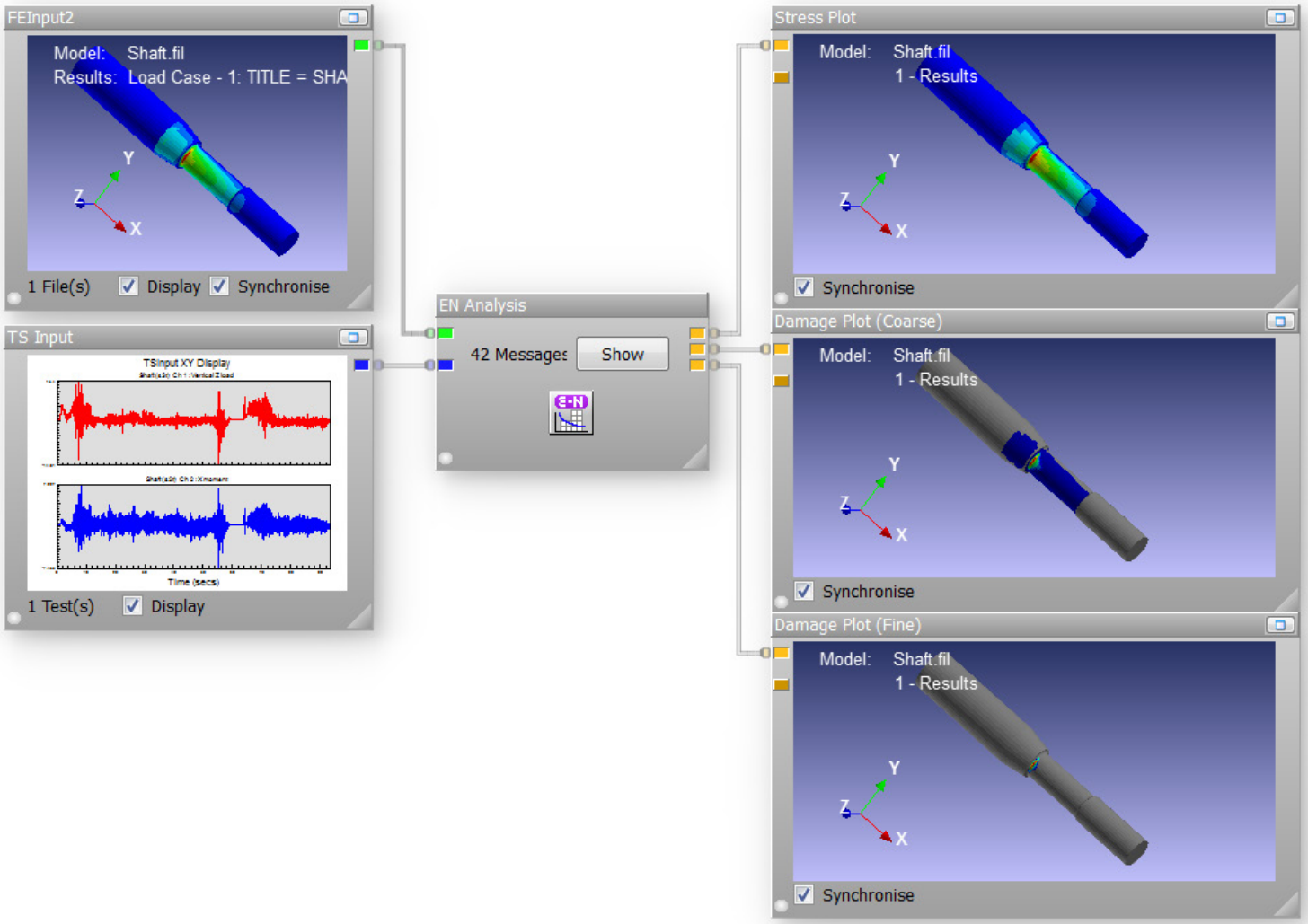
The example to the right has 3 runs that filter elements by:

1. A simple stress assessment to find high stress elements
2. A simple fatigue damage assessment with time history compression to find high damage elements
3. A detailed fatigue damage assessment with no time history compression to get the right answer in the critical areas



Multiple Run with 3 Passes

- These are the graphical results of the 3 runs



Computational Improvements with Multiple Runs

- The computation time for three sample processes with different run scenarios was evaluated
- In all three scenarios, the *Detailed Damage* mode produced the same results for the 122 elements that have the highest damage
- The *Damage Filter* mode also produced results for the elements it evaluated
  - This is not always necessary and was used here for comparison purposes
  - These results are less precise than the *Detailed Damage* results

Scenario	Run	Elements	Analysis Mode	Computation Time	Reduction in Time	Worst Case Element	
				[mm:ss.00]	%	ElementID	Damage
One Run	1	18252	Detailed Damage	**11:58.35**	**0%**	86335	2.92E-06
Two Runs	1	18252	Damage Filter	00:08.50		86335	2.16E-06
	2	122	Detailed Damage	00:06.31		86335	2.92E-06
				00:14.81	**97.9%**		
Three Runs	1	18252	Stress Filter	00:01.50			
	2	5476	Damage Filter	00:02.79		86335	2.16E-06
	3	122	Detailed Damage	00:06.31		86335	2.92E-06
				00:10.60	**98.5%**		

Fatigue Analysis Roadmap

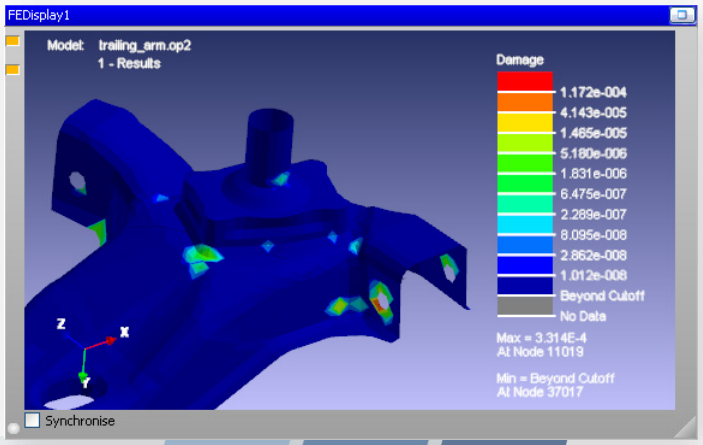
Loading Environment

Geometry

Material Properties

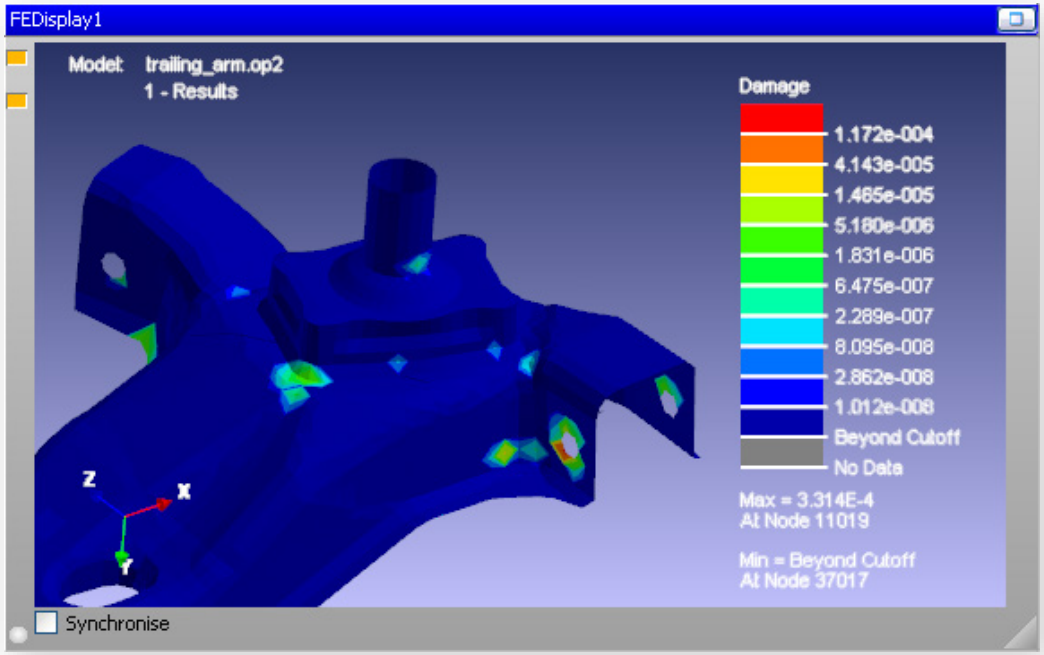
Fatigue Analysis

Fatigue Results



FEDisplay Glyph

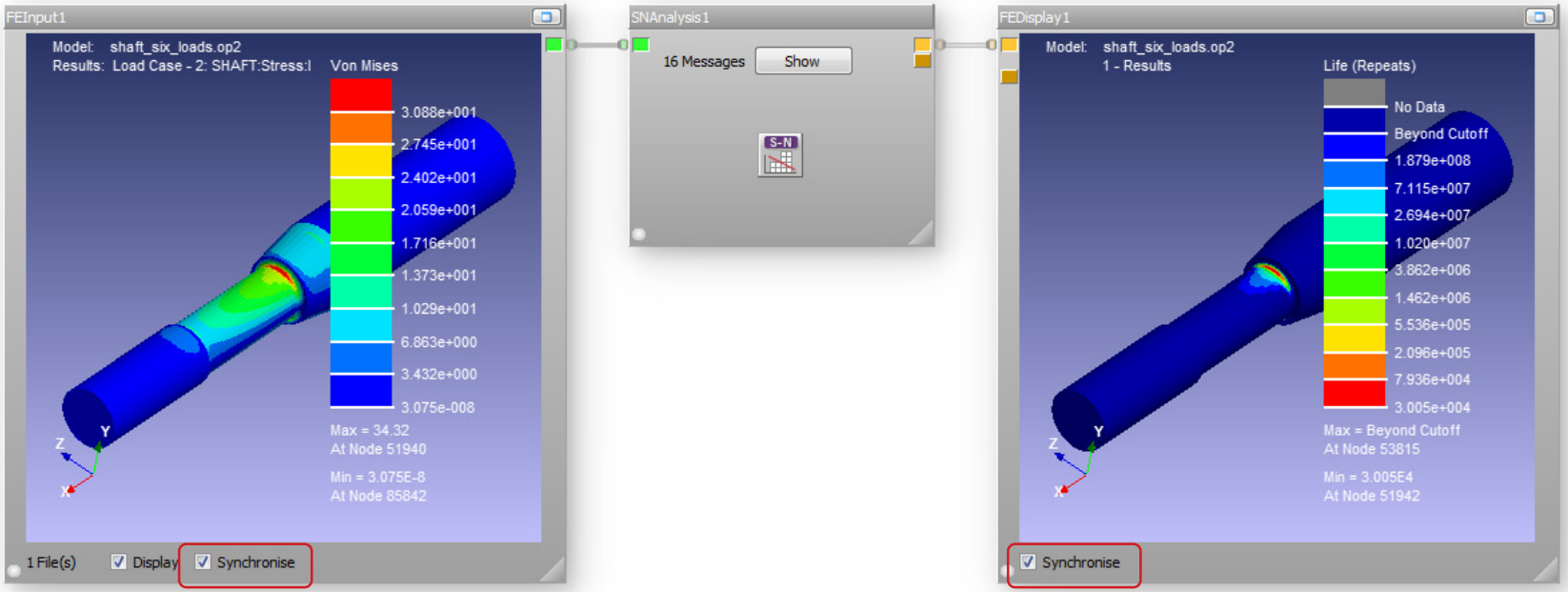
- This glyph has features similar to the FEInput glyph
- It has two input pads
  - *FE Results*
  - *Feature List*



- These are common results
  - Life
  - Damage
  - Max/Min Stress
  - etc.

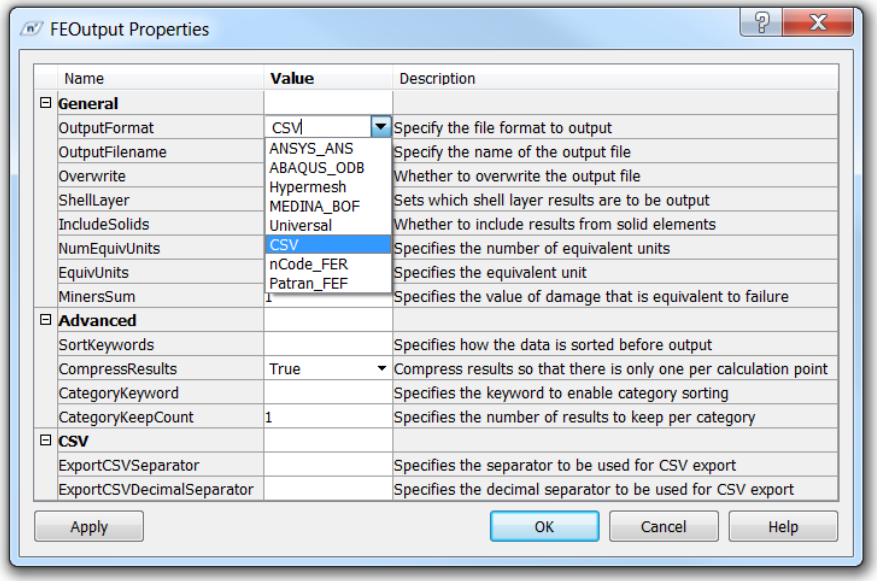
Synchronizing Displays

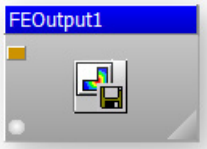
- Allows you to view any number of displays on the workspace from the same angle
- As you manipulate one display, the others follow



