SIEMENS

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Durability Knowledge booklet

Testing Knowledge Base compilation

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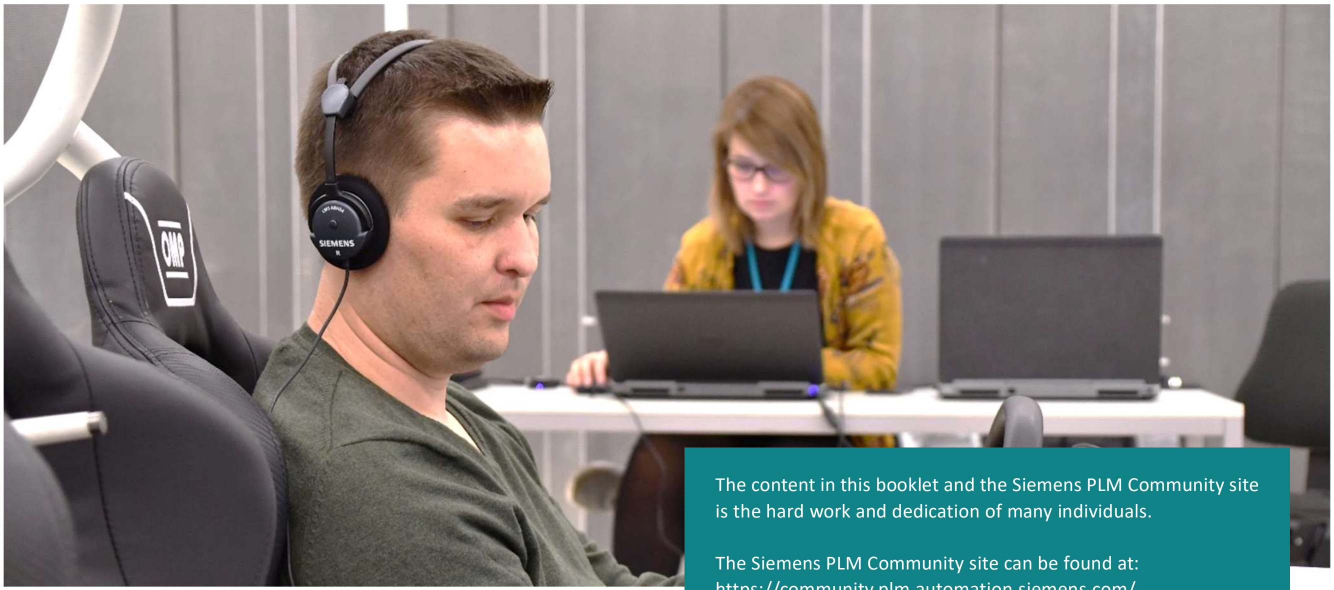

The content in this booklet and the Siemens PLM Community site is the hard work and dedication of many individuals.

The Siemens PLM Community site can be found at: https://community.plm.automation.siemens.com/

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The History of Fatigue

1678 – Sir Robert Hooke proposes Hooke’s Law, establishing linear elastic relationship between stress and strain.

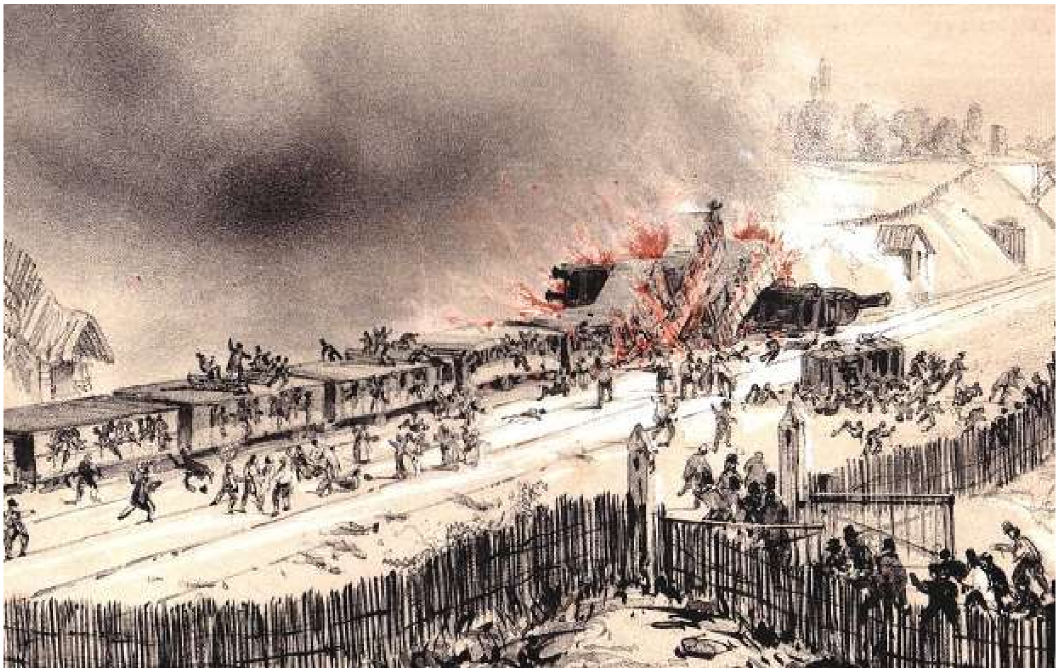
Sir Robert Hooke, 1635-1703

1839 - Jean-Victor Poncelet, designer of cast iron axles for mill wheels, officially used the term "fatigue" for the first time in a book on mechanics. Jean-Victor postulated that the axles became tired, or fatigued, after a period of usage before breaking.

Jean-Victor Poncelet, 1788-1867

Jean-Victor Poncelet was also a military engineer in the French Army under Napoleon Bonaparte. He was held as a prisoner of war by the Russians from 1812 to 1814.

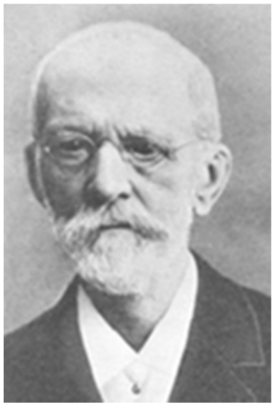
1842 – The Versailles train crash of 1842 is often pointed to as the beginning of understanding the mechanism of cyclic fatigue.



Versailles train crash of 1842

The axle of a locomotive broke unexpectedly, resulting in the deaths of over 50 people. It was poorly understood at the time that the accumulation of many small stress cycles could lead to a crack and sudden failure in a metallic part.

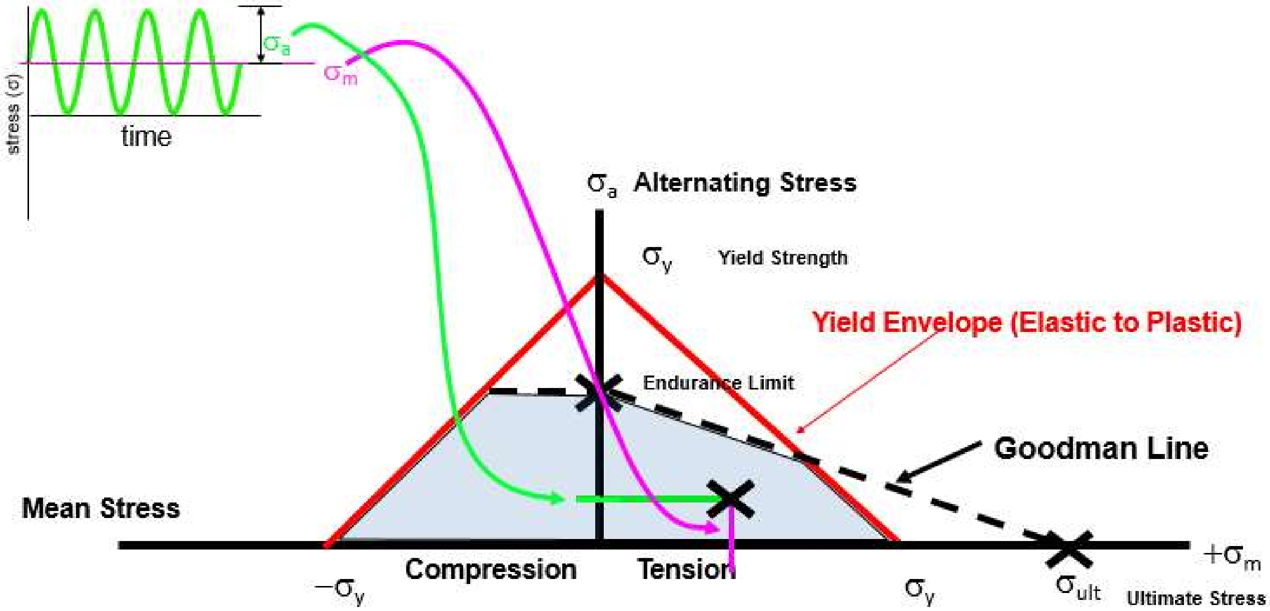
1867 – At the Paris Exhibition of 1867, August Wöhler presents his work on metal fatigue curves (called either Wohler curves or SN Curves) that relate the number of stress cycles to failure.



August Wöhler, 1819-1914

These curves were a direct result of the investigation into the Versailles train crash. Wohler developed an apparatus to apply repeated loads to railroad axles and chart the relationship between load level and number of repeated cycles to failure.

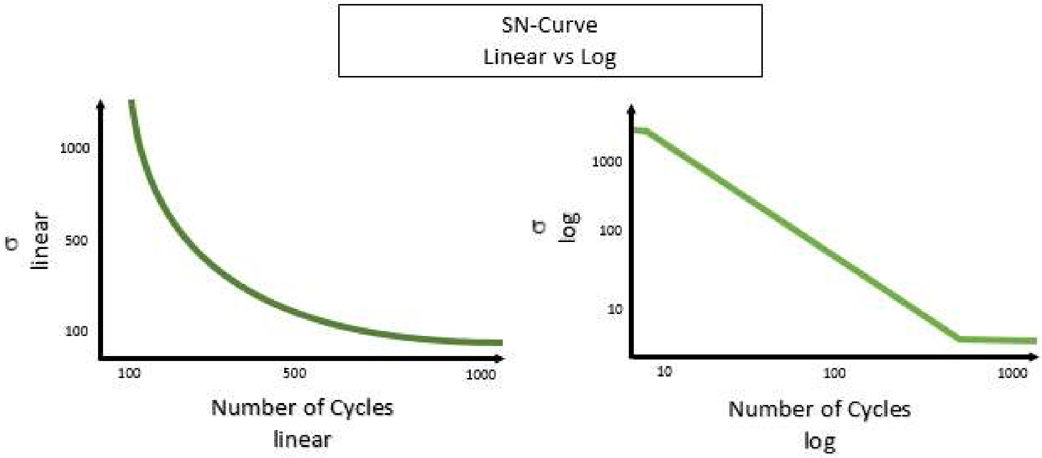
1899 – Goodman-Haigh diagram proposed to quantify the interaction of mean and alternating stress on fatigue life of a material.



Light blue area of Goodman-Haigh Diagram is safe operating stresses

The diagram indicates a safe envelope of operation for the alternating and mean stresses of a given material for infinite life.

1910 - O.H. Baskin defined the shape of a typical S-N curve by using Wöhler's test data and proposed a log-log relationship.