FE Output

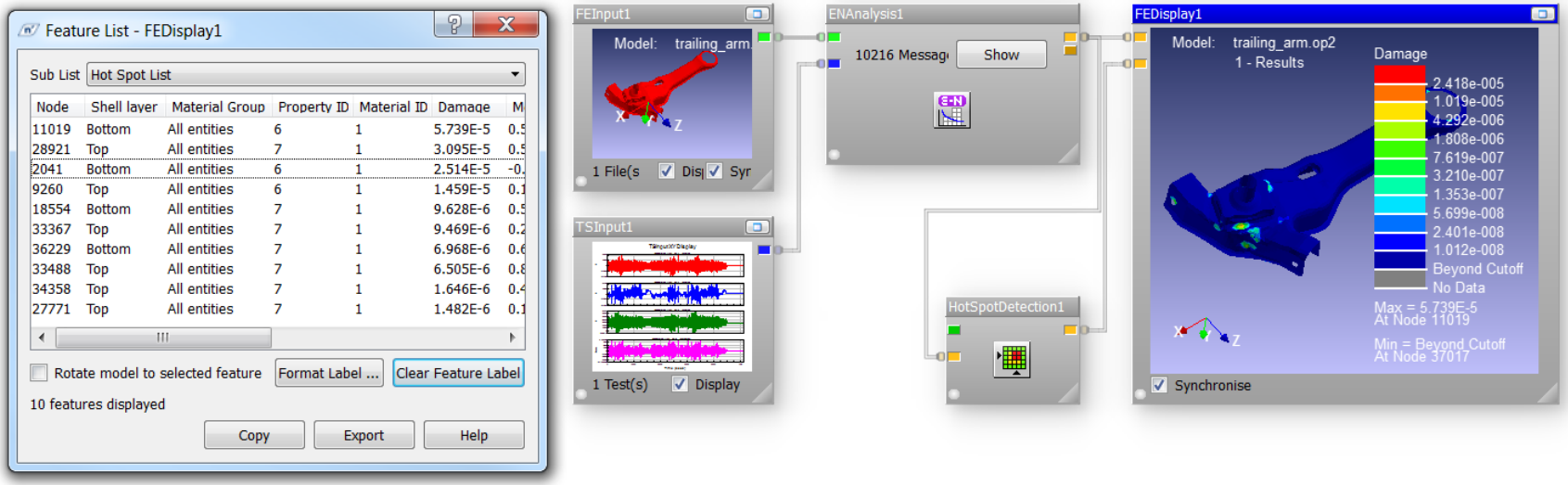
- Write out FE results for different postprocessors including:
  - ANSYS *.ans*
  - ABAQUS *.odb*
  - Hypermesh *.hyp*
  - Medina *.bof*
  - I-DEAS *.unv*
  - ASCII *.csv*
  - nCode *.fer*
  - PATRAN *.fef*





Hot Spot Detection Glyph

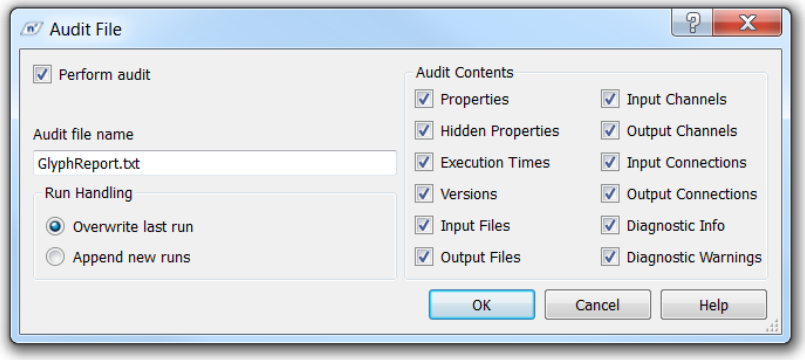
- Provides the FEDisplay glyph with a list of critical locations
- Locations are maxima in the distribution of damage and may exclude adjacent entity results



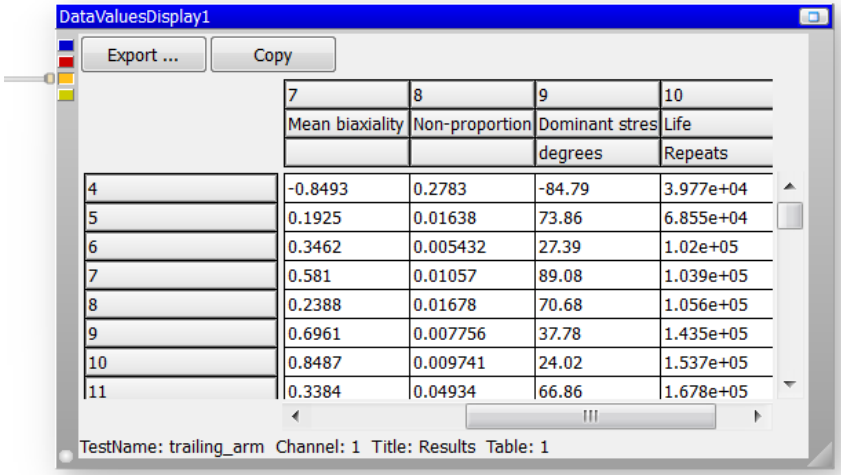
- Check boxes are available to select which hotspots are displayed

Other Important Glyphs

- *Audit Display*
  - Record properties used by all the glyphs in the executed process

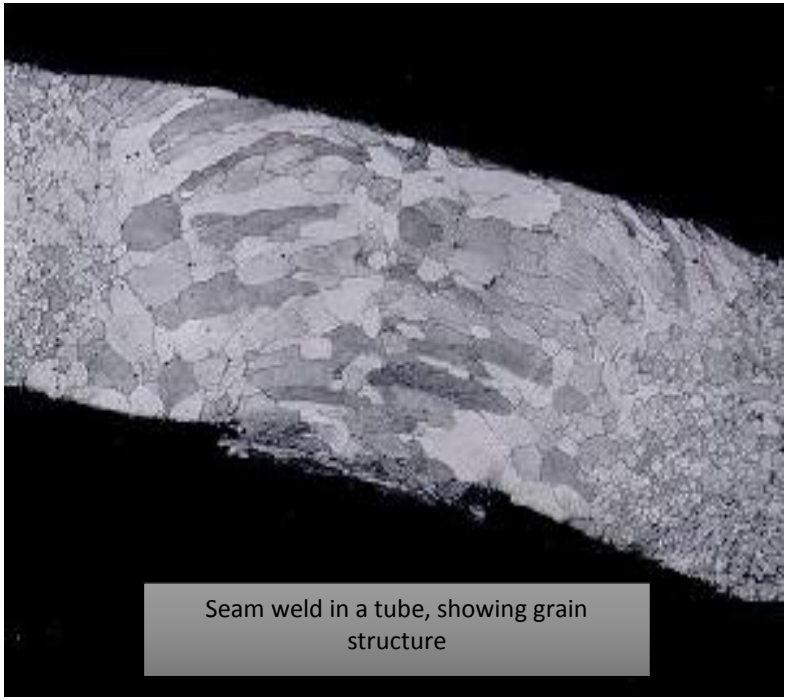


- *DataValues Display*
  - Tabulated results



- *Studio Display*
  - Make professional reports

Problematic Welds

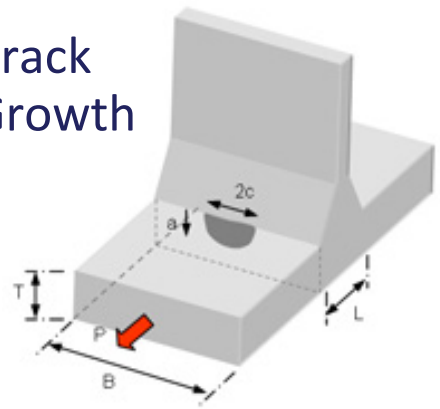


Seam weld in a tube, showing grain structure

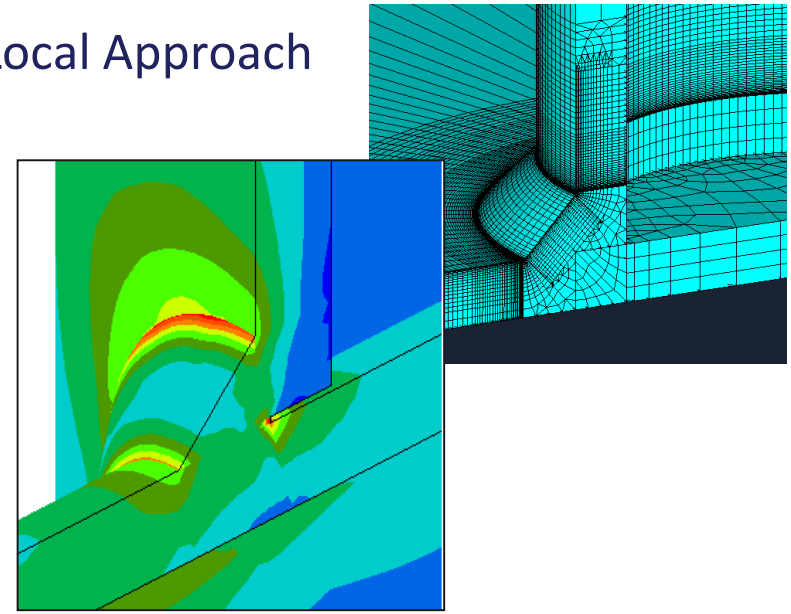
- 2,751 ‘Liberty Ships’ were built between 1941 – 1945.
- First mass production of ships with welded hulls.
- Low temperatures of the North Atlantic result in embrittlement of the steel.
- The hulls broke without any warning.
- Crack initiation and propagation in 400 ships; catastrophic failure in 145.