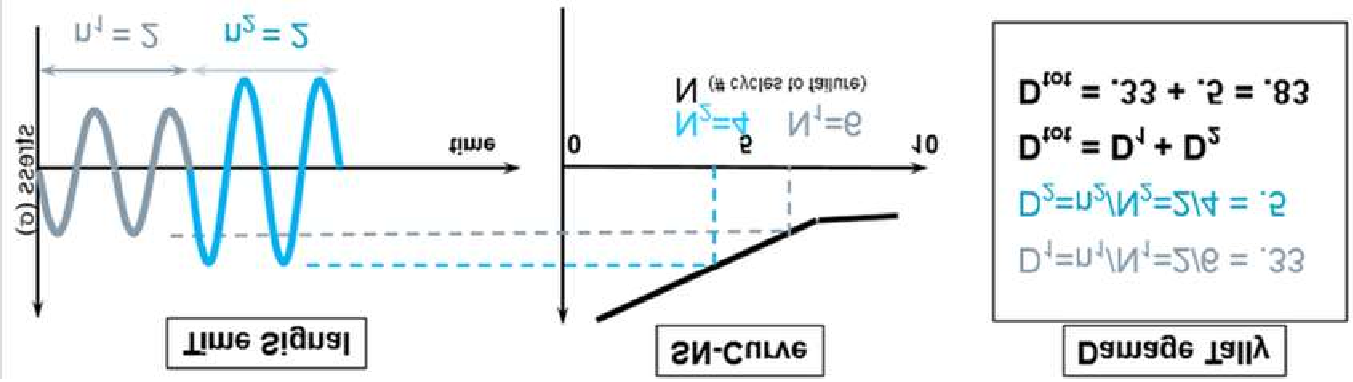
Linear versus log-log relationship of number of cycles to stress level

1938 – Modern bonded wire resistant strain gauge invented by Edward E. Simmons (Caltech) and Arthur C. Ruge (MIT) independently.

Three strain gauges in rosette arrangement on beam

MIT released the rights to Ruge's invention, saying that, while “interesting,” the strain gauge didn’t show much potential.

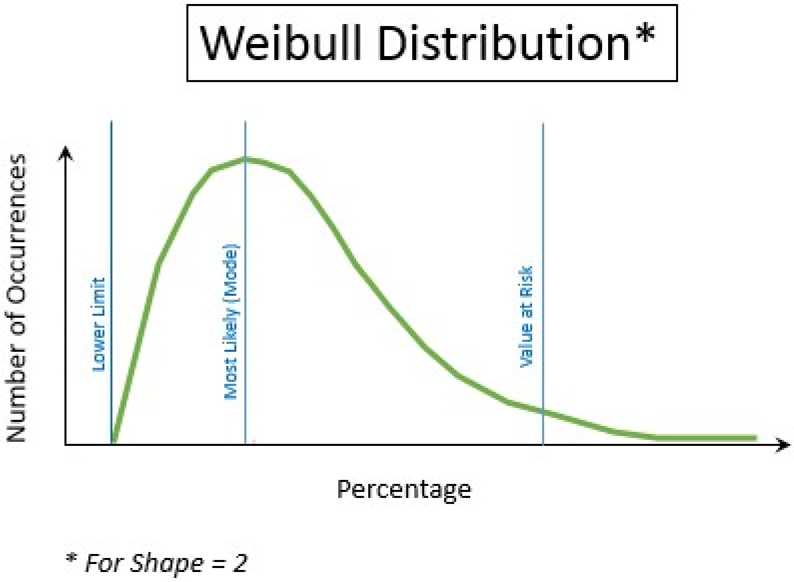
1945 – M. A. Miner makes popular a damage model first proposed by A. Palmgren in 1924. The damage model is called **Miner's rule** or the Palmgren-Miner linear damage hypothesis.



Miner’s Rule and Damage Tally

Miner’s rule is a linear damage accumulation model where fatigue failure occurs when damage is equal to 1.

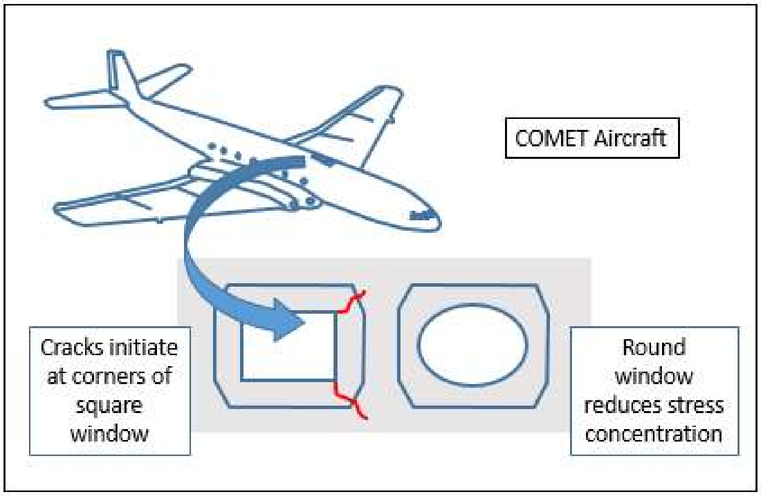
1951 – Swedish mathematician Waloddi Weibull presents paper on the Weibull distribution to the American Society of Mechanical Engineers (ASME).



Weibull Distribution for shape function equal to 2

Weibull carried out thousands of tests on bolts and aluminum to develop a statistical probability distribution for failures. He found that fatigue failure probabilities could not be described using classic Gaussian distributions, and instead developed his Weibull distribution which included a shape function.

1954 – Three different de Havilland COMET aircraft, the world's first pressurized plane, breakup in mid-air within approximately one year of each other. During the subsequent crash investigation, it is determined that the escape hatch windows on top of the plane, with their square design, were the cause.



Stress concentrations created by geometry

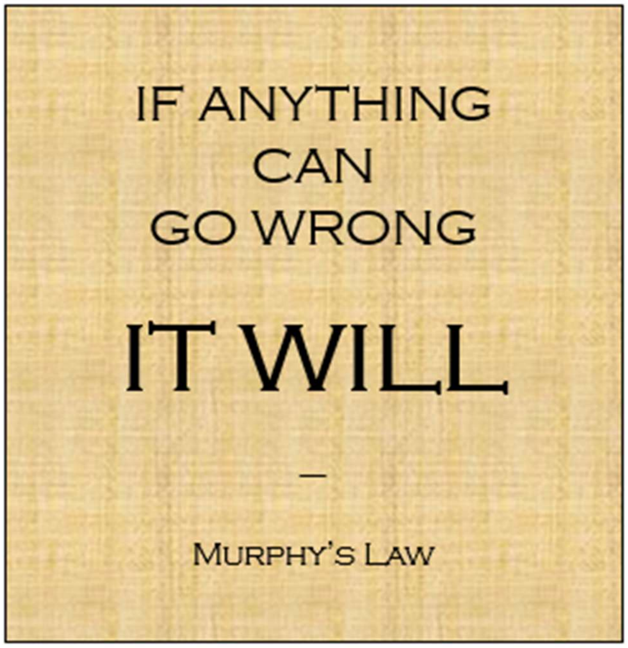
The windows were square with sharp corners, creating a stress concentration area. Under repeated cycling from pressurization, cracks would initiate at the corners. Subsequent designs used rounded windows to reduce the stress concentrations.

1954 – Manson-Coffin relationship established to describe fatigue behavior in the low cycle, plastic region of materials where strain governs the fatigue life.

L.F. Coffin

S.S. Manson of NASA Lewis in Cleveland, OH and L.F. Coffin of Knolls Atomic Power in Niskayuna, New York publish their findings on strain life separately.

1958 – Edwards Airforce base strain gauge failures give rise to "Murphy's Law": *If anything can go wrong, it will*



IF ANYTHING
CAN
GO WRONG

IT WILL

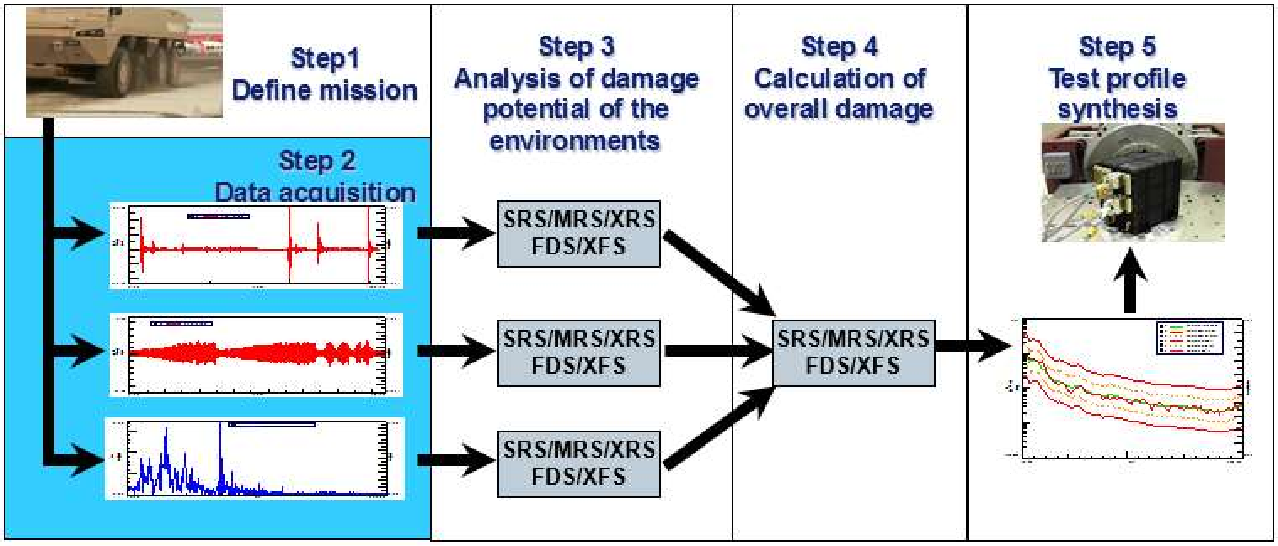
—

MURPHY'S LAW

Murphy's Law

According to the story, it was named after Captain Edward Murphy, who was said to have exclaimed in frustration: “If there is any way to do it wrong, he will”. He was referring to a technician who had wired strain gauge bridges incorrectly, resulting in no useful data being acquired during a test.

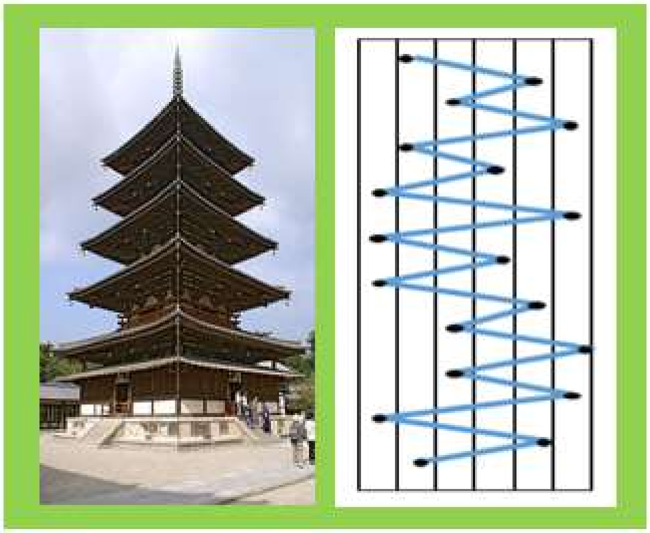
1962 - The first edition of MIL-STD-810 for environmental test tailoring is published by the United States Department of Defense.



MIL-STD-810 flowchart and process

MIL-STD-810, titled *Environmental Engineering Considerations and Laboratory Tests*, is a United States Military standard. It provides guidelines for determining what conditions a piece of equipment will experience during its lifetime and how to replicate those conditions in a test laboratory. The standards are often used for non-military product development.

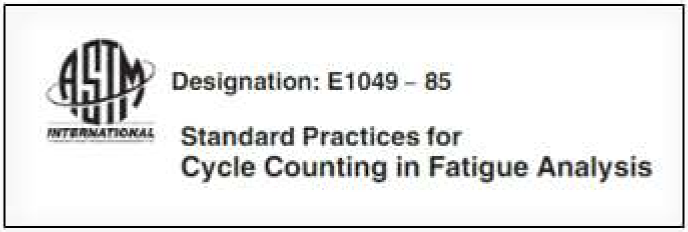
1968 – Tatsuo Endo (1925 – 1989), a Japanese engineer, develops the rainflow counting algorithm to extract individual fatigue cycles from complex load histories.



It is said that the rainflow counting method was inspired by pagoda style roof systems….

Endo developed the algorithm while a visiting professor at the University of Illinois in Urbana-Champaign along with M. Matsuishi.

1986 – First ASTM Rainflow Counting standard E1049-85 is published.



Designation: E1049 – 85

Standard Practices for
Cycle Counting in Fatigue Analysis

ASTM E1049-85

Covers multiple methods including peak counting, range-pair counting, and rainflow counting.

What are stress and strain?

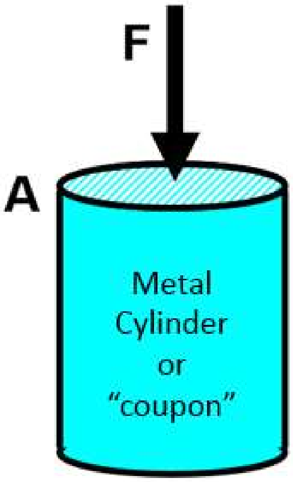
Stress and strain are two measurable engineering quantities that are important in understanding the durability or fatigue life of a product.

Picture 1: Stress/strain test of metal coupon sample. Left: Original sample. Middle: Sample with necking. Right: Sample with failure

Stress

Stress, represented by the Greek sigma symbol, can be simply thought as a force distributed over an area. Stress has units of MPa.

For example, the force could be applied to metal cylinder (ie, a metal coupon) like so:



Picture 2: Force being applied to metal cylinder or coupon

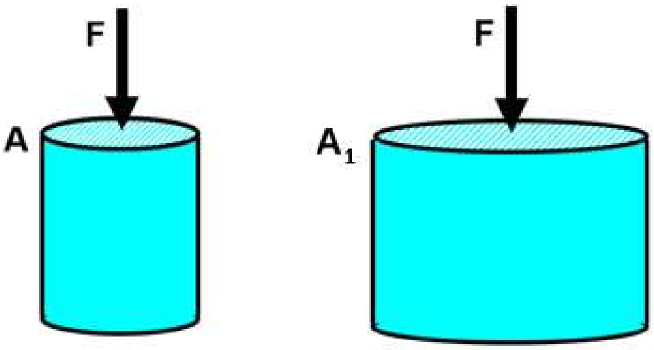
To calculate the stress, one would divide the force by the cross-sectional area of the cylinder:

$$\sigma = F/A$$

How can the stress on the metal cylinder be reduced? There are only two options:

- Reduce the force
- Increase the area

By increasing the diameter, the stress on the metal coupon would be reduced:



Picture 3: By changing from area A to area A1, the stress on the part is reduced.

This illustrates a classic issue with when designing for increased fatigue life: added weight and cost.

Weight

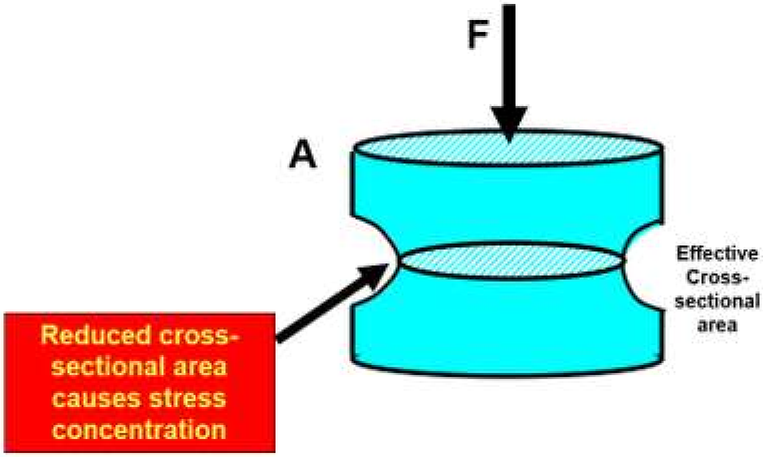
By increasing the area, the weight and material cost of the part has been increased. Not only is the part more expensive, it is also heavier. The added weight will affect the energy efficiency of operating the final product – it will take more fuel and/or power to move the heavier design.

It is of great importance to really understand the loading environment extremely well. If the actual loads are smaller than anticipated, than the part would not require as large of a cross-sectional area to survive for the intended life.

Many manufacturers today are undergoing "lightweighting" initiatives with their products. In order to increase energy efficiency, the weight of the product must be reduced. A key step in this process is to verify the assumed loads expected during the product lifetime to ensure that they are appropriate and not causing an over-design situation.

Geometry

Another engineering challenge may be that another department, perhaps the design department, may decide that a “coke bottle” glass shape would be better than a plain cylinder. They may decide to “neck down” in the middle of the cylinder for a more “pleasing” appearance.



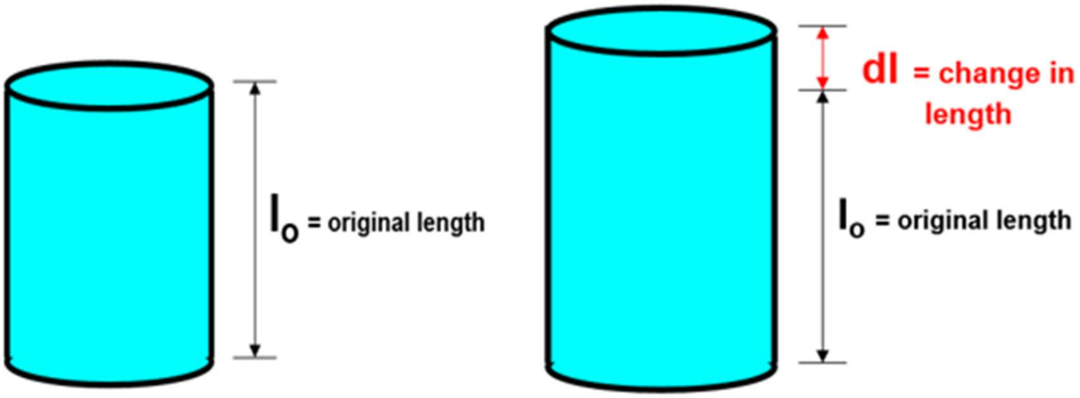
Picture 4: Geometry change reduces the effective cross-sectional area and creates a stress concentration

By doing this “necking” and reducing the effective cross-sectional area, the stress has increased, despite the fact the area had previously been made larger to decrease the stress.

The neck itself also creates a stress concentration area. Because of the sudden change in geometry, the chances of a failure have been increased in that area.

Strain

Imagine that the same metal cylinder, after having a force applied, becomes a little bit longer (ie, elongated). Strain is defined as a change in length over the original length.



Picture 5: Strain is defined as a change in length over the original length

The strain is the change in length of the cylinder divided by the original length of the cylinder.

Strain:

$$\varepsilon = dl / l_o$$

Because strain has a unit of length in both the numerator and denominator, it can be thought of as dimensionless.

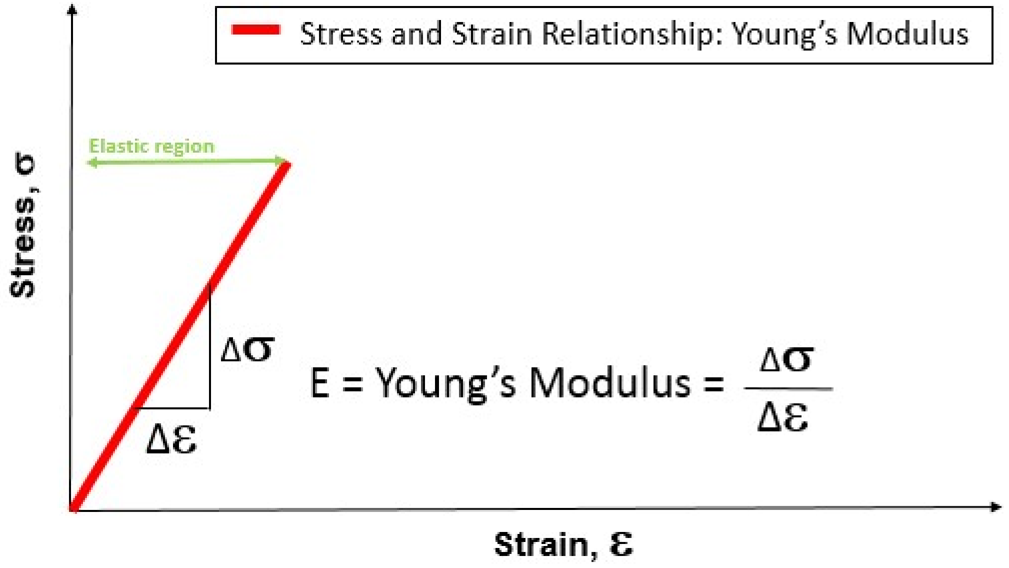
However, because the change in length of parts, like the metal cylinder, are typically so small, it is common to use “units” of microstrain (sometimes abbreviated “muE”) to describe the change in length.

Microstrain changes the decimal place by a million, or 6 digits. For example, a strain “value” of 0.000050 becomes 50 muE or microstrain.

Linear Relationship between Stress and Strain

When applying a load to a part, initially the relationship between stress and strain is linear. While the relationship remains linear, it is considered the *elastic region* of the material.

In the elastic region of the material, when the stress is removed, the part returns to its original shape.



Picture 6: Relationship between stress and strain in the elastic region of a material

This linear stress-strain relationship yields "E", which is the Young's Modulus (or spring rate) of the part or material. The Young's modulus is the change in stress over the change in strain.

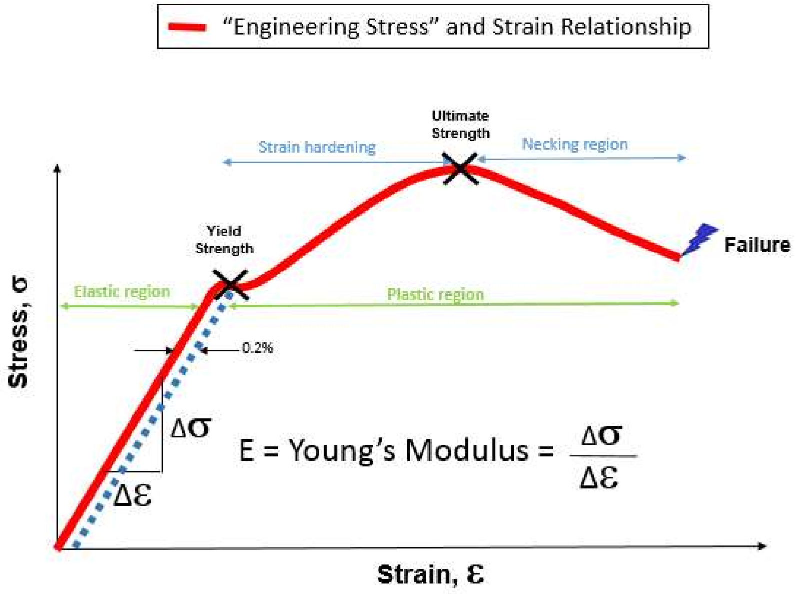
$$\sigma = E\,\varepsilon$$

E = Young's Modulus

This linear relationship is described by Hooke's Law, which was proposed by Sir Robert Hooke in 1660.

Non-Linear Relationship between Stress and Strain

With a high enough load, the relationship between stress and strain becomes non-linear. Instead of linear elastic behavior, the relationship becomes non-linear plastic behavior as shown in Picture 7.



Picture 7: Stress vs strain relationship in both plastic and elastic regions of material

The point beyond which the relationship between stress and strain becomes non-linear is called the *yield strength*. Applying loads beyond the yield strength results in "plastic" deformation of the material.

While the yield strength is thought of as a single number or point on the curve, in reality, there is a small transition zone between the elastic and plastic region; it is not an instantaneous transition. Therefore the yield strength is defined by using a line offset 0.2% from the elastic line and plotting its intersection on the stress/strain curve as shown in Picture 7.