Weld Fatigue Calculation Strategies

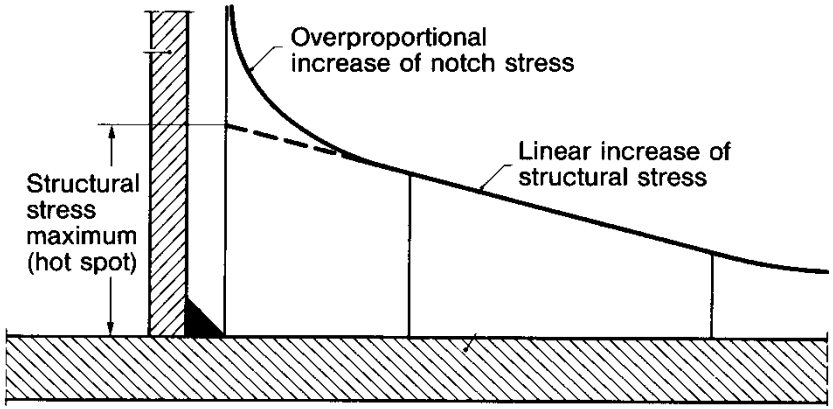
Crack Growth

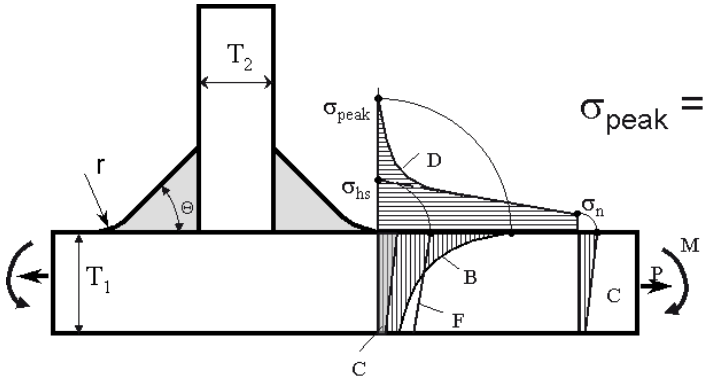


Local Approach



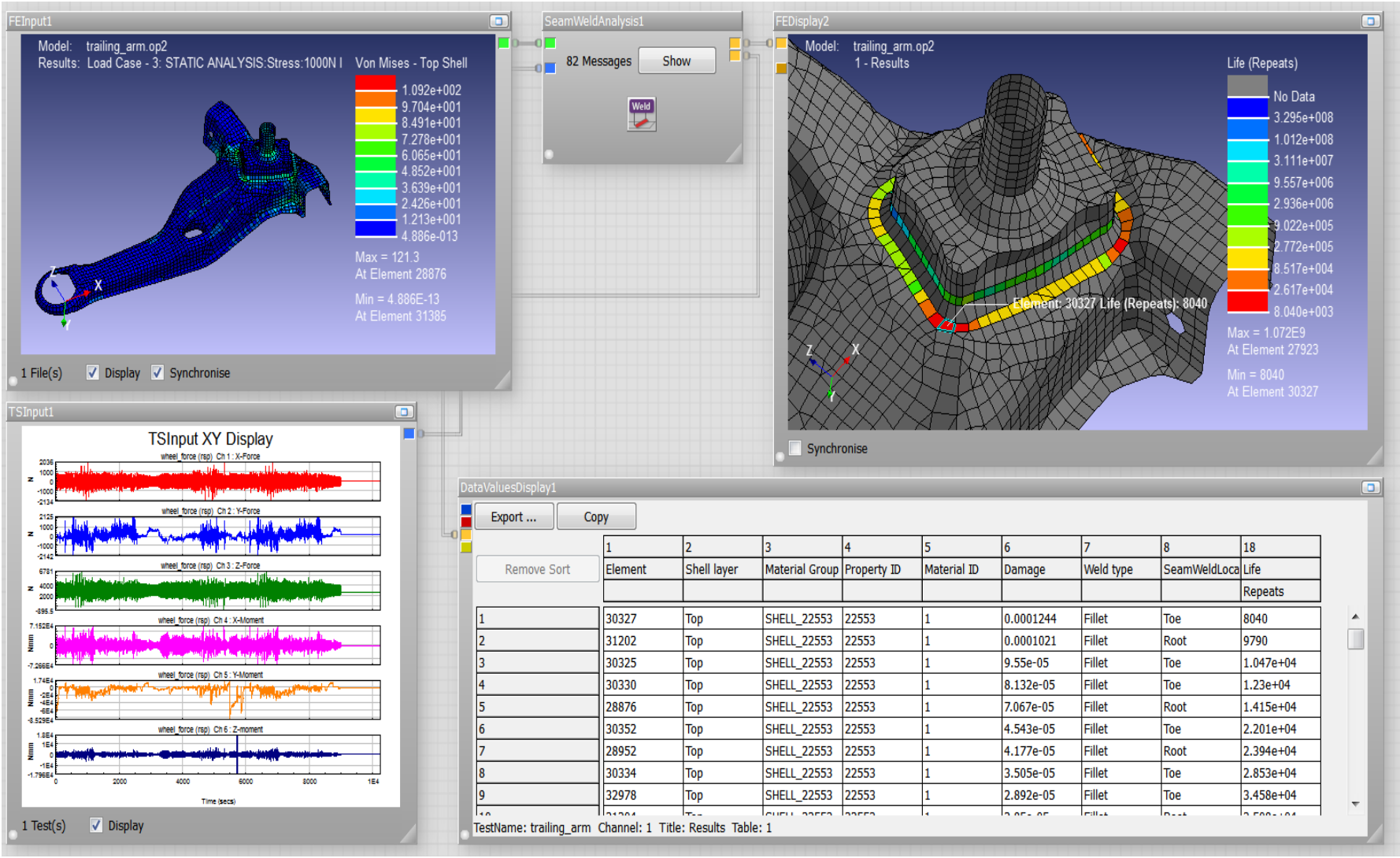
Structural Stress





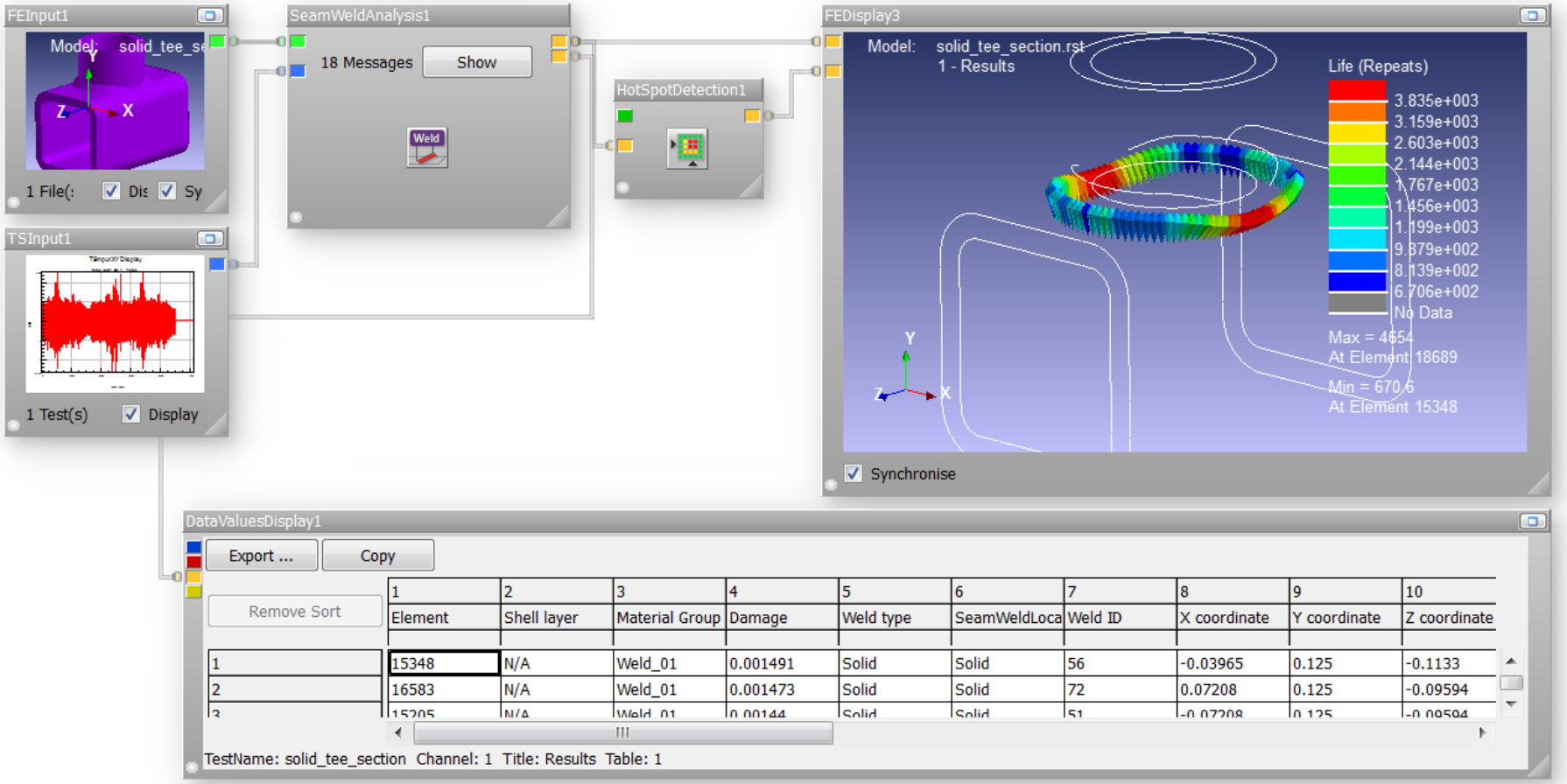
$\sigma_{peak} = K_t * \sigma_{hs}$

nCode DesignLife Process of welded sheet structures



	1	2	3	4	5	6	7	8	18
	Element	Shell layer	Material Group	Property ID	Material ID	Damage	Weld type	SeamWeldLoca	Life
									Repeats
1	30327	Top	SHELL_22553	22553	1	0.0001244	Fillet	Toe	8040
2	31202	Top	SHELL_22553	22553	1	0.0001021	Fillet	Root	9790
3	30325	Top	SHELL_22553	22553	1	9.55e-05	Fillet	Toe	1.047e+04
4	30330	Top	SHELL_22553	22553	1	8.132e-05	Fillet	Toe	1.23e+04
5	28876	Top	SHELL_22553	22553	1	7.067e-05	Fillet	Root	1.415e+04
6	30352	Top	SHELL_22553	22553	1	4.543e-05	Fillet	Toe	2.201e+04
7	28952	Top	SHELL_22553	22553	1	4.177e-05	Fillet	Root	2.394e+04
8	30334	Top	SHELL_22553	22553	1	3.505e-05	Fillet	Toe	2.853e+04
9	32978	Top	SHELL_22553	22553	1	2.892e-05	Fillet	Toe	3.458e+04

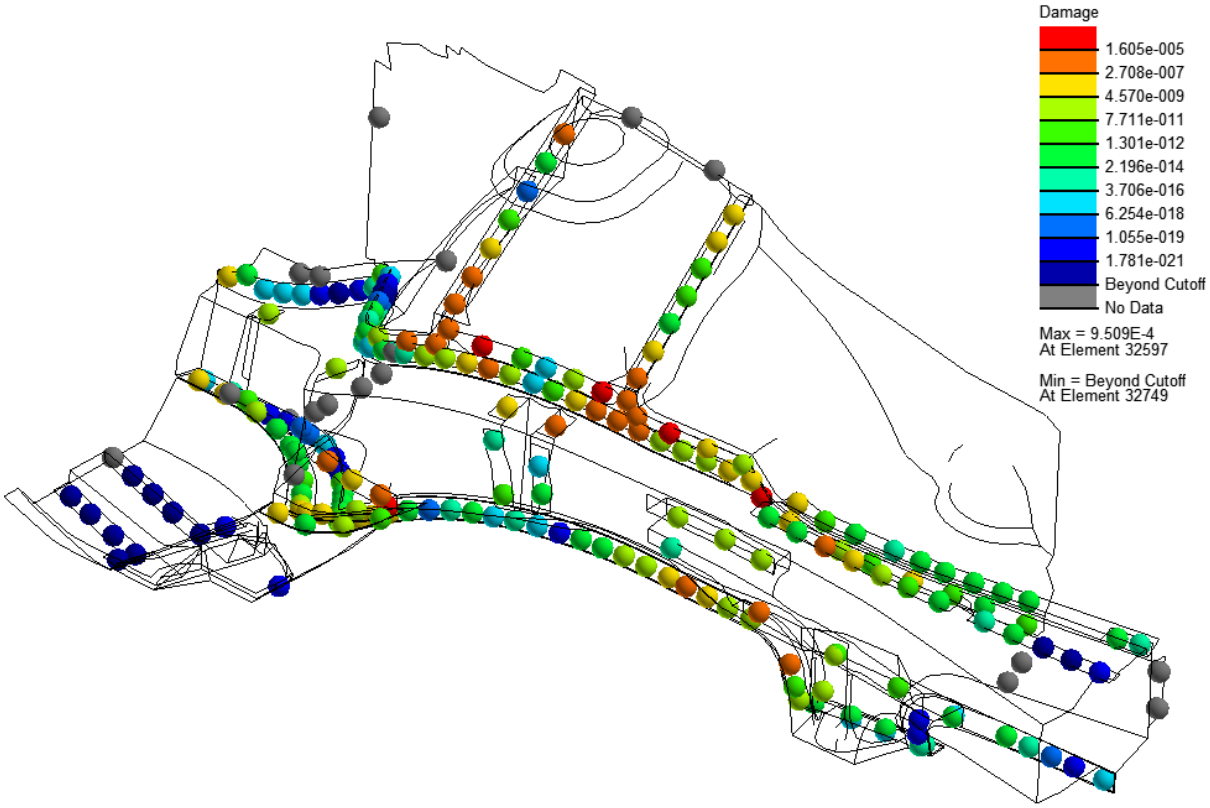
nCode DesignLife Process for Welded Solid Structures



	1	2	3	4	5	6	7	8	9	10
	Element	Shell layer	Material Group	Damage	Weld type	SeamWeldLoca	Weld ID	X coordinate	Y coordinate	Z coordinate
1	15348	N/A	Weld_01	0.001491	Solid	Solid	56	-0.03965	0.125	-0.1133
2	16583	N/A	Weld_01	0.001473	Solid	Solid	72	0.07208	0.125	-0.09594
3	15205	N/A	Weld_01	0.00144	Solid	Solid	51	-0.07208	0.125	-0.09594

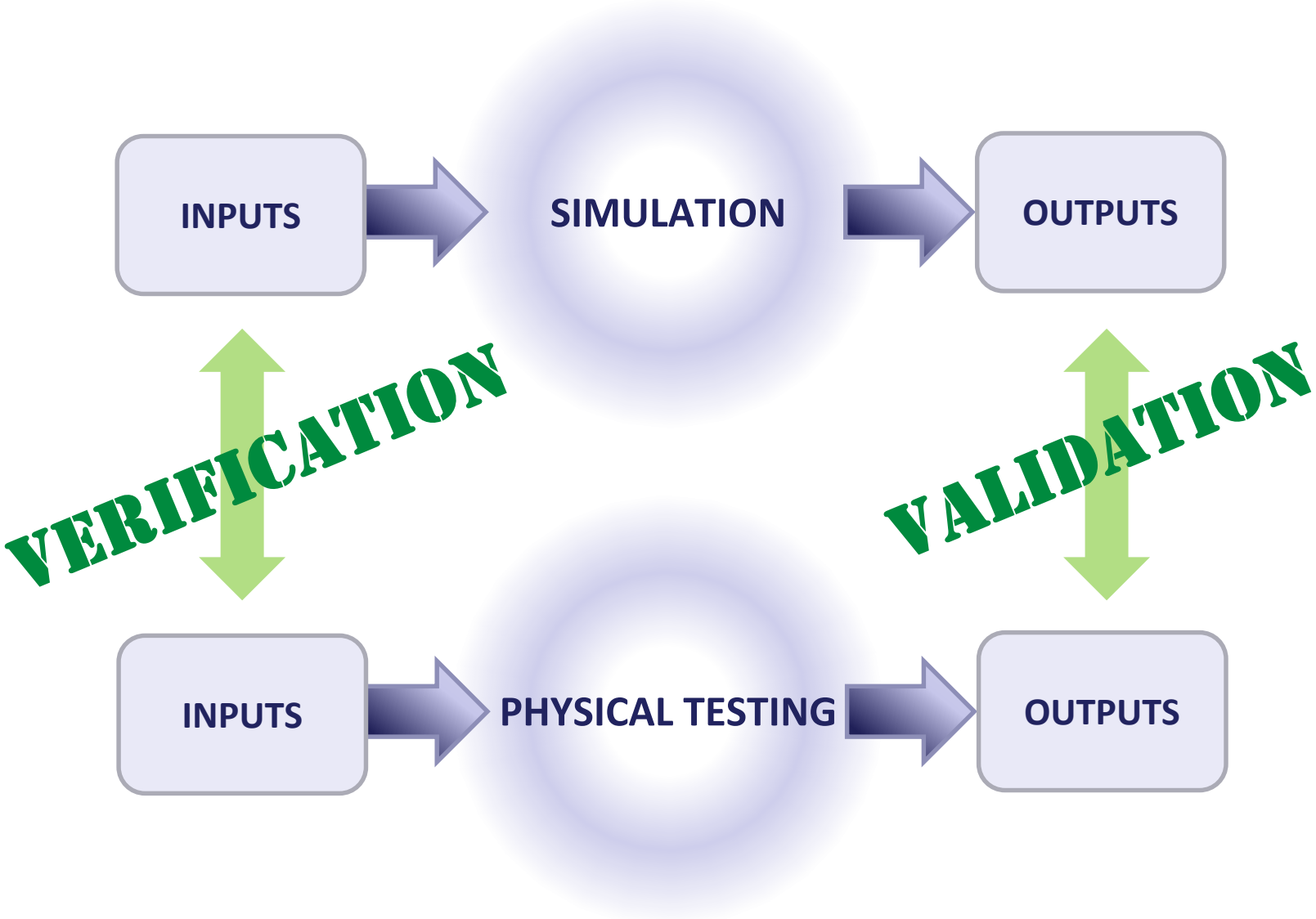
CAE Analysis Engine Inputs

- *Spot Weld Analysis* engine
  - Input: global forces and moments
  - Material models: spot weld SN