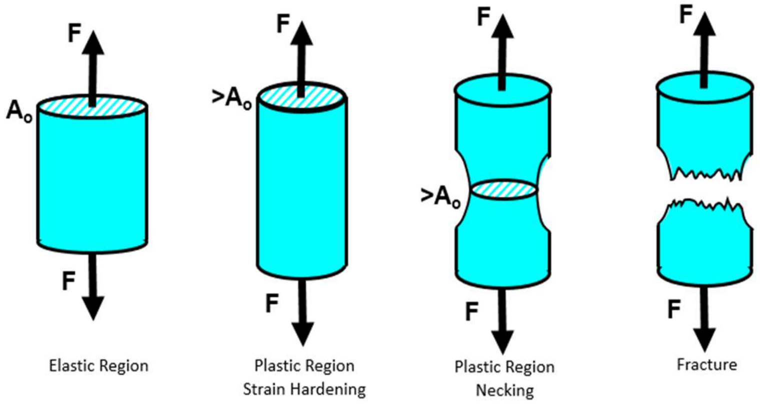
In the *plastic region* of the material, the part deforms permanently, and will not return to the original shape when the stress is removed.

At another point of increasing load/stress, there is a point where the part starts to fail, or "neck". This is the *ultimate strength* of the material.

With a high enough load/stress applied, the part will eventually pull apart, fracture or fail.

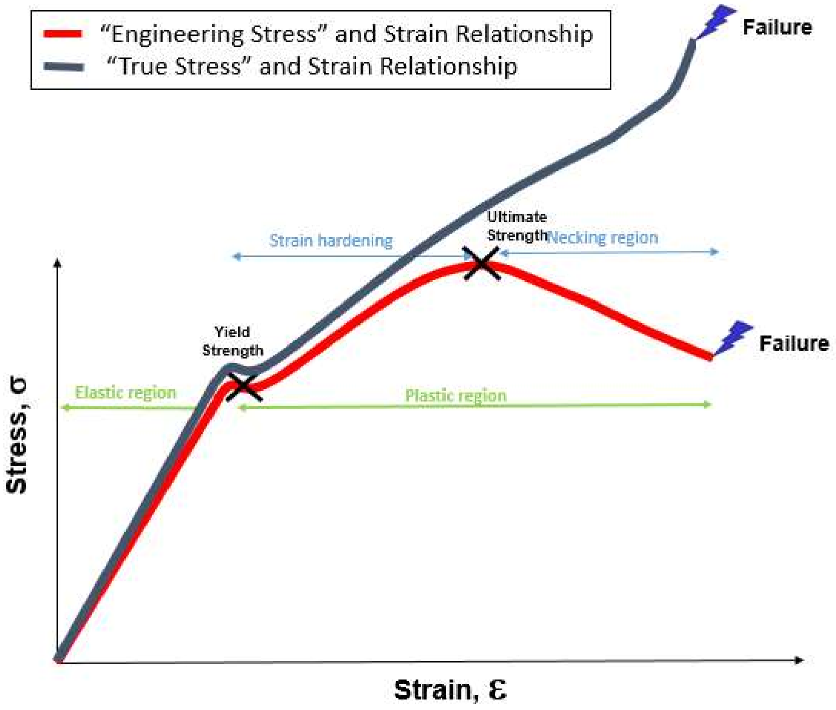
Engineering Stress vs True Stress

As the part under load deforms, the original area (Ao) decreases as the load increases. When stress vs strain is plotted against the original area (Ao), it is called the *Engineering Stress* curve. Engineering Stress does not consider that the area is changing.



Picture 8: Differences in cross-sectional area as metal coupon undergoes increasing stress level (from left to right)

If the stress and strain relationship are plotted using the actual cross-sectional area of the part, the plot result is called the *True Stress* curve, rather than the *Engineering Stress* curve.



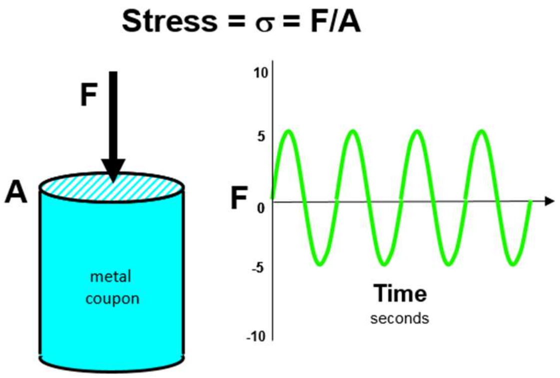
Picture 9: The True Engineering stress curve (Blue) versus the Engineering Stress curve (Red) for a coupon undergoing increasing load levels

Looking at True Stress versus strain, one can observe that the stress in fact increases in the part with increasing load. However, features like the ultimate strength are difficult to observe in the True Stress curve, and are easier to see in the Engineering Stress curve.

Calculating Damage with Miner’s Rule

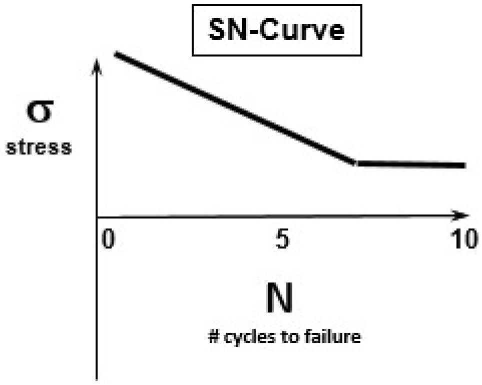
According to Miner's Rule, when damage is equal to “1”, failure occurs. The definition of failure for a physical part varies. It could mean that a crack has initiated on the surface of the part. It could also mean that a crack has gone completely thru the part, separating it. In this article, a conservative approach to failure will be used: a crack starts to appear on the surface of the part.

Applying a constant amplitude, cyclical stress to a metal coupon causes it to fail (a crack appears) after a specific number of cycles. Stress is defined as Force (F) divided by Area (A) or F/A.



Cyclic Stress Load on Metal Coupon

By repeating this test at different stress levels, one could develop a material SN-curve. For example the SN-curve* may look like this:



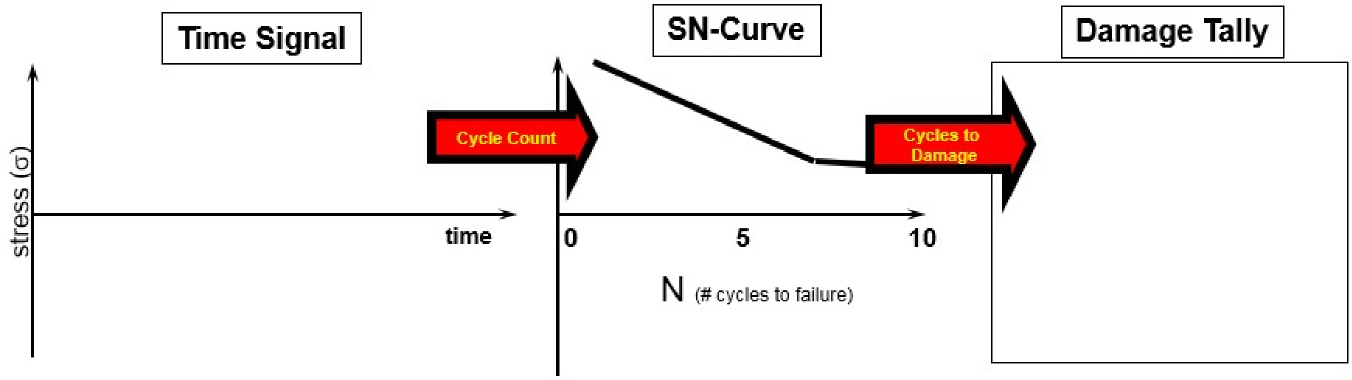
SN-Curve: Cyclic Stress Level versus Number of Cycles to Failure

SN-Curves are developed with testing machines that apply constant amplitude loads. They can be axial loads, torsional loads, bending loads, etc. Different stress levels are tested and the number of cycles to failure are recorded.

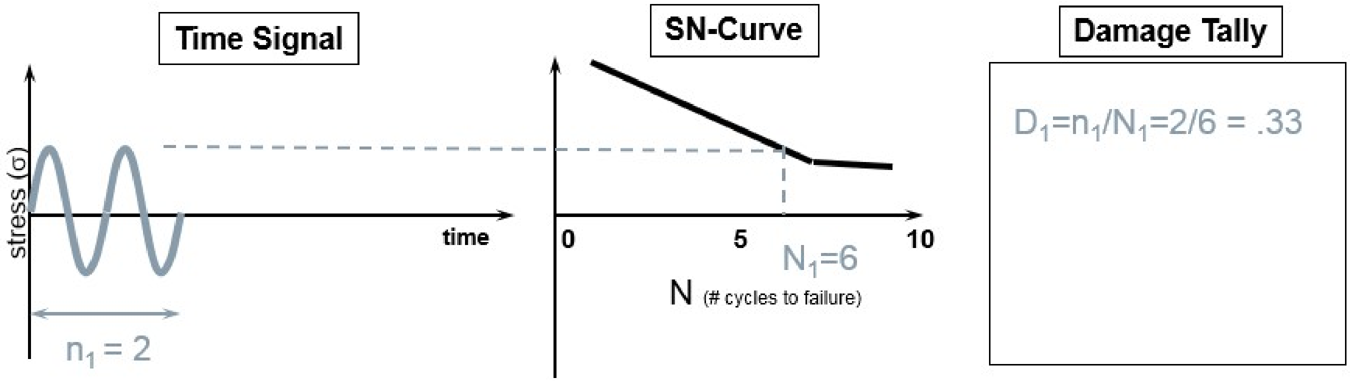
Axial fatigue test machine for material coupons

Damage Accumulation

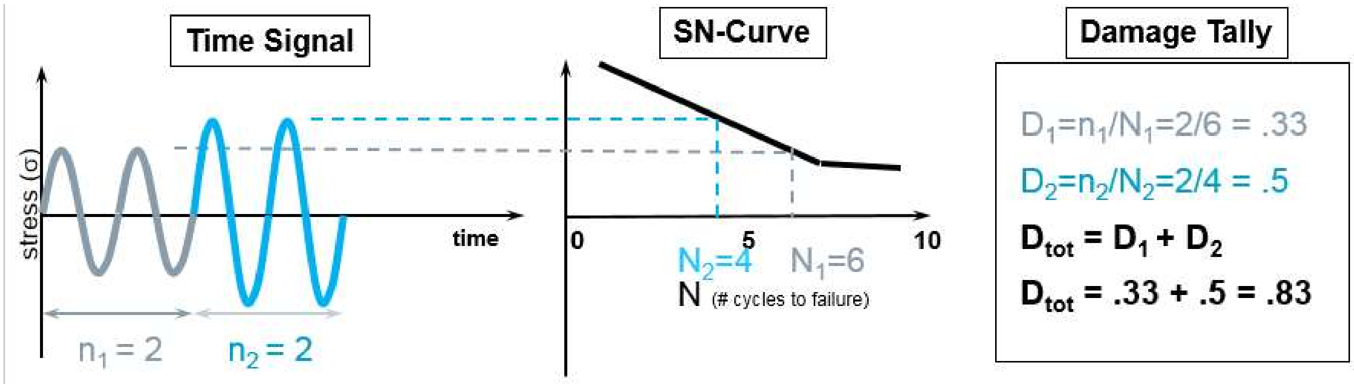
When a physical part undergoes stress cycles**, Miner's Rule works like this:



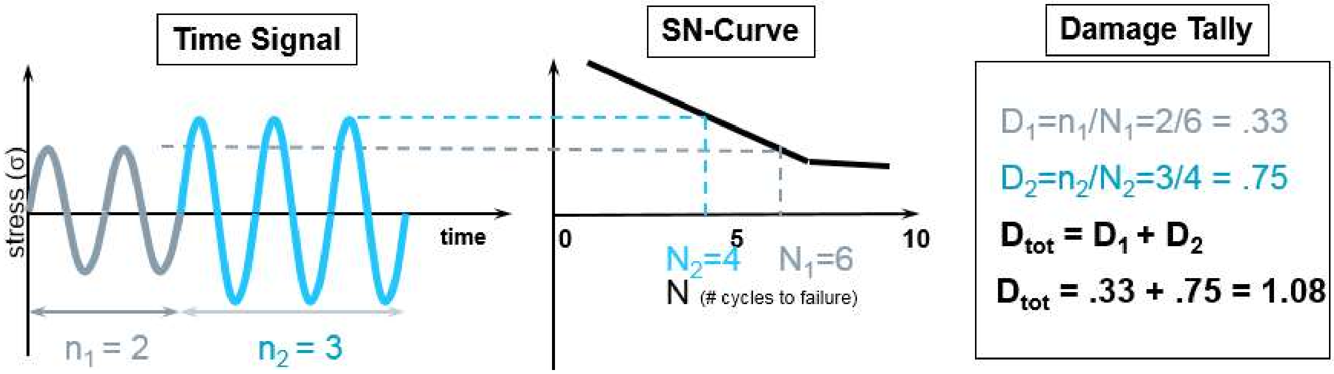
On the left graph, there is a loading time history. The SN-Curve is the middle graph, and a damage tally is kept on the right side.



In this case, two cycles at a specific amplitude are applied to the part. At this amplitude the part could take 6 cycles before it would fail. Dividing two cycles by six cycles, the accumulated damage is 0.33. A third of the life of the part has been used.



Two more cycles of a higher amplitude are applied. At this higher amplitude, four cycles would be required for failure to occur. Dividing two cycles by four cycles, an additional 0.5 of damage has occurred. The total accumulated damage is now 0.83. According to Miner’s Rule, no failure has occurred.



One more cycle of the higher amplitude is now applied. The accumulated damage is now 1.08. Failure has occurred!

History

In 1945, M. A. Miner popularized a rule that had first been proposed by A. Palmgren in 1924. The rule is variously called Miner's rule or the Palmgren-Miner linear damage hypothesis.

Limitations of Miner's Rule

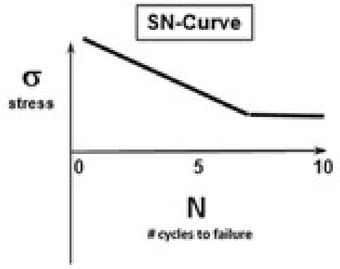
Miner's Rule does not take into account the sequencing or order in which in the cyclic loads are applied. For example, if loads are applied in the plastic region, the endurance limit is no longer in effect.

Other Notes

*Note: Real SN curves for metals are log-log curves and easily range into millions of cycles.

**Note: The loads applied to product in the real world are usually not constant amplitude cycles. To break down a real world load history into cycles, a cycle counting method called 'Rainflow Analysis' is used.

What is a SN-Curve?

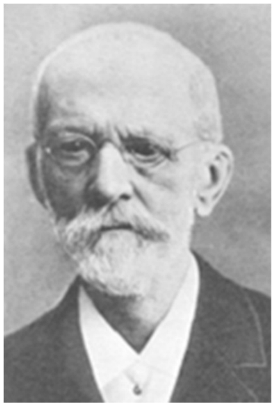


A SN-Curve (sometimes written S-N Curve) is a plot of the magnitude of an alternating stress versus the number of cycles to failure for a given material. Typically both the stress and number of cycles are displayed on logarithmic scales.

Given a load time history and a SN-Curve, one can use Miner's Rule to determine the accumulated damage or fatigue life of a mechanical part.

History

SN-Curves were developed by the German scientist August Wöhler (*Picture 1*) during the resulting investigation of an 1842 train crash in Versailles, France. In this crash, the axle of the train locomotive failed under the repeated "low level" cyclic stress of everyday usage on the railroad.



Picture 1: August Wöhler (1819 to 1914) developed SN-Curves to understand railcar axle failures

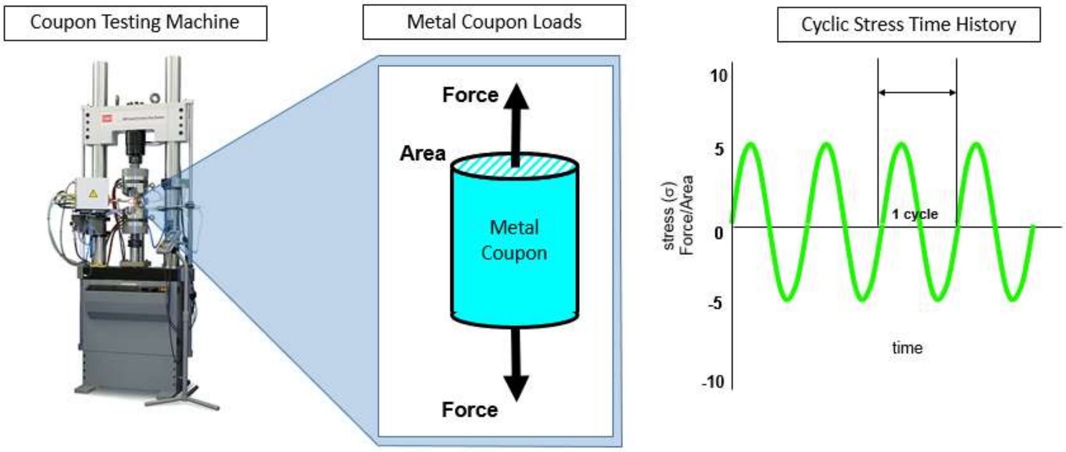
While investigating, Wöhler discovered that cracks formed and slowly grew on an axle surface. The cracks, after reaching a critical size, would suddenly propagate and the axle would fail. The level of these loads was less than the ultimate strength and/or yield strength of the material used to manufacture the axle.

Wöhler developed an apparatus to apply repeated loads to railroad axles and chart the relationship between load level and number of repeated cycles to failure. "Wöhler Curves" plot the relationship of alternating/cyclic stress levels against the number of cycles to failure.

Designing an axle to withstand the initial static loads associated with holding up a locomotive was well understood. It was fairly obvious if an axle could carry the weight of a train if it did not collapse immediately. The concept of low level cyclic stresses, repeated over a long time, was relatively new and not well understood. For many observers at the time, it seemed unpredictable when an axle might suddenly fail. It was not until Wöhler developed his SN-Curves that cyclic stress became better understood, and fatigue life could be predicted in a more consistent manner.

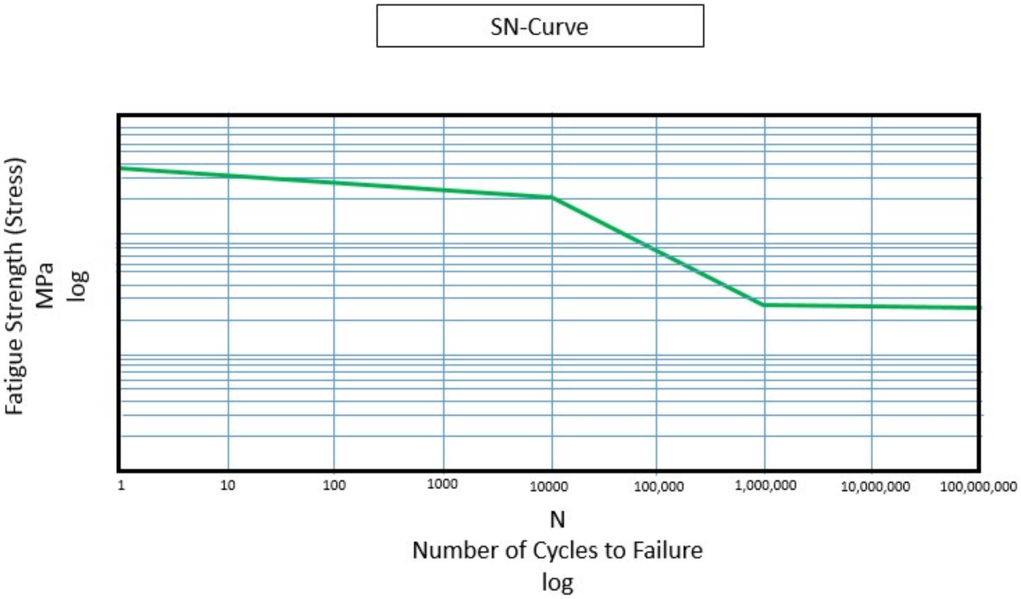
How is a SN-Curve created for a given material?

Today, these curves are often developed by using a metal coupon testing machine (*Picture 2*). A small metal coupon is placed into the machine and subjected to a cyclic (or alternating) stress time history until a crack or failure occurs in the metal coupon.



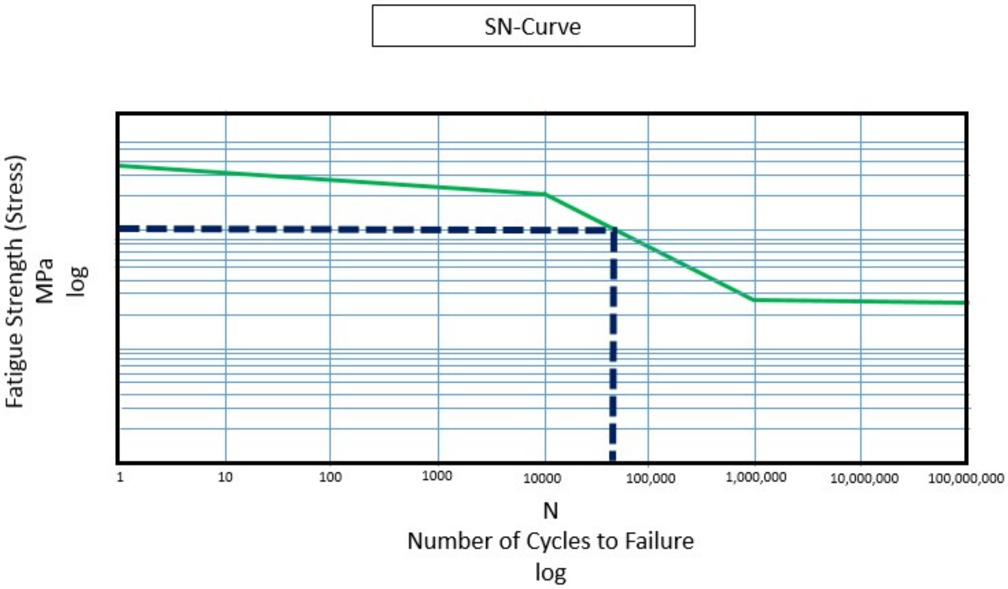
Picture 2: Coupon testing is used to create SN-Curves for materials

Several coupons must be tested at different stress levels to develop a SN-Curve. *Picture 3* illustrates a typical SN-Curve derived from testing metal coupons.



Picture 3: SN-Curve for a material: Higher amplitude stress cycles resulting in lower number of cycles to failure

A SN-Curve functions as a "lookup table" between alternating stress level and the number of cycles to failure. Most SN-Curves generally slope downward from the upper left to the lower right. This indicates that high level amplitude cycles have fewer number of cycles to failure compared to lower level amplitude cycles.



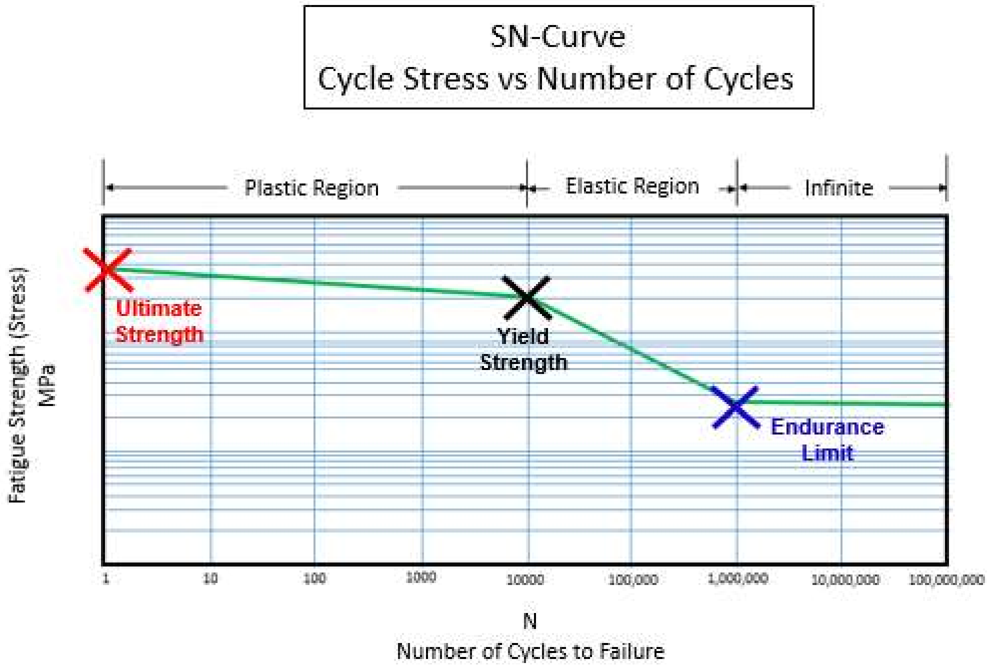
Picture 4: SN-Curve relating Alternating Stress Level to corresponding Number of Cycles to Failure via dashed dark blue line

In a fatigue test like this, the frequency at which the cycles are applied is not considered to be a factor in the number of cycles to failure. It is strictly the number of cycles, and not the rate at which the cycles are applied, that affect the SN-Curve results.