FE Correlation using Virtual Strain Gauge

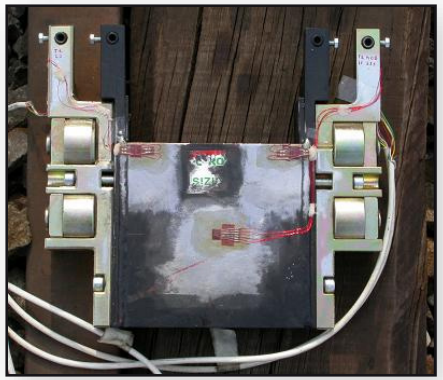
Verification & Validation

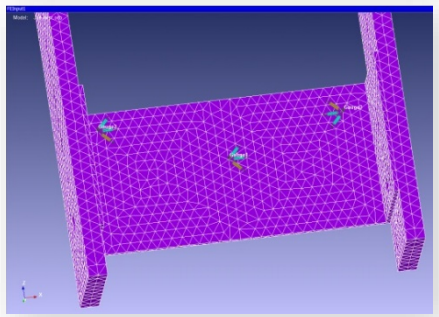


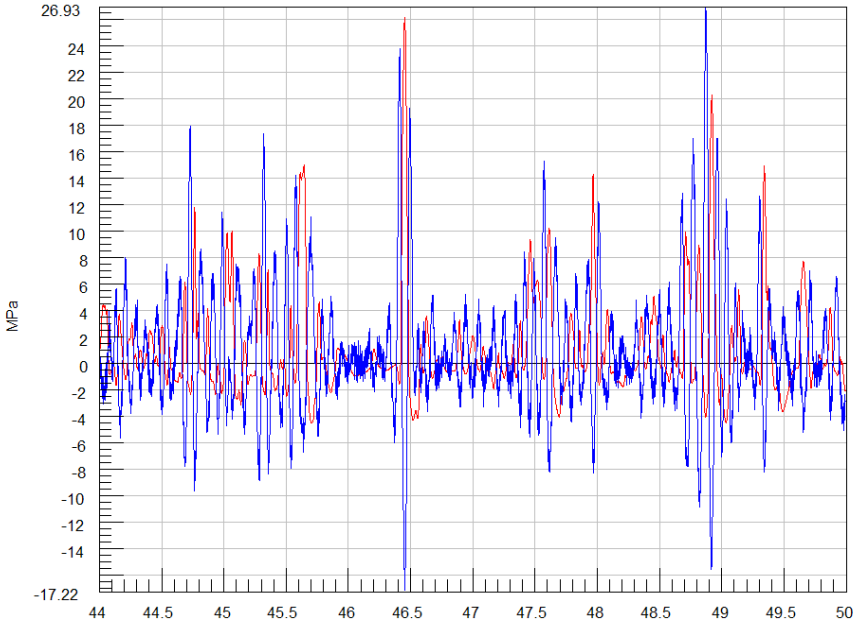
Virtual Strain Gauge

Correlating the FE Model with Reality:

- Does the FE model predict stress or strain correctly?
- The virtual strain gauge outputs strain time series
- These may then be correlated to real measured strain gauge data

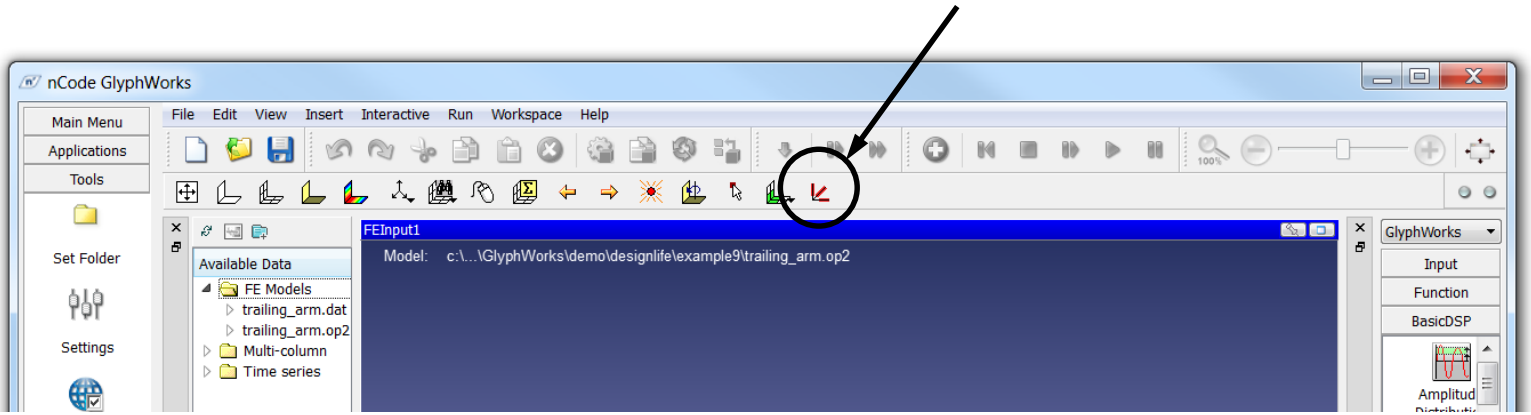






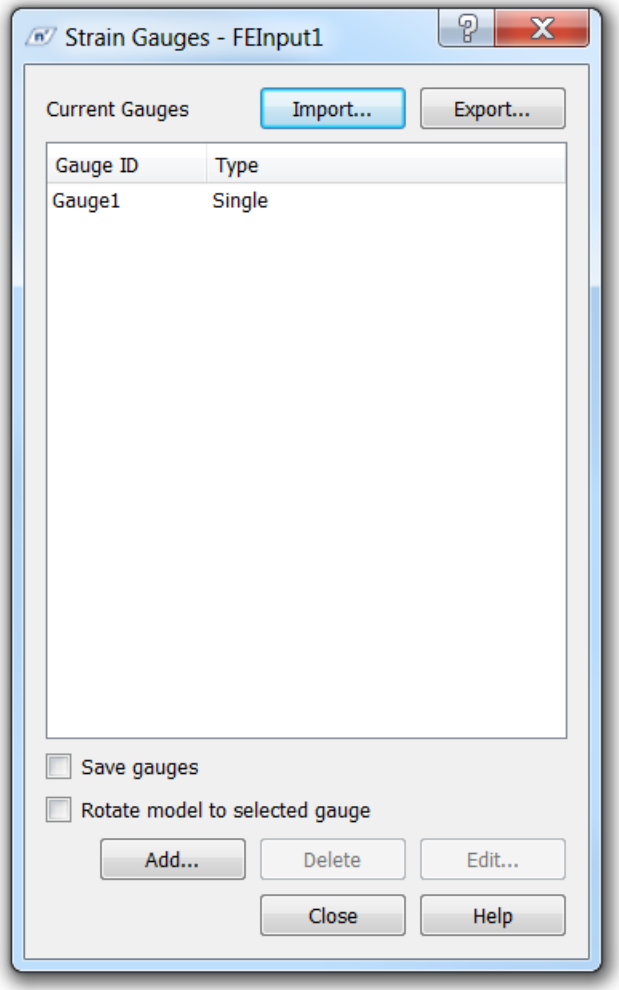
Virtual Strain Gauge

- The **Virtual Strain Gauge** provides a unique, powerful way to correlate physical tests with FE models
- This tool is available in the FEInput glyph via a toolbar icon
- Once activated, the user can place the gauge with one of the following options
  - Manually keyed IDs
  - Coordinates
  - Pick tool



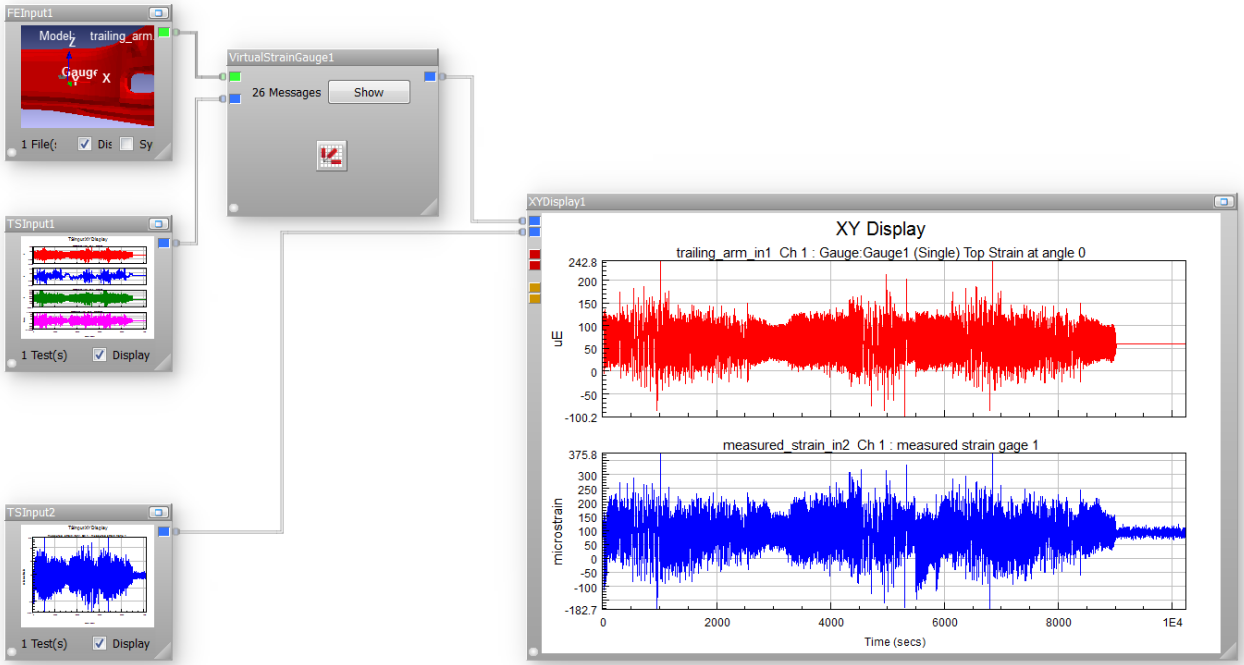
Virtual Strain Gauge

- Multiple virtual strain gauges can be placed on a model
- Gauges can be imported/exported
- Gauges can be saved in a process



Strain Gage Correlation

- Comparison of virtual strain and measured strain
  - Are they similar in shape?
  - If one goes up, does the other?
  - If one is active, is the other?



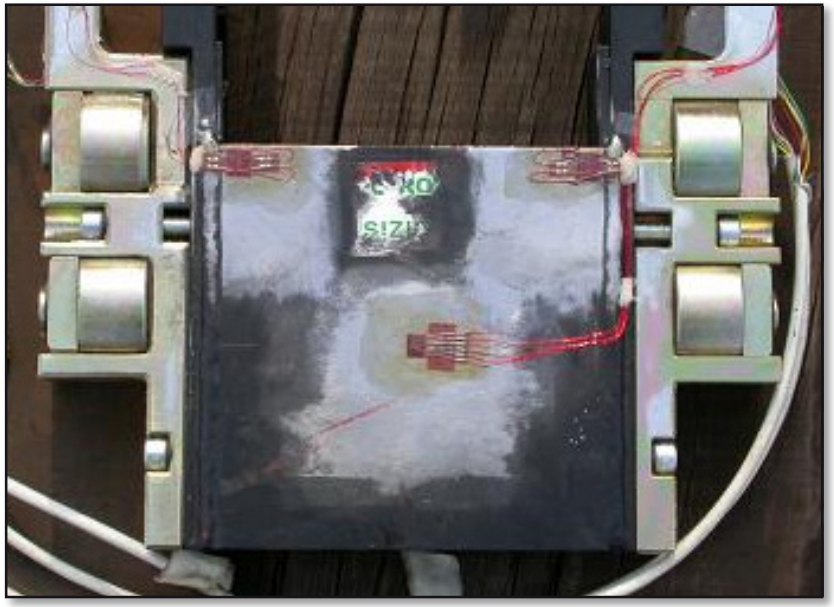
See DesignLife Worked Examples #12

Correlation and Hotspot Strains

Engineering Task	Details	Gage Location	Advantage	Disadvantage
Structural analysis	• Measure peak strain • Predict strength and durability	Local hotspots	Measures peak strain	Very sensitive to location and orientation
Correlation with FEA	• Compare with FE strains • Validate FE model	Nominal stress areas	Insensitive to location and orientation	Doesn't measure peak strain

Don't try to correlate virtual and measured strains in areas of high stress concentration.

Focus on areas with low stress gradients.

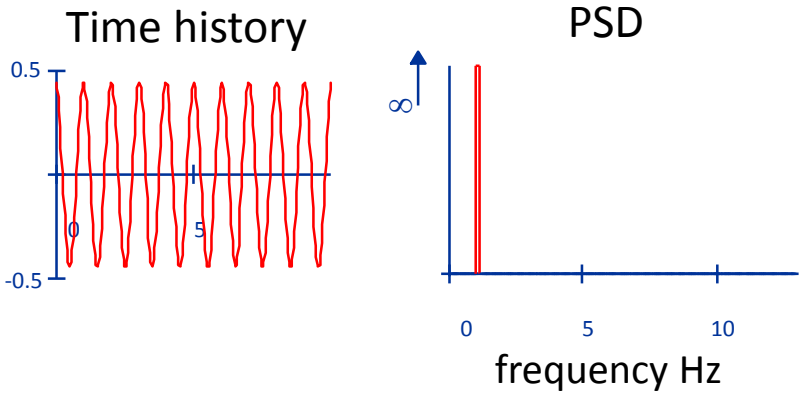


FE Correlation using Experimental Modal Analysis

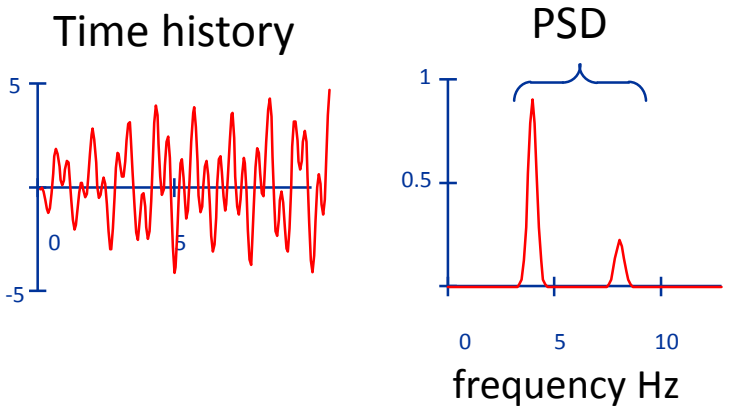
What is modal analysis?