In real life, the frequency of the cycles can be a factor, especially if the loading frequency coincides with a natural frequency or resonance of the object which amplifies the magnitude of the cycles.

Plastic, Elastic and Infinite Regions

A SN-Curve can contain several different areas: a plastic region, an elastic region and an infinite life region.

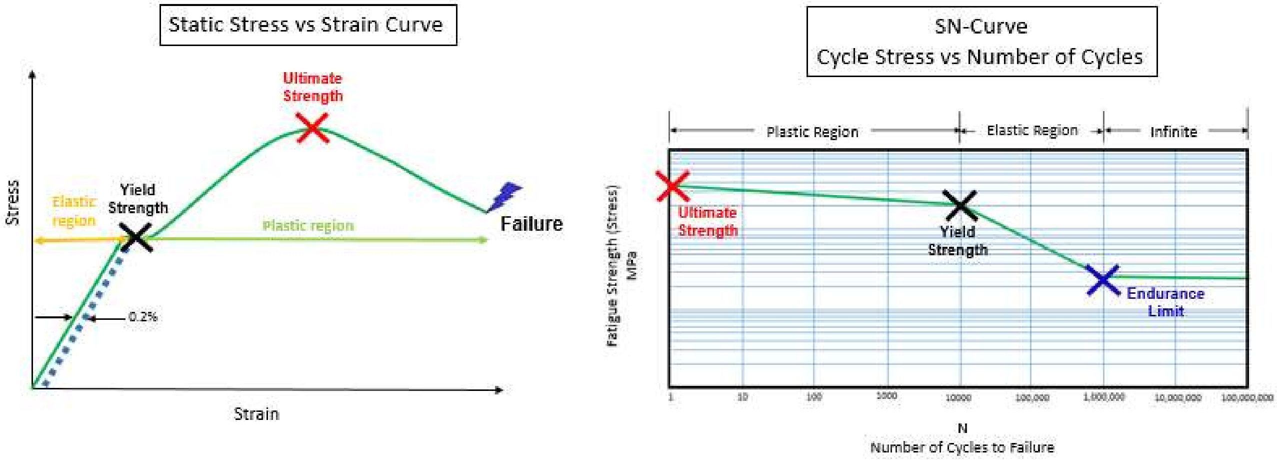


Picture 4: Ultimate Strength, Yield Strength and Endurance Limit on SN-Curve

There are three key values that separate the plastic, elastic and infinite life regions (*Picture 4*):

- Ultimate Strength: Stress level required to fail with one cycle
- Yield Strength: Dividing line between elastic and plastic region
- Endurance Limit: If all cycles are below this stress level amplitude, no failures occur

Several of the values on the SN-Curve can be found by doing a static stress-strain test on a material coupon (see *Picture 5*).

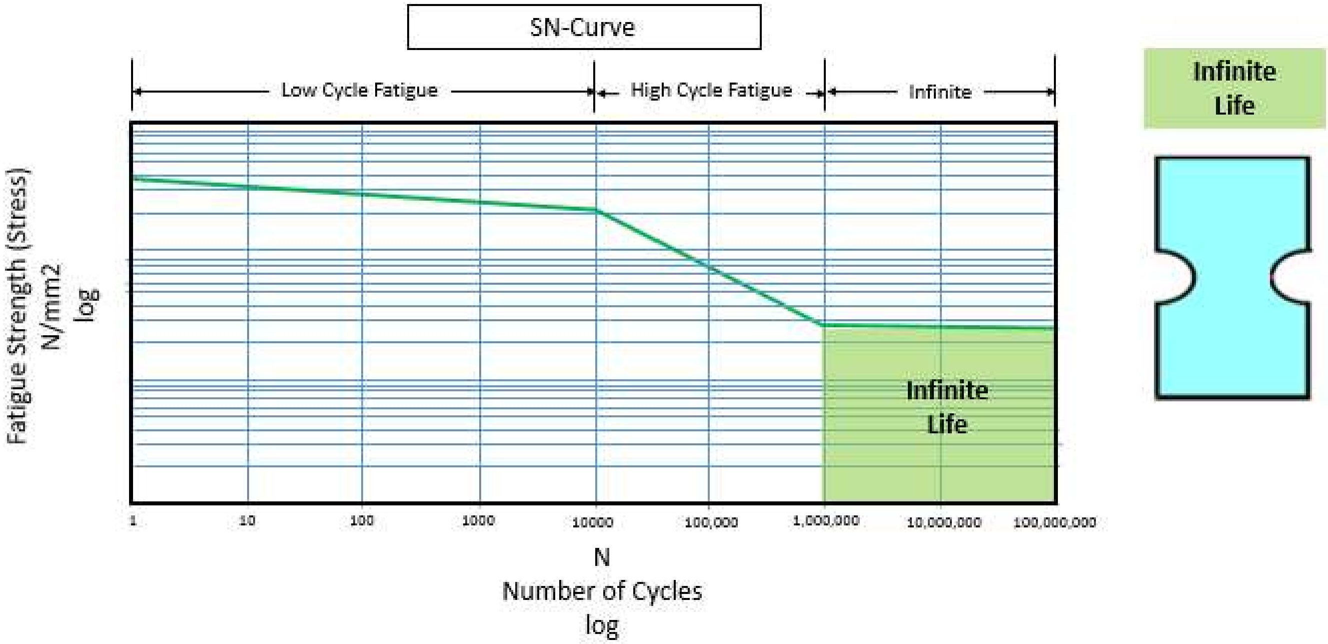


Picture 5: Ultimate Strength and Yield strength can be determined from static stress-strain tests

For example, the Ultimate Strength stress is the value that causes a failure for one cycle. The Yield Strength stress level divides the plastic and elastic region.

Infinite Life

Some materials, like steel, exhibit an infinite life region (*Picture 6*). In this region, if the stress levels are below a certain level, an infinite number of cycles can be applied without causing a failure (of course, no test has been performed for an infinite number of cycles in real life, but a million+ cycles is typical).



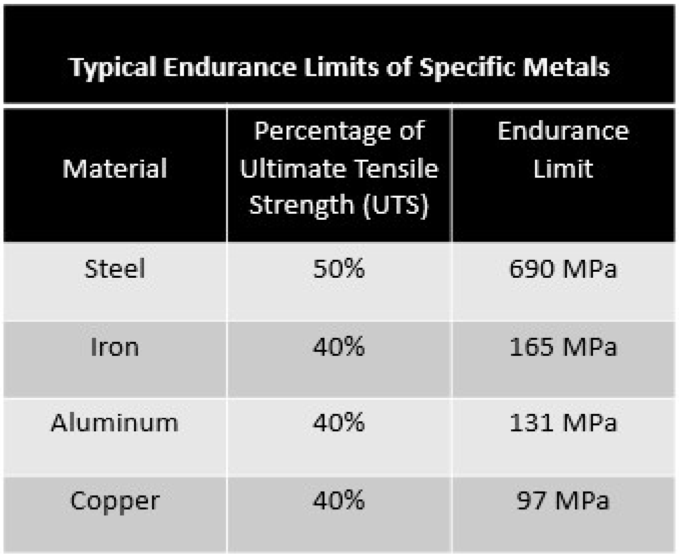
Picture 6: Infinite life region of SN-Curve

Critical components (ie, engine crankshafts and rods) are usually designed for infinite life because cycles are speed dependent and accumulate quickly. All the cyclic stress levels that the part is subjected to must be below the endurance limit to have infinite life.

Infinite life is not in effect under certain conditions:

- Infinite life is only based on number of stress cycles, it assumes corrosion and other factors are not present.
- If any of the cyclic stress levels are higher and in the plastic or elastic region, then the endurance limit is no longer in effect.

Different metals have different endurance limits. Some typical endurance limits are show in *Table 1*.

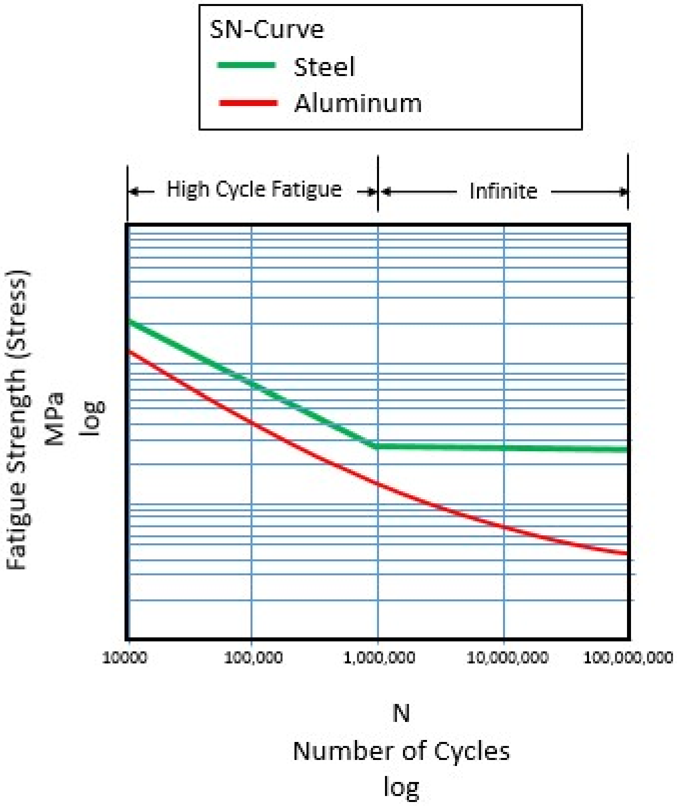


Typical Endurance Limits of Specific Metals

Material	Percentage of Ultimate Tensile Strength (UTS)	Endurance Limit
Steel	50%	690 MPa
Iron	40%	165 MPa
Aluminum	40%	131 MPa
Copper	40%	97 MPa

Table 1: Typical Endurance limits of specific metals

Many non-ferrous metals and alloys, such as aluminum, magnesium, and copper alloys, do not exhibit well-defined endurance limits *(Picture 7)*.

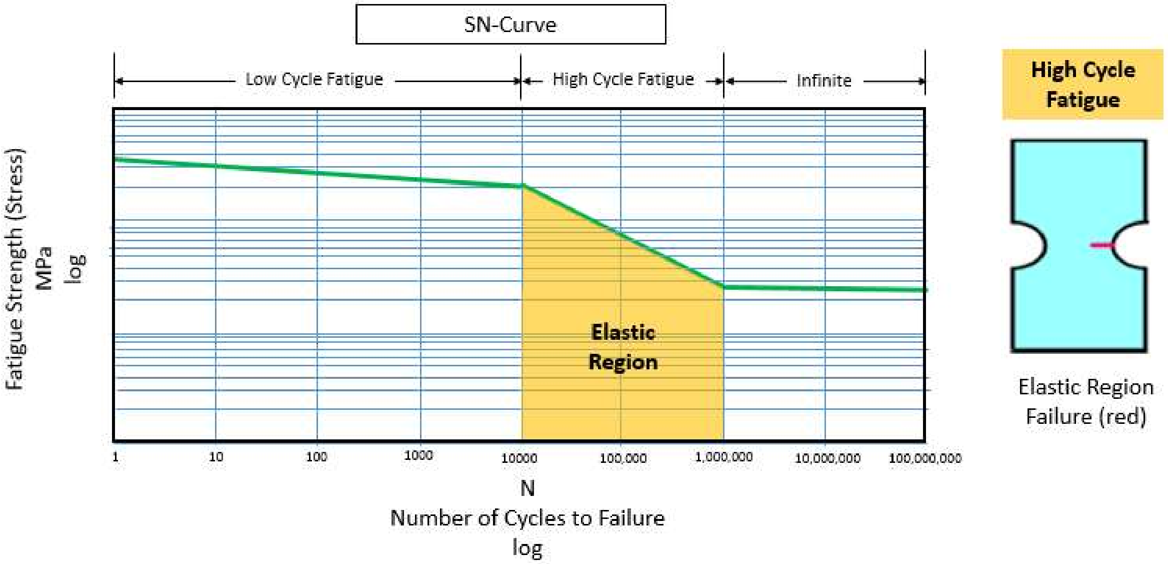


Picture 7: Endurance limit of aluminum (red) is not as well defined as steel (green)

Where steel has a definite change in slope at the endurance limit, aluminum and other metals do not always have a distinct change.