Earlier, we looked at the frequency domain and PSDs

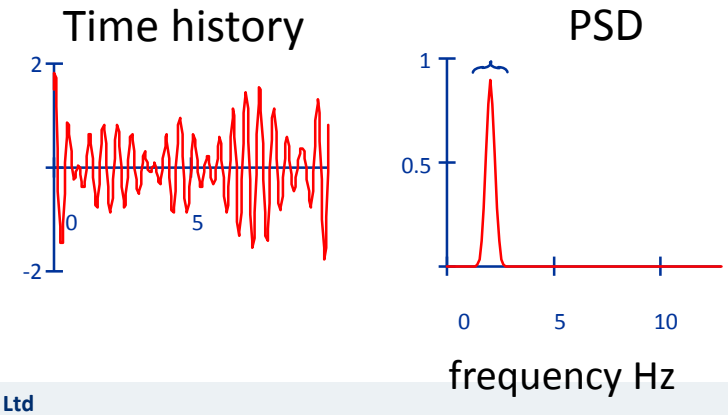
Sine wave



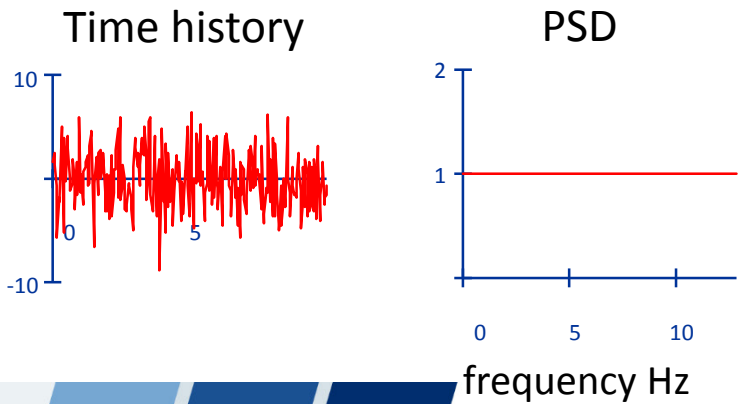
Broad band process



Narrow band process

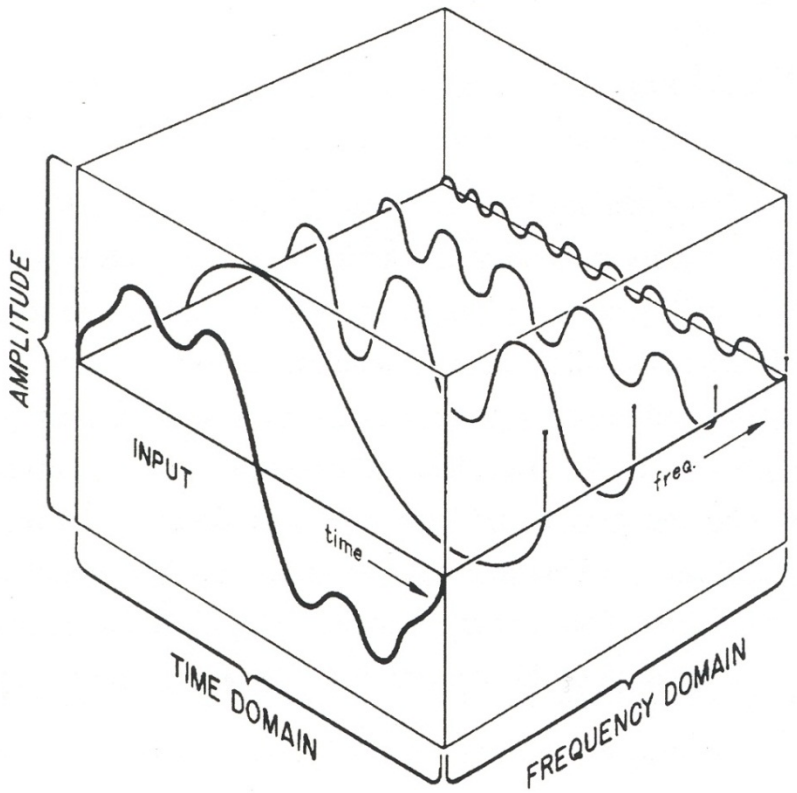


White noise process

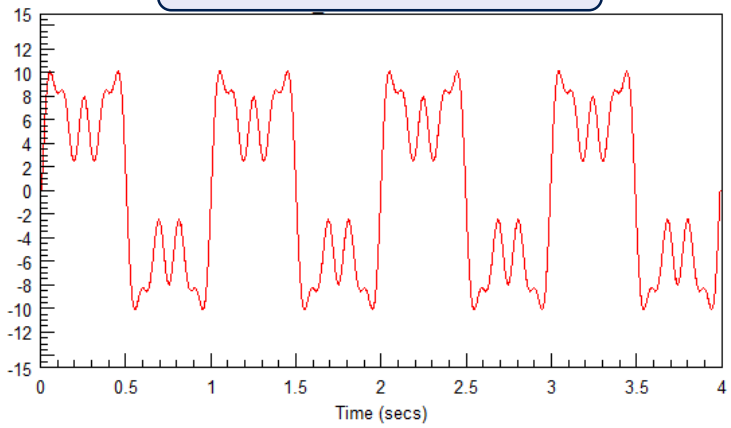


What is Modal Analysis?

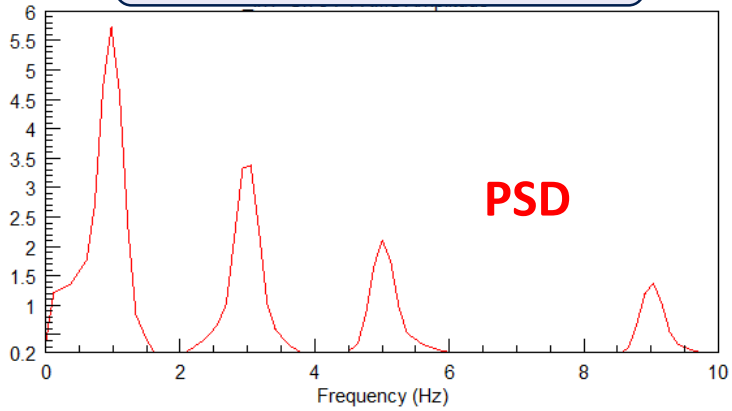
Earlier, we looked at the frequency domain and PSDs…



Time Domain

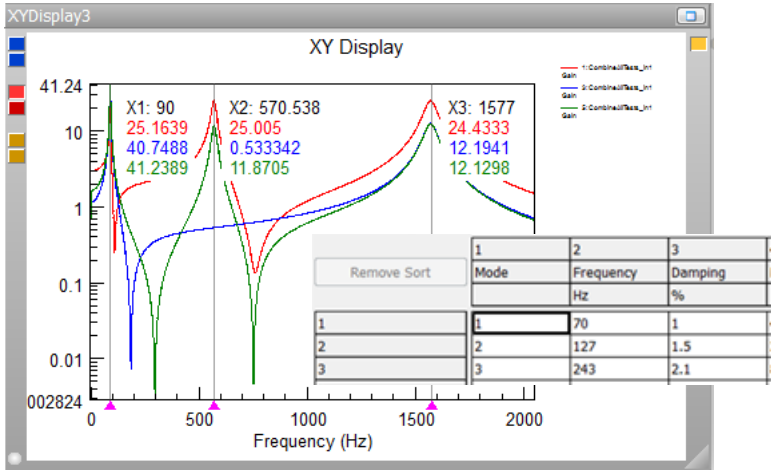


Frequency Domain



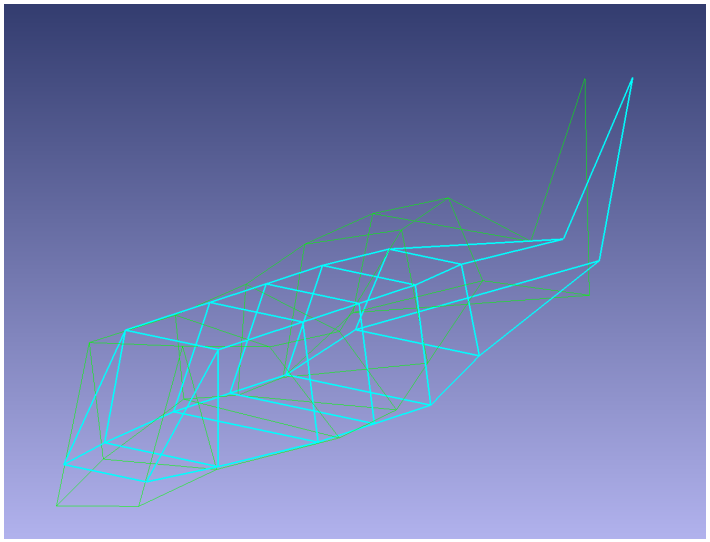
What is modal analysis?

Modal Analysis is the process of characterizing the dynamics of a machine or structure in terms of its dynamic properties.



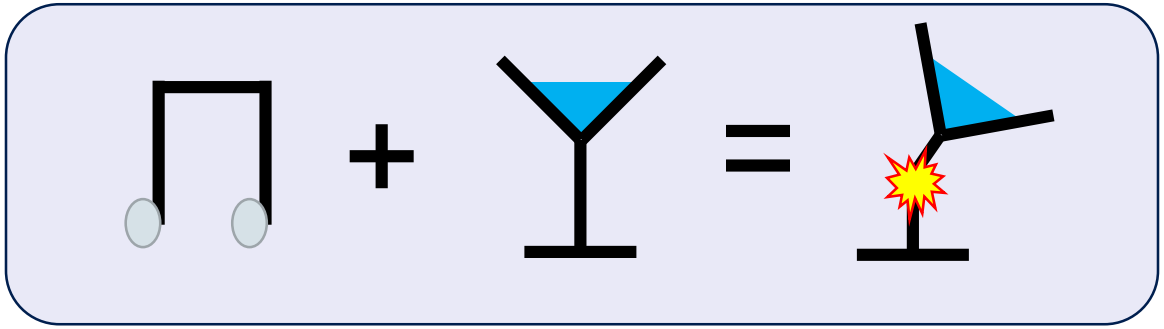
The dynamic characteristics include:

- Modal **Frequency**
- Modal **Damping**
- Mode **Shape**



Frequency Response Analysis

- Objects have a frequency at which they will oscillate at when disturbed
- If a forcing function is applied to an object, energy transfer reinforces the oscillation of the natural frequency, and causes energy build up in the object
- Incorrect damping at this point can have catastrophic results

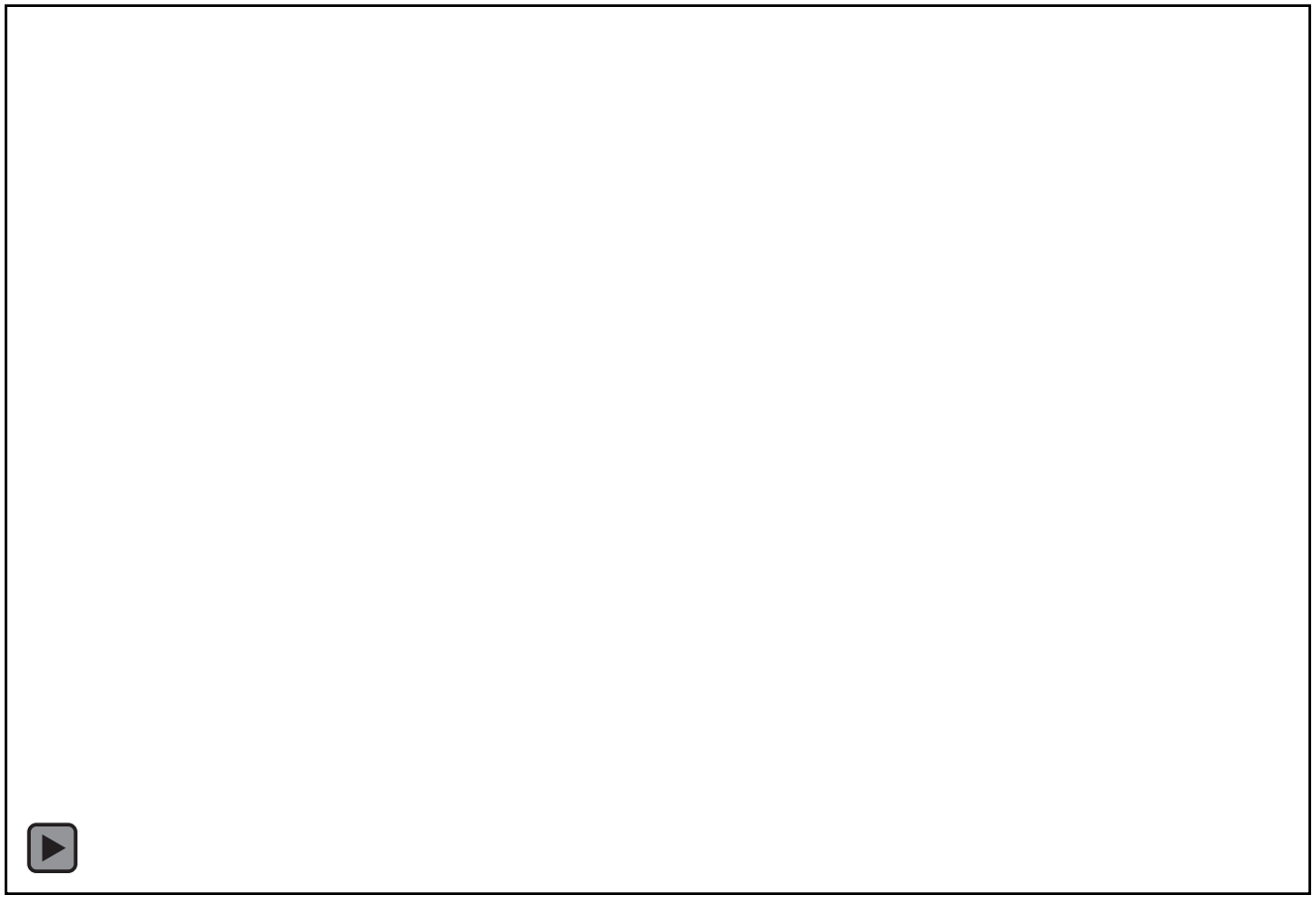


- Chinook helicopter ground resonance video on YouTube;
  - - back: https://www.google.co.uk/?gws_rd=ssl#q=chinook+ground+resonance
  - - side: http://www.youtube.com/watch?v=RihcJR0zvfM

  - The videos are from ground ballistics testing at the Aberdeen proving ground. They were setting up to shoot something at the aircraft while it was running and instead the chained down aircraft tore itself apart when it went into ground resonance

Helicopter Ground Resonance

- Rotor imbalance tends to cause motion in the surrounding structure
- This imbalance frequency can align with the helicopter's rigid body roll mode
- Unless damped, results can be catastrophic!



Frequency Response Analysis

This analysis characterises the dynamic properties of a structure:

- Frequencies of Resonance
- Mode shapes
- Modal parameters (damping)

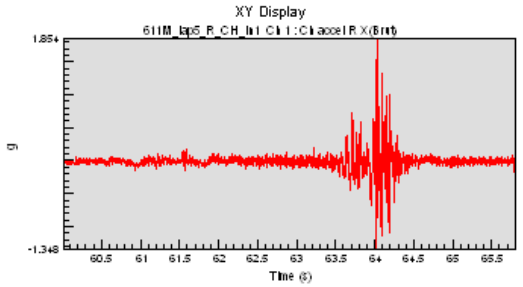
Relationships between Input and Response can be described in:

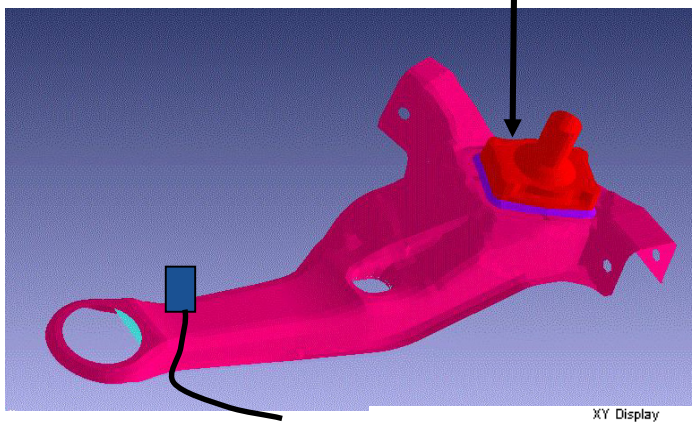
- Time domain: Impulse Response
- Frequency domain: Frequency Response Function (FRF)

Typical outputs are:

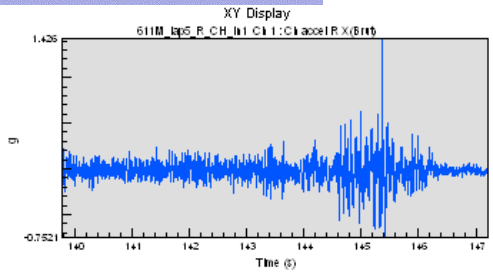
- Gain
- Phase
- Coherence
- Auto-Spectrum and Cross-Spectrum

Input
Force/excitation



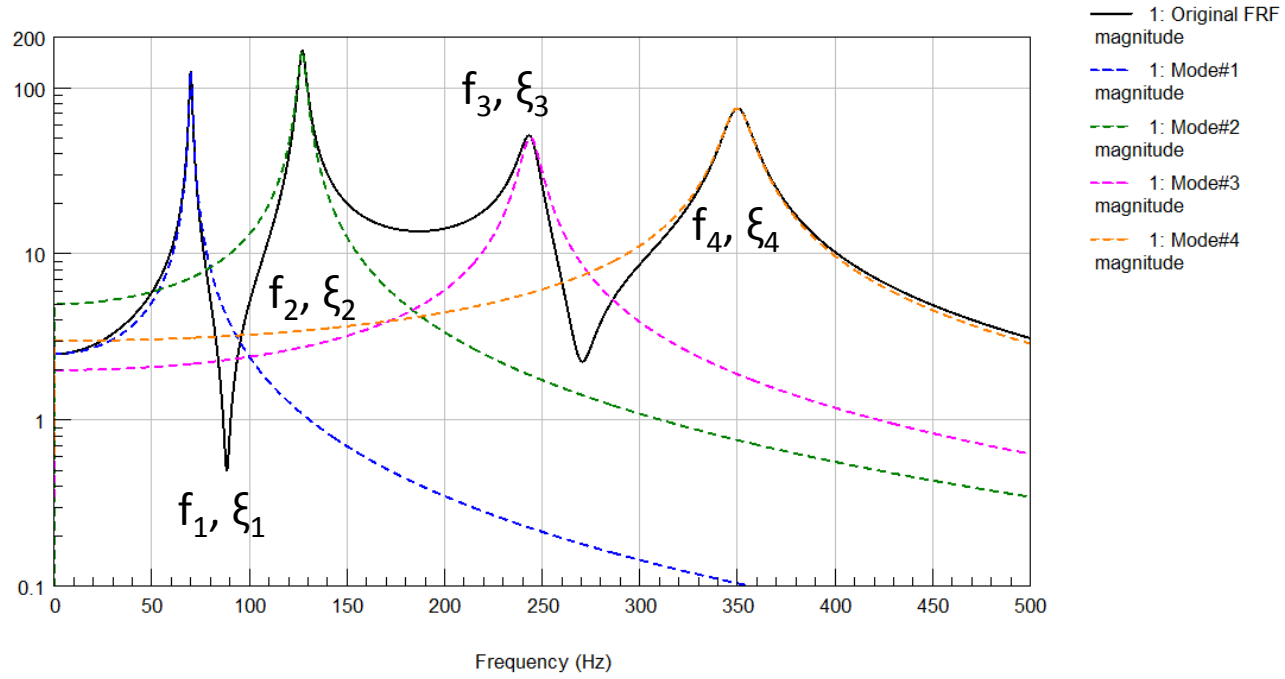


Output Vibration



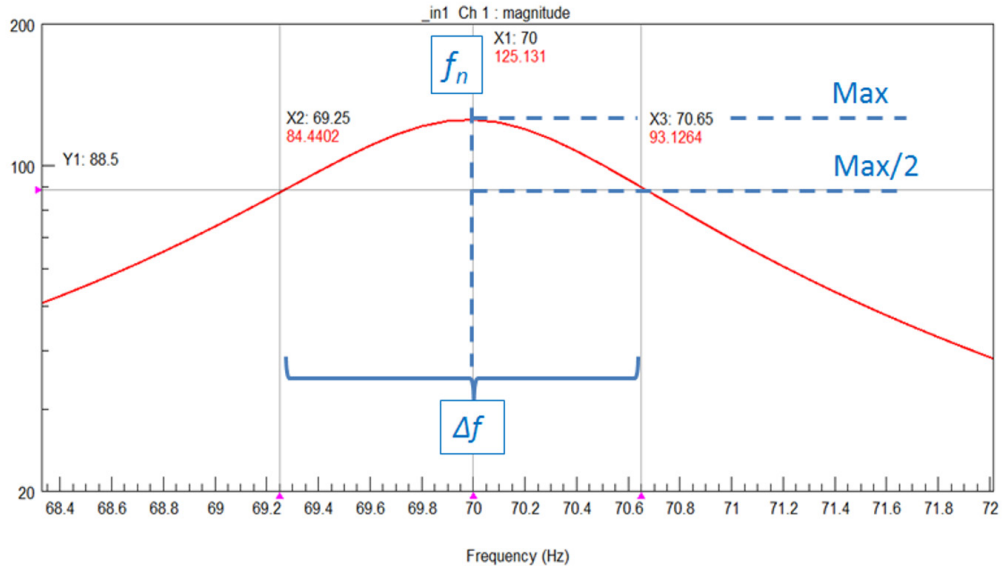
Modal Analysis: concept

- Also known as Curve fitting or modal parameter estimation
- The measured FRF is basically broken down into the principal components that make up the measured data – into many single degree of freedom (SDOF) systems
- Obtain frequency, damping and mode shapes



The PeakPick Approach for Modal Analysis

It is a SDOF approach, well-know, fast and robust



For a particular mode at frequency f_n, the damping ratio ξ can be found from the following equation:

$$\xi = \frac{\Delta f}{2 f_n}$$

So each mode is defined by a frequency and a damping ratio

Experimental Modal Analysis glyph

The EMA glyph expects FRFs in:

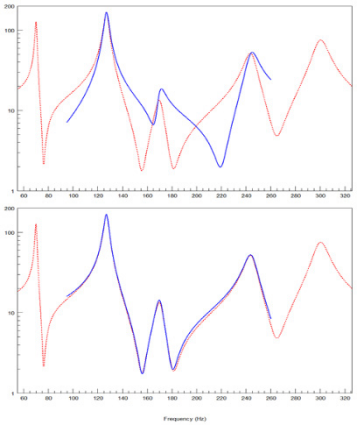
- Gain
- Phase

Analysis properties include:

- Frequency range
- List of natural frequencies
- Whether to account for residual modes

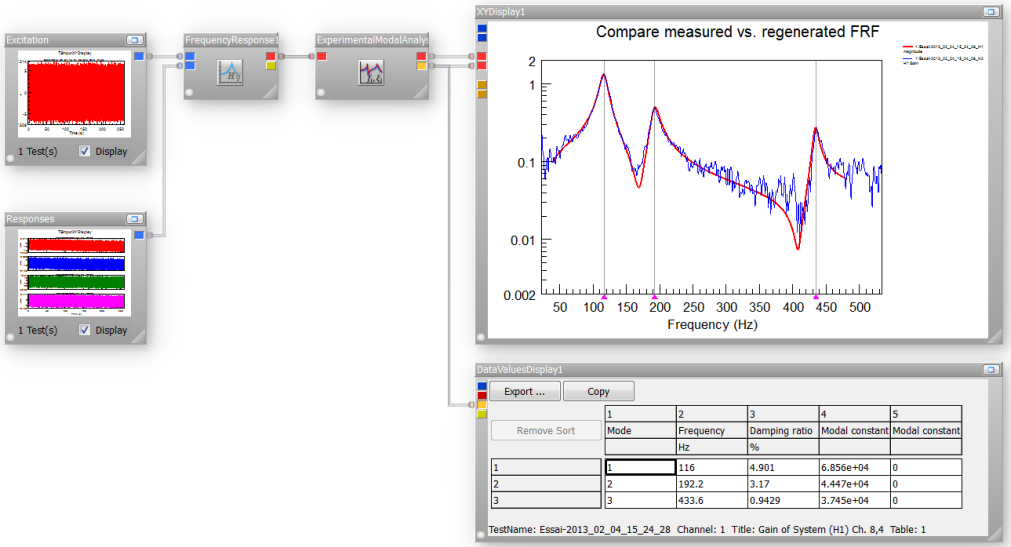
Results are:

- The Regenerated FRFs in Gain and Phase
- A multichannel modal table containing the damping ratios



FRF regenerated w/o residuals

FRF regenerated with residuals



Experimental vs. FEA-based Modal Analysis

Experimental Modal Analysis uses experimental data taken from a test structure. Parameter estimation (curve fitting) is used to obtain modal parameters from the experimental data.

FEA-based Modal Analysis synthesizes equations of motion for a structure using Finite Element Method (FEM). Modal parameters are solutions of the equations of motion.

Advantages

- The analytical model can be built **before** the prototype hardware.
- **"What If ?"** investigations are cheaper, faster and easier than modifying real hardware.

Disadvantages

- The analytical model can be **inaccurate.**
- Some aspects are still **difficult to model** such as contact, damping, nonlinearities, etc.

On the influence of the damping ratio on fatigue Life

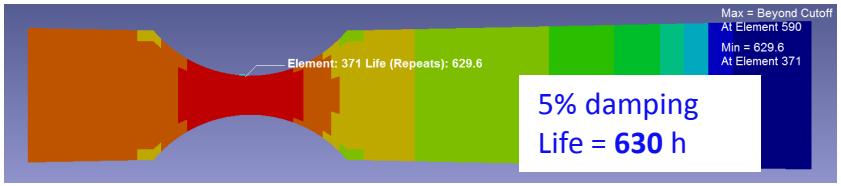
- Damping is an important property to set up when performing a dynamic simulation
- It is often overlooked and a default value (typ. 5%) is used for all modes

- A small error in damping can lead to a large error in the fatigue life estimate.
- Example: 3% versus 5% damping ratio can lead to fatigue life estimates of **an order of magnitude** apart

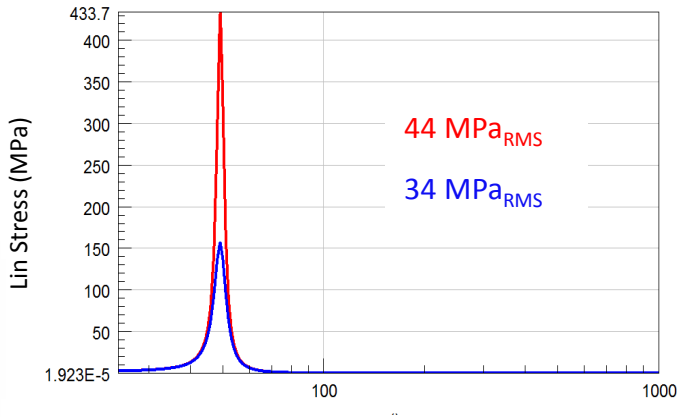
- This is due to the calculated RMS value which is higher with low damping

Good fatigue life predictions rely heavily on using realistic damping ratios

Compare contour plots of fatigue Life (b=10)

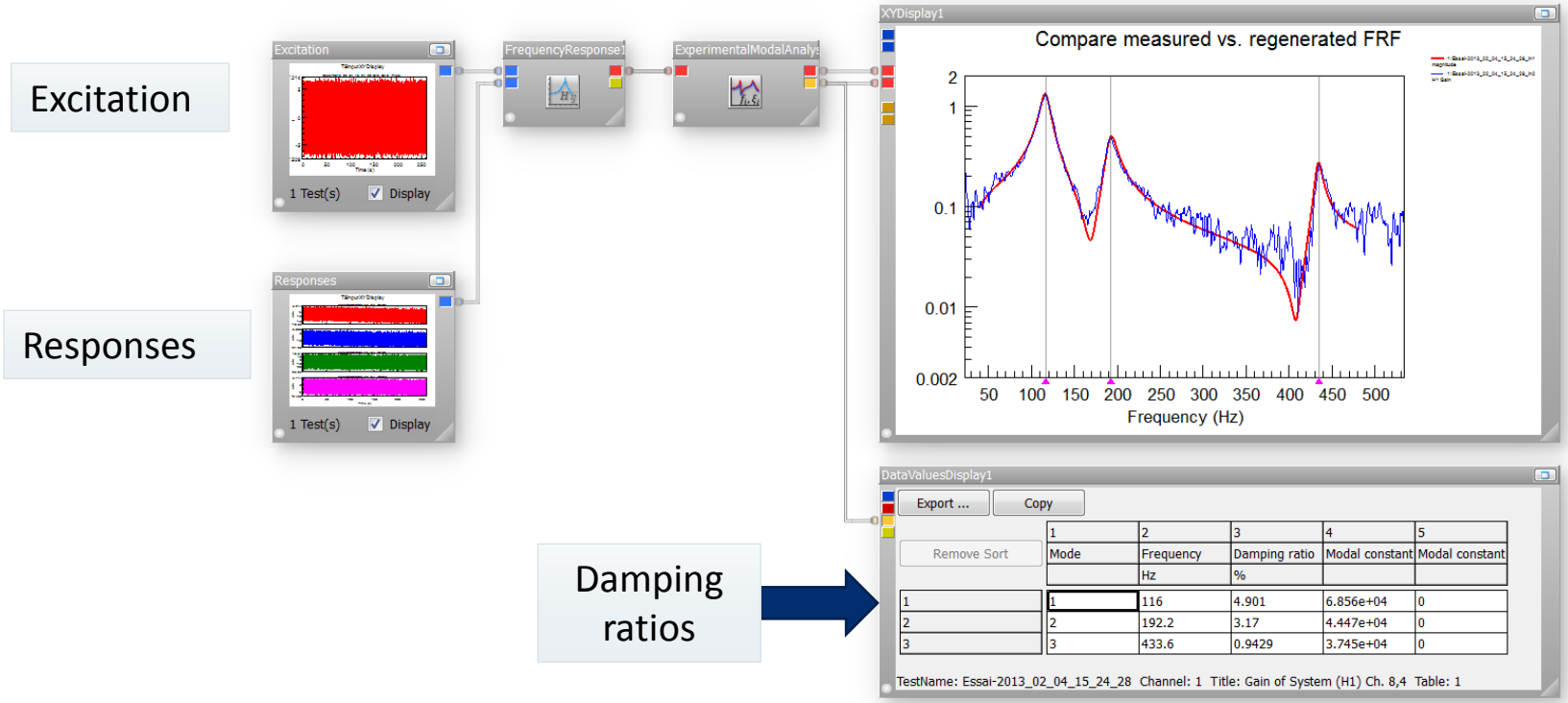


Stress PSD at critical element



VibeSys Demonstration

VibeSys includes the Experimental Modal Analysis glyph for determining accurate damping ratios using the frequency domain

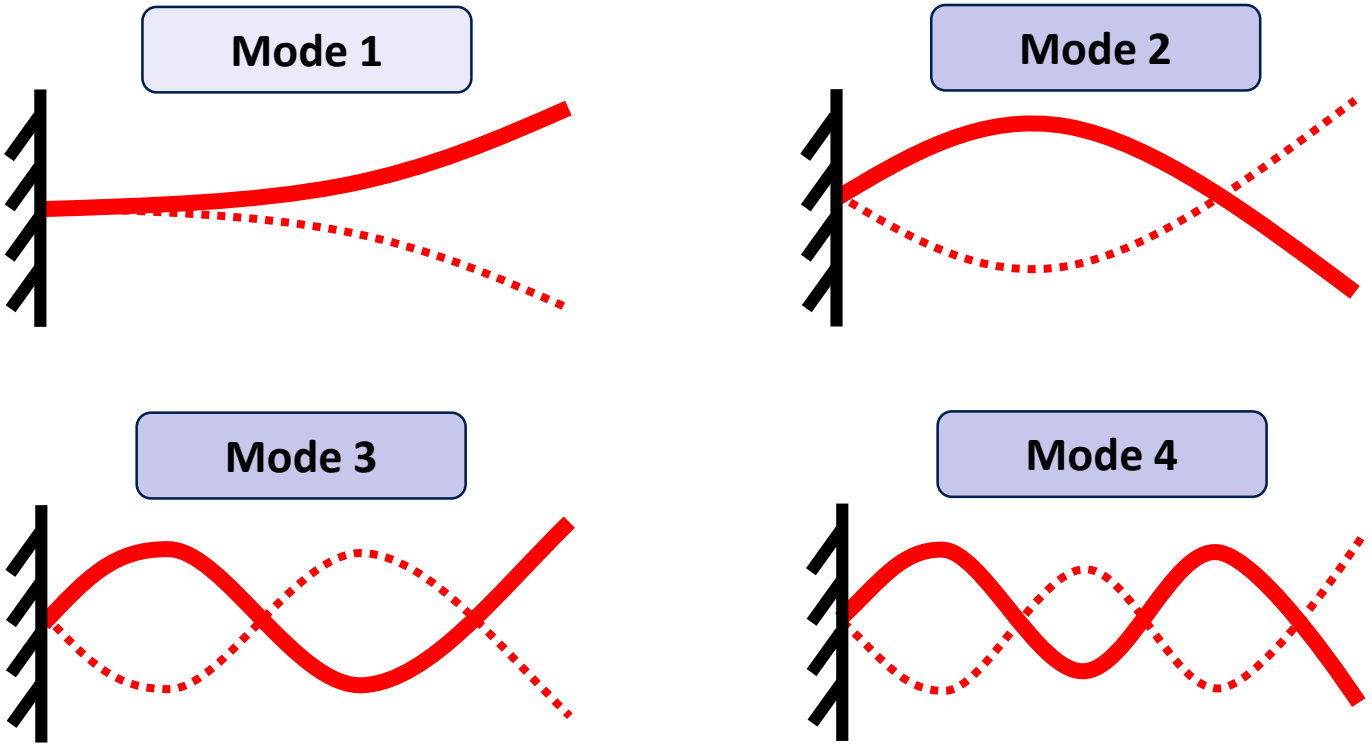


See VibeSys Worked Example #11

Correlation using Operational Deflection Shapes

Operational Deflection Shapes

When a mode shape is excited, a structure will resonate with a particular shaped response. For a cantilever beam, the first 4 mode shapes are:

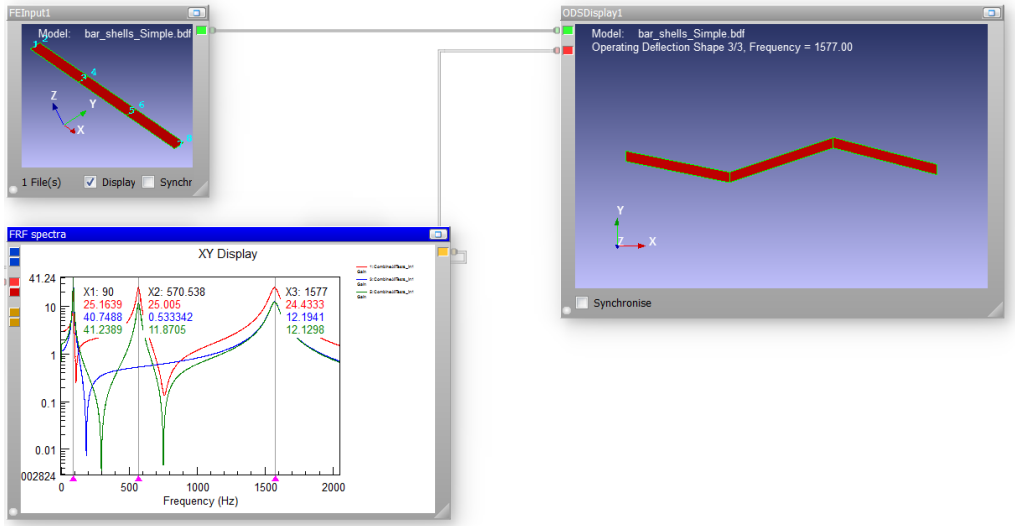


By comparing the frequencies and shape of each mode (from experiments) with the modal frequencies found during FEA, the accuracy of your simulation can be evaluated, and validated

Operating Deflection Shapes glyph

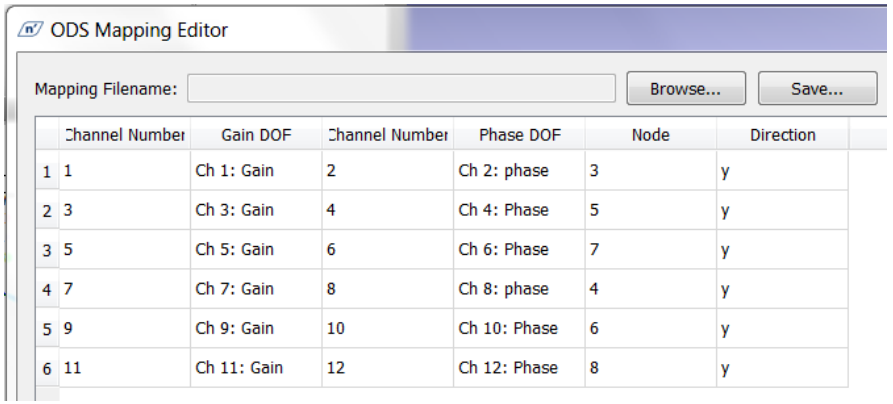
The ODS glyph expects :

- A geometry
  - UNV, BDF/DAT, INP
  - FE results files
- Nodal Displacements
  - Time series
  - FRF spectra
  - Modal Table (from EMA)



The mapping between nodes and measurements can be done via:

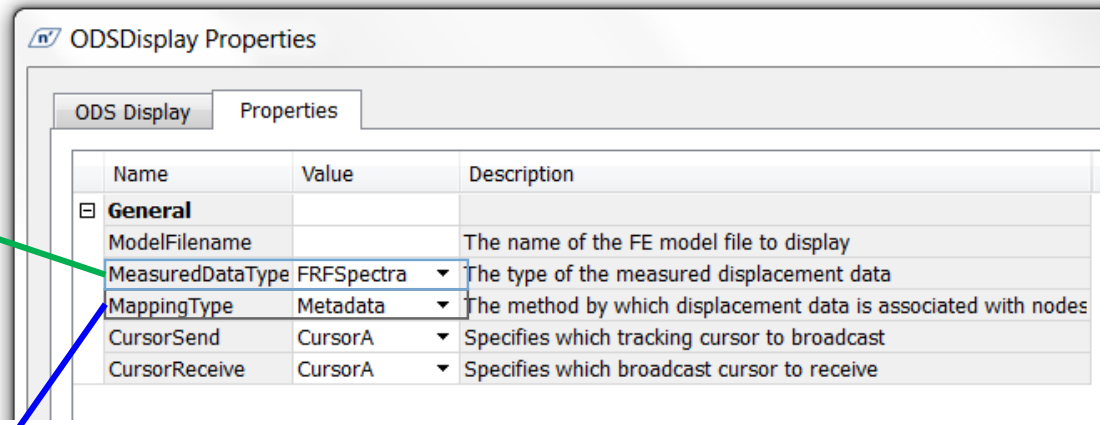
- The ODS Mapping Editor
- A text file
- Some Metadata *#DOFIdentification.Node#* and *#DOFIdentification.Direction#*



	Channel Number	Gain DOF	Channel Number	Phase DOF	Node	Direction
1	1	Ch 1: Gain	2	Ch 2: phase	3	y
2	3	Ch 3: Gain	4	Ch 4: Phase	5	y
3	5	Ch 5: Gain	6	Ch 6: Phase	7	y
4	7	Ch 7: Gain	8	Ch 8: phase	4	y
5	9	Ch 9: Gain	10	Ch 10: Phase	6	y
6	11	Ch 11: Gain	12	Ch 12: Phase	8	y

ODS Glyph: properties

Select the nature of the nodal displacements here



Select how to map nodes with displacements

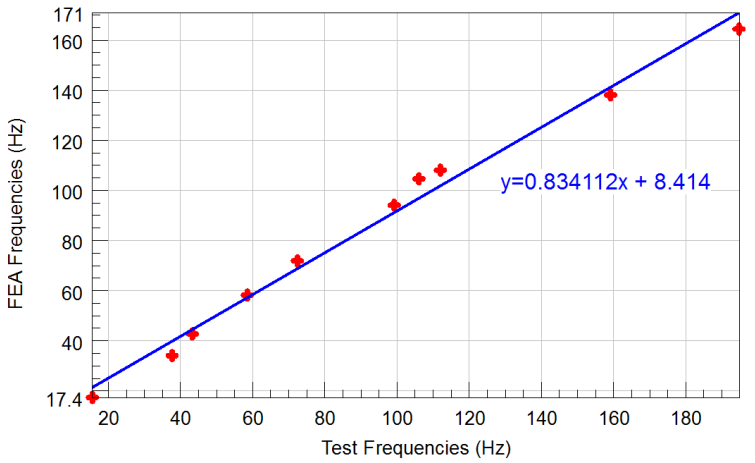
Metadata	File	User
Metadata are looked for in the input pipe containing the displacements	A file is expected to contain the mapping information	A dedicated GUI appears to map nodes and displacements

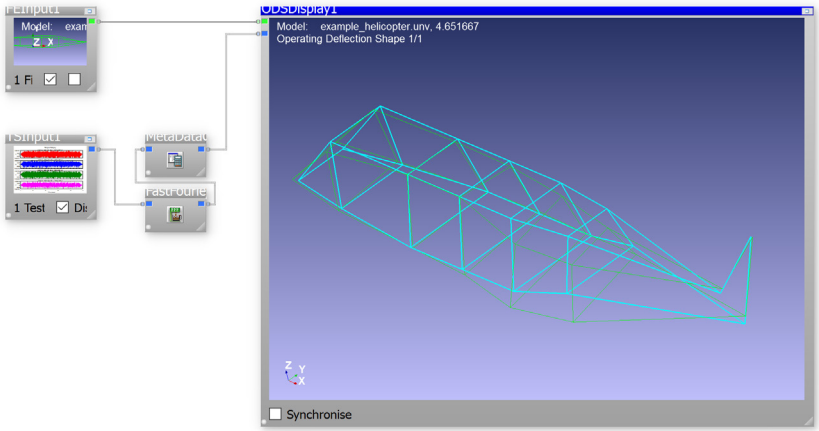
How to check my FE simulation is realistic?

- Compare the calculated vs measured modal frequencies

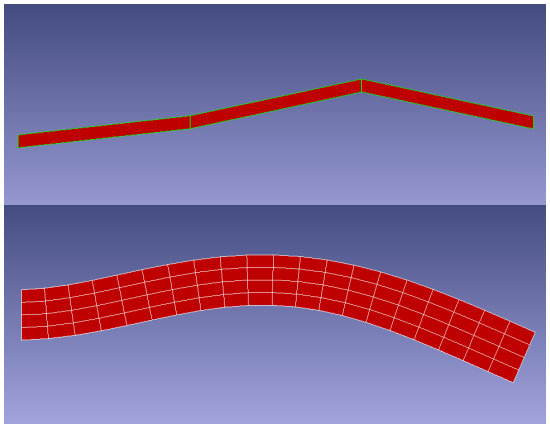
- Use the ODS glyph to compare the mode shapes

Compare modal frequencies



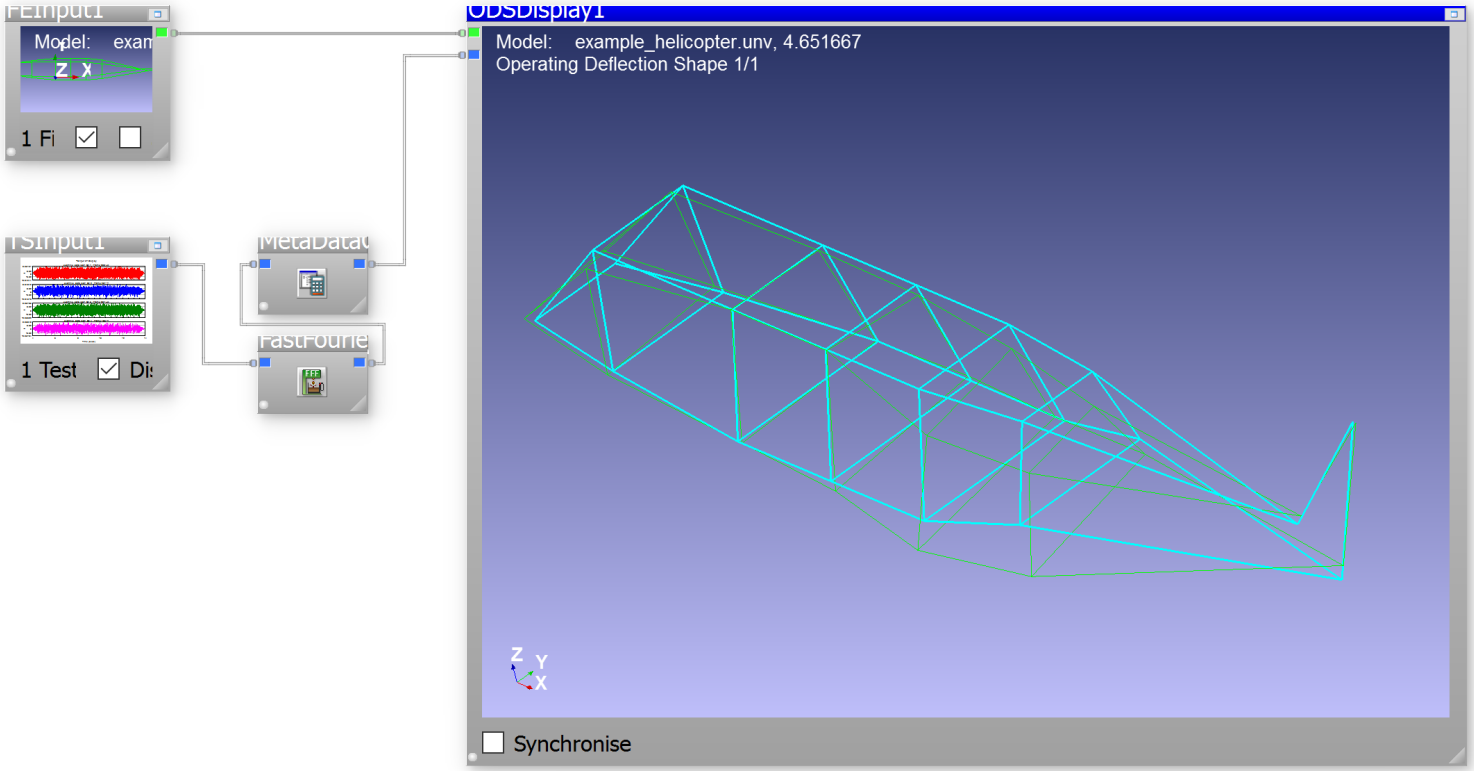


Compare mode shapes



VibeSys Demonstration

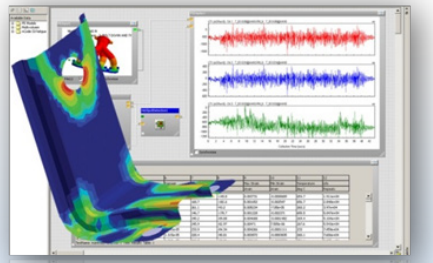
VibeSys includes the Operational Deflection Shape glyph allowing you to compare experimental and simulated mode shapes



See VibeSys Worked Example #11

Summary

nCode Product Range



nCode DesignLife

CAE DURABILITY

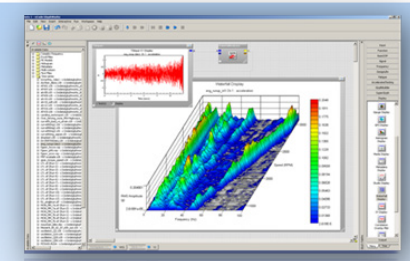
- Fatigue analysis technology for FEA
- Process encapsulation
- Fast, configurable, and scalable

nCode GlyphWorks

DATA PROCESSING FOR DURABILITY

- Complex analysis to report, simply done
- Graphical, interactive & powerful analysis
- World leading fatigue analysis capabilities

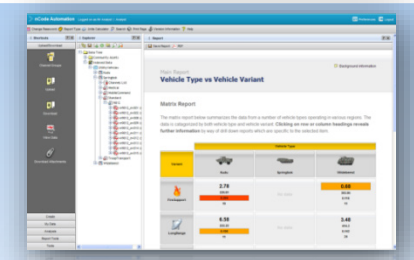
nCode CDS Licensing



nCode VibeSys

ACOUSTIC & VIBRATION ANALYSIS

- Powerful and simple-to-use
- Noise and Vibration analyses including rotating machinery, structural dynamics and human perception



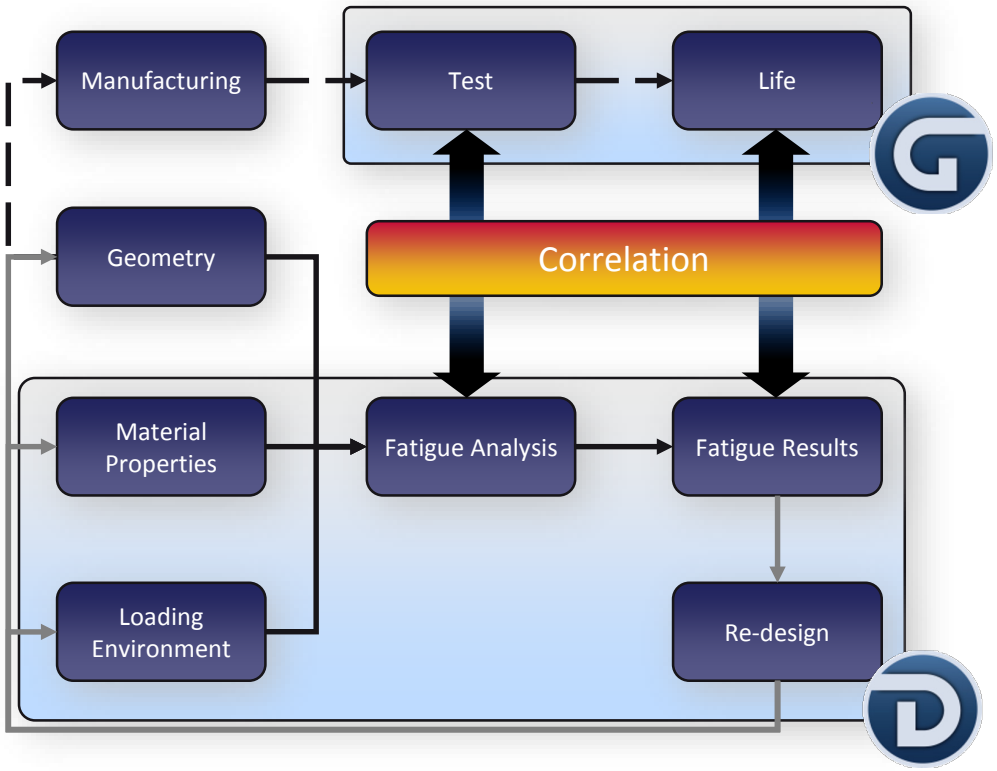
nCode Automation

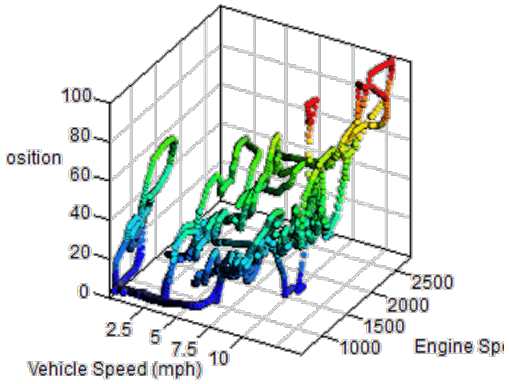
MAXIMIZING ROI ON TEST & DURABILITY

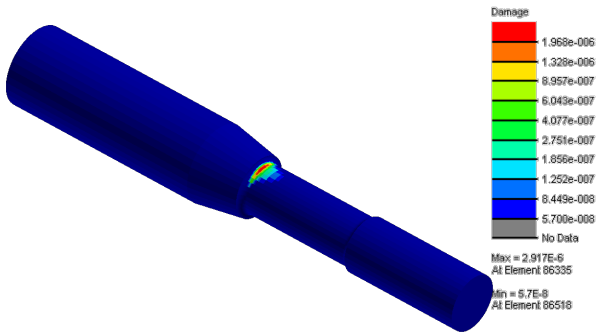
- Enables collaboration, data management, and standardized analyses
- Search, query and reporting through secure web access.
- Data to decisions

Design for Durability: Present Time

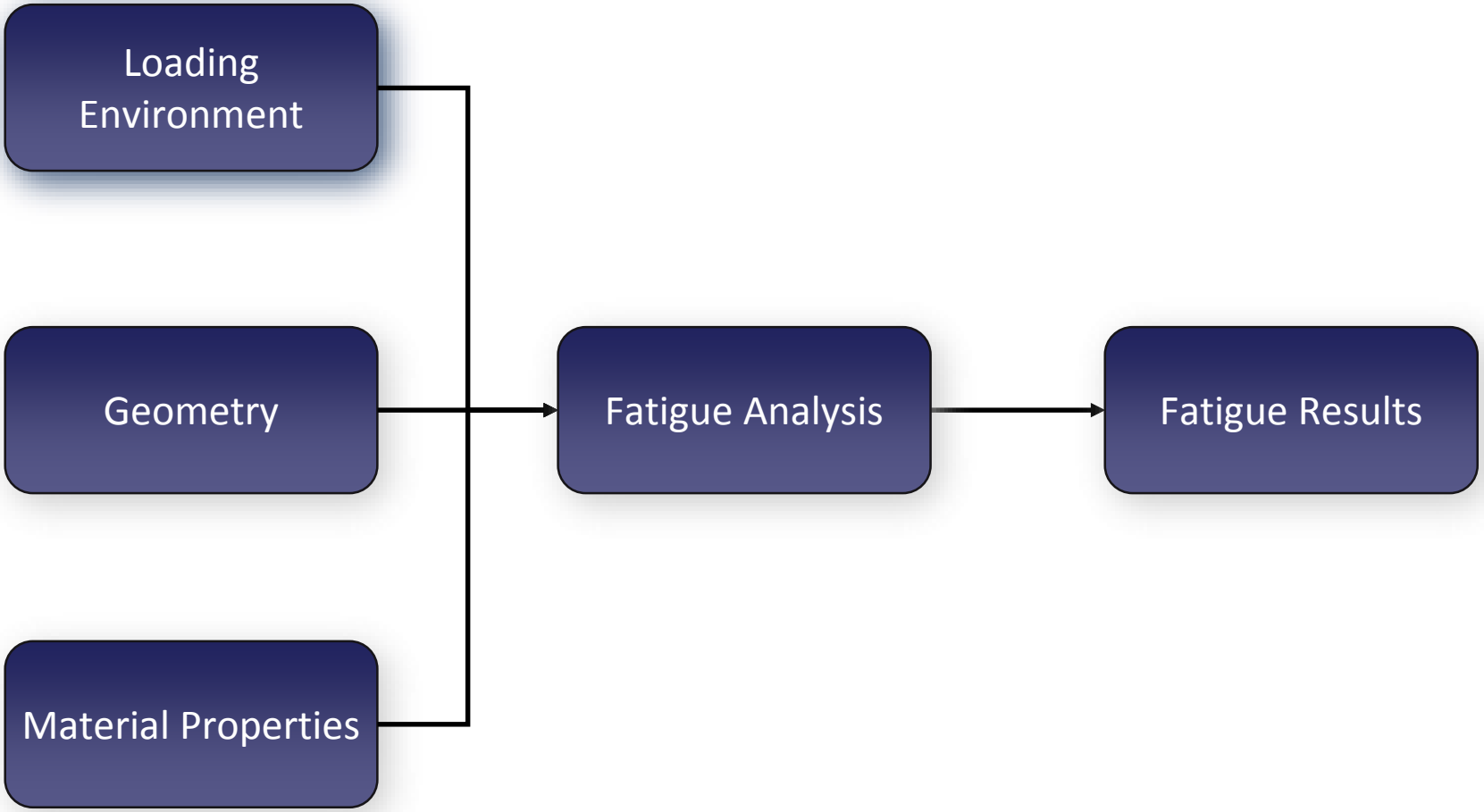
- **GlyphWorks** provides data processing capabilities to understand customers and loading, and test results
- **DesignLife** provides the capability of predicting fatigue in a virtual environment
- Fatigue failures can be addressed before parts are manufactured







Fatigue Analysis Roadmap



Thank you!

Please provide training feedback at:

https://www.research.net/r/HBM_Prenscia_Training_Feedback