Elastic Region

In the elastic region (*Picture 8*), the relationship between stress and strain remains linear. When a cycle is applied and removed, the material returns to its original shape and/or length. This region is also referred to as the “High Cycle Fatigue” region, because a high number of stress cycles, at a low amplitude, can cause the part to fail.

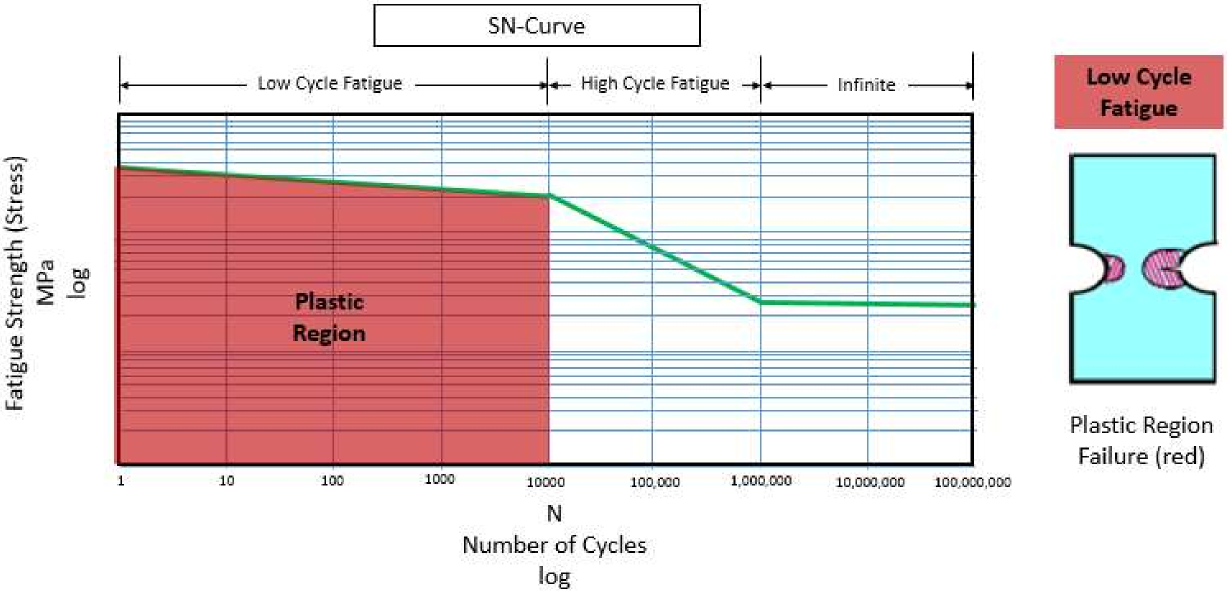


Picture 8: Elastic life region of SN-Curve

Typical factors that influence the performance of a material in the elastic region are residual stresses and geometric considerations. For example, a severe geometry change in the material may be more likely to have a crack initiate than a smooth geometry change.

Plastic Region

In the plastic region (*Picture 9*), the material experiences high stress levels, causing the shape and/or geometry to change due to the repeated application of stress cycles. This region is also referred to as the "Low Cycle Fatigue" region of the SN-Curve, where a low number of stress cycles, with a high amplitude, result in failure.



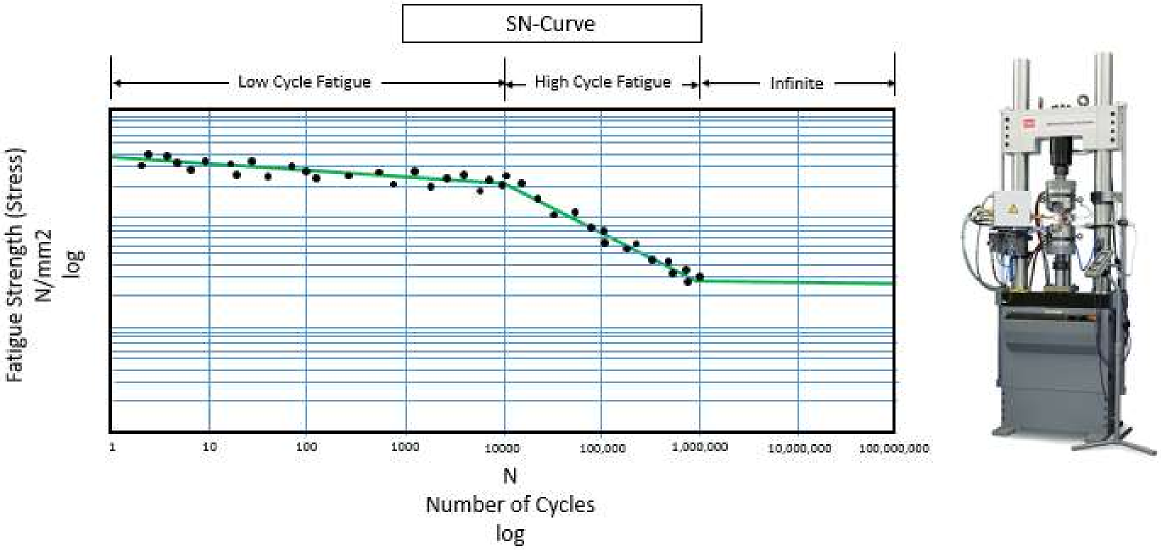
Picture 9: Plastic life region of SN-Curve

Material plasticity and geometry are big influences on the number of cycles to failure in the plastic region.

Calculating fatigue life or damage in the plastic region of a material with a SN-Curve is probably best avoided. If cyclic stress levels are in the plastic region, a strain life approach would typically be recommended instead, which includes an E-N (Strain vs Number of cycles) as part of the analysis. Strain life also takes into account the order or sequence in which loads are applied.

SN-Curve Libraries

Tests for materials can be expensive to run. Ideally, the tests should be repeated many times and at many different stress levels. With enough experiments, the SN-Curve would consist of a series of confidence intervals around the main curve.



Picture 10: SN-Curve consists of many individual tests and is actually a curve fit to a distribution of data (black dots)

Some materials have well known curves because they are very commonly used. Some materials do not. When a new alloy is developed, the SN-Curve may be completely unknown and testing will be required to determine the curve. Conventionally, five different stress levels with three repeats at each level is considered the minimum to determine a SN-Curve.

The book "FKM Analytical Strength Assessment" contains many material SN-curves. It is published by the VDMA (Verband Deutscher Maschinen- und Anlagenbau e.V.), a German engineering association of engineering companies, which includes Siemens.

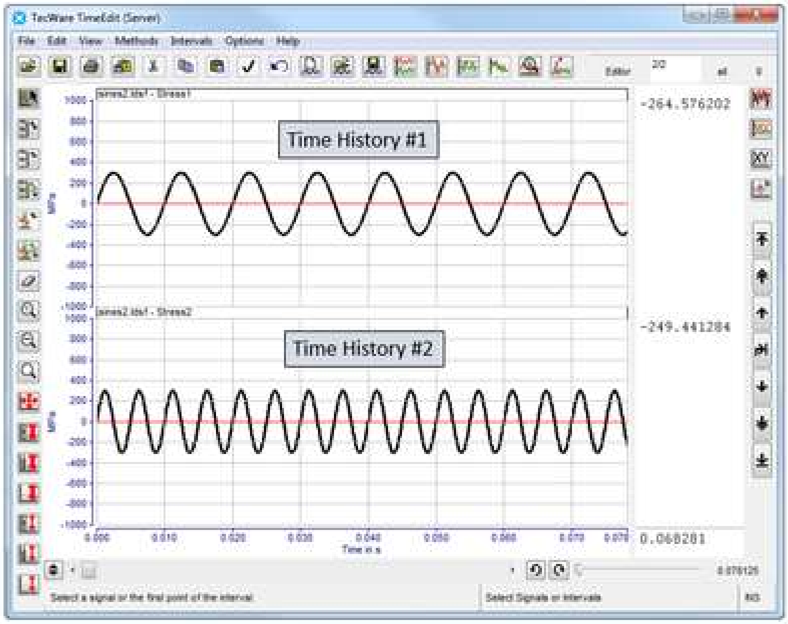
Logarithmic Nature of SN-Curve: Double amplitude vs Double cycles example

Consider the following hypothetical time histories to be evaluated for damage:

1. Alternating Stress of 300 MPa for 1000 cycles
2. Alternating Stress of 300 MPa for 2000 cycles
3. Alternating Stress of 600 MPa for 1000 cycles

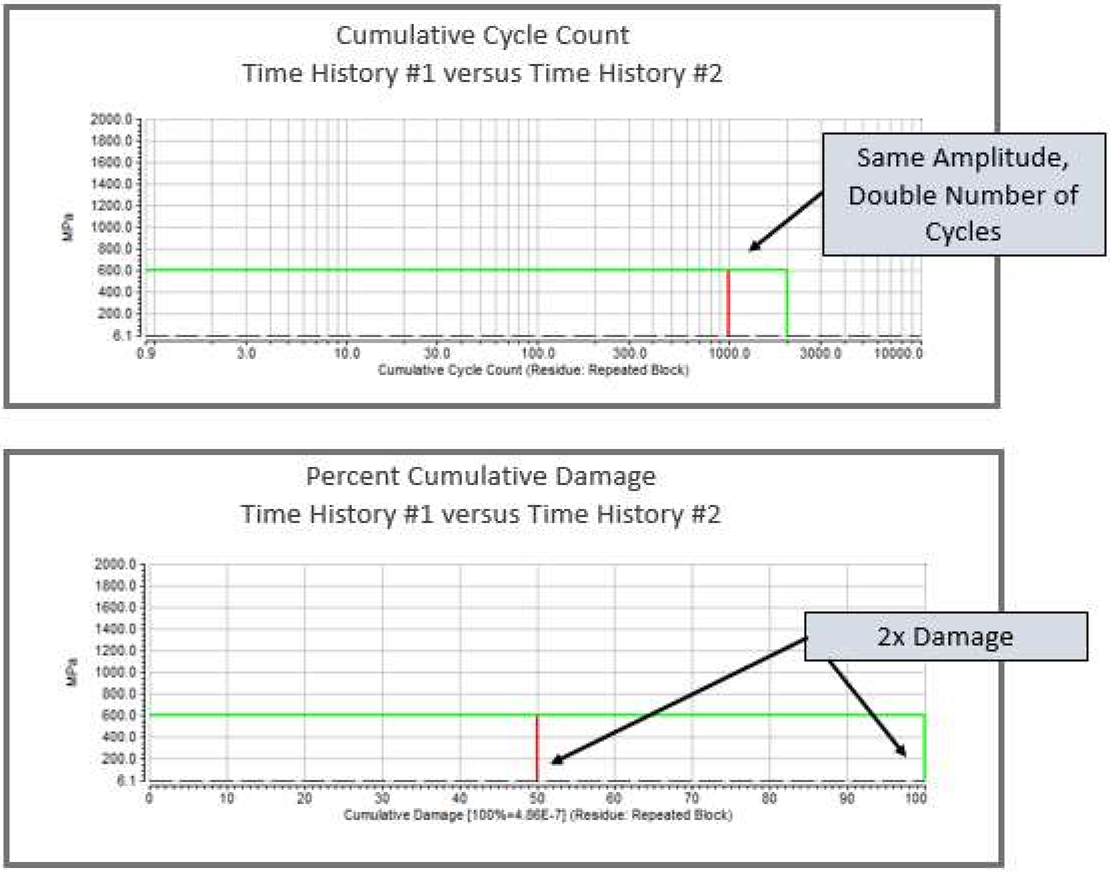
First consider time history #1 and time history #2. These time histories have:

- The same amplitude cycles
- Different number of cycles (one is double the other)



Picture 11: Time history #1 vs Time history #2

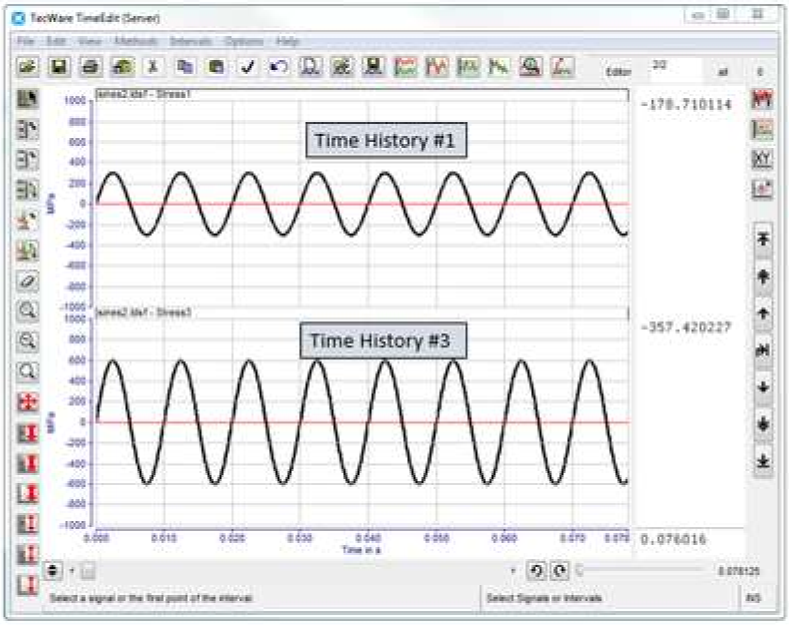
Using Miner's Rule, one sees that the cumulative damage of time history #2 is ***double*** compared to time history #1 (see *Picture 12*).



Picture 12: Cumulative cycle count and cumulative damage of Time history #1 vs Time history #2

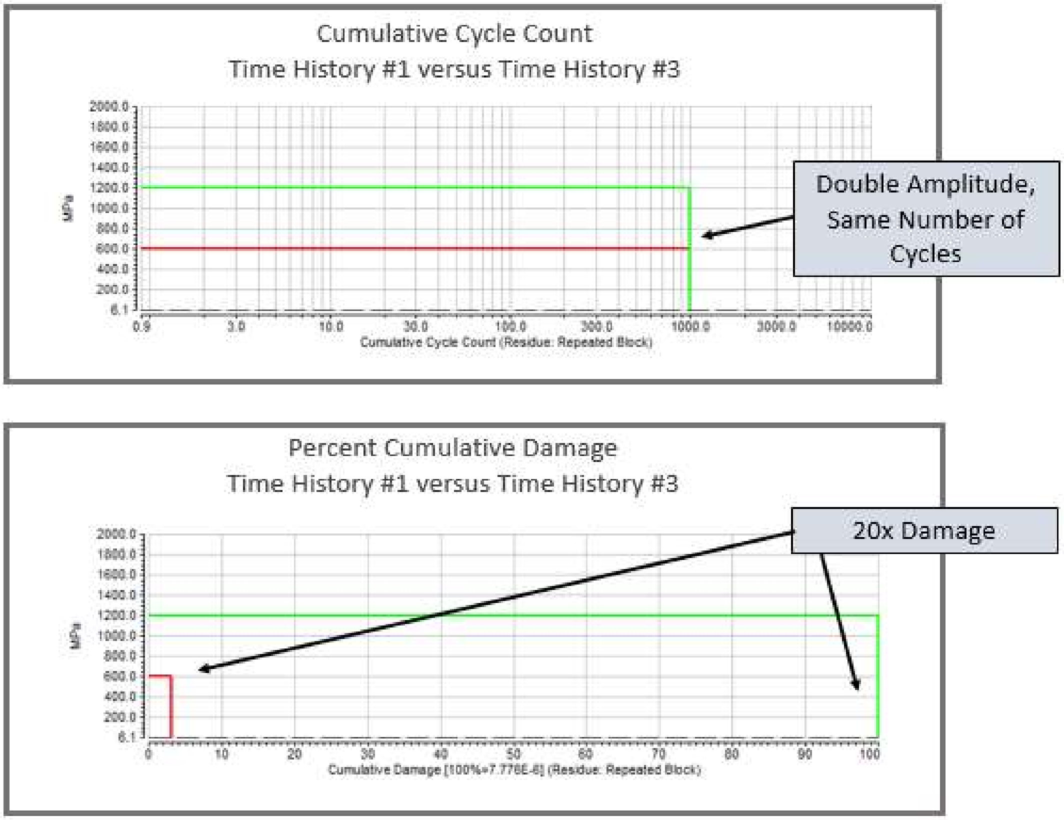
Next compare the damage potential in load time history #1 vs time history #3. These time histories have:

- Different amplitude cycles (time history #3 is double the amplitude of time history #1)
- Same number of cycles



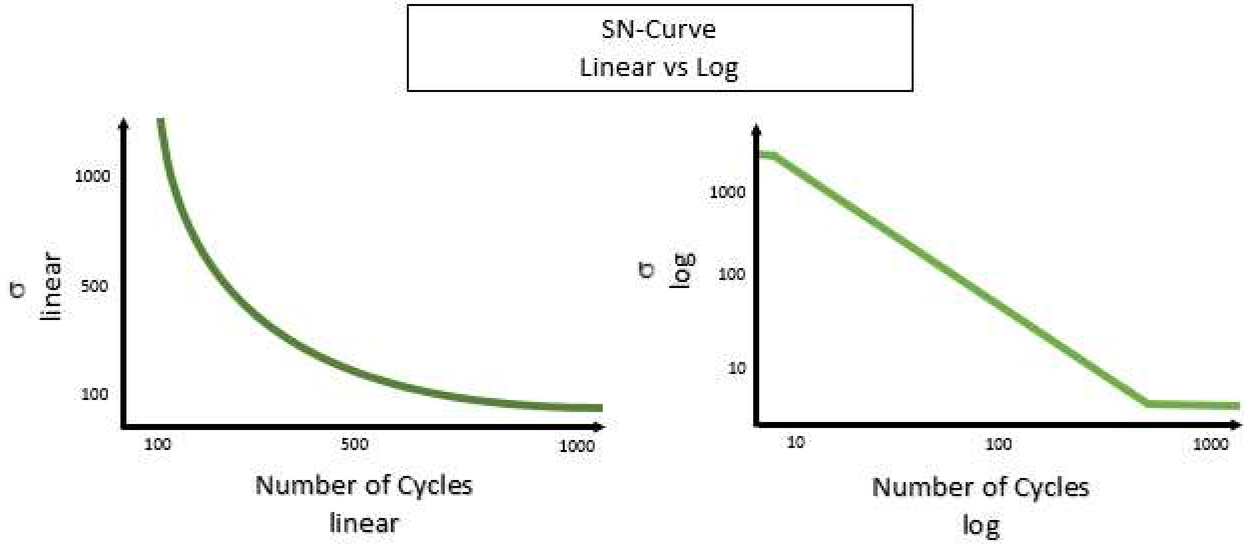
Picture 13: Time history #1 vs Time history #3

Using Miner's Rule to analyze the load time history with a SN-Curve, one sees that the cumulative damage of time history #3 is *20 times* compared to time history #1 (*Picture 14*), even though the amplitude of the cycles are *only double* in time history #3 compared to time history #1.



Picture 14: Cumulative cycle count and cumulative damage of Time history #1 vs Time history #3

Why does *doubling* the stress level result in *twenty* times the damage? This is because the SN-Curve is actually a log vs log graph, which is easy to forget when viewing what appears to be straight lines in the log-log representation of the SN-Curve (*Picture 15*).



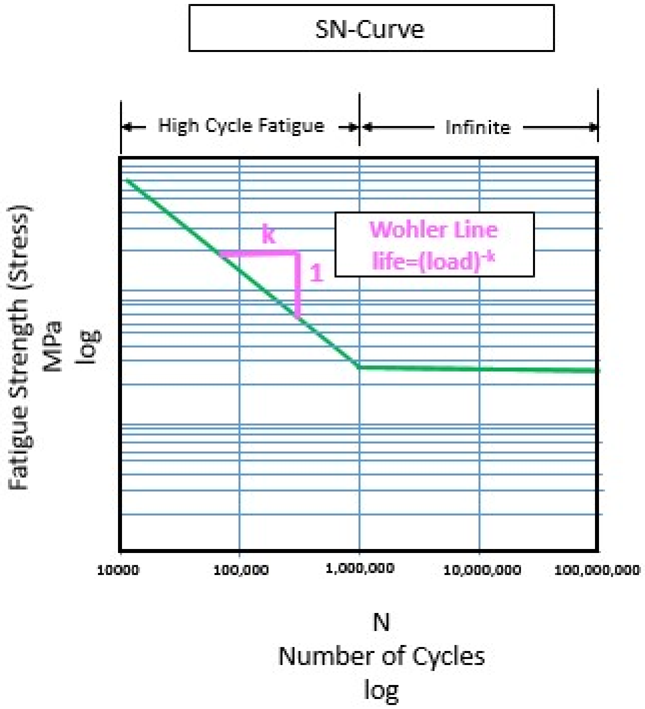
Picture 15: SN-Curves plotted in Linear vs. Linear and Log vs. Log

The relationship between stress level and number of cycles to failure is not linear, which has very important implications for fatigue life.

SN-Curve Slope: K-factor

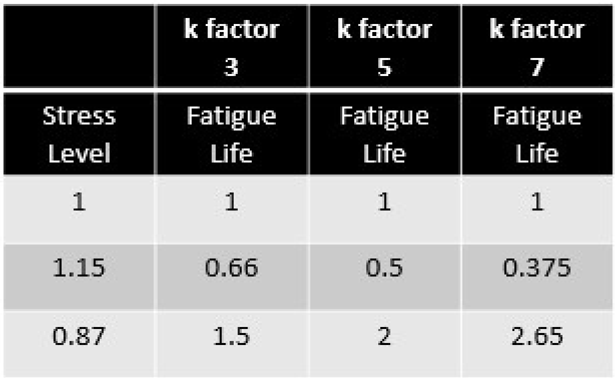
The slope of the log-log SN-Curve is defined by "k-factor". This "k-factor" governs the relationship between the stress level and the number of cycles to failure.

The "k-factor" was developed by Wöhler to easily relate the load (ie, stress) to the life (number of cycles to failure). *Picture 16* shows how the Wöhler curve relates load to life via the k-factor in the elastic region of a SN-Curve.



Picture 16: Slope of SN-Curve is expressed by the k-factor

Because of this log vs log relationship, it means that a small change in load amplitude can have a very large change in the fatigue life or damage. In *Table 2* below, with k-factor of 5, a *15% change* in load results in a *factor of 2* change in damage/fatigue life.



	k factor 3	k factor 5	k factor 7
Stress Level	Fatigue Life	Fatigue Life	Fatigue Life
1	1	1	1
1.15	0.66	0.5	0.375
0.87	1.5	2	2.65

Table 2: k-factor versus stress level and fatigue life

The logarithmic relationship between alternating stress level and the number of cycles to failure is an important consideration in accelerating fatigue testing. As the k-factor gets larger, small increases in load (ie, stress) create larger and larger changes in life. This can be used to accelerate a durability test. By increasing the load a small amount, so that the failure mode is not changed, one can still get large reductions in test time.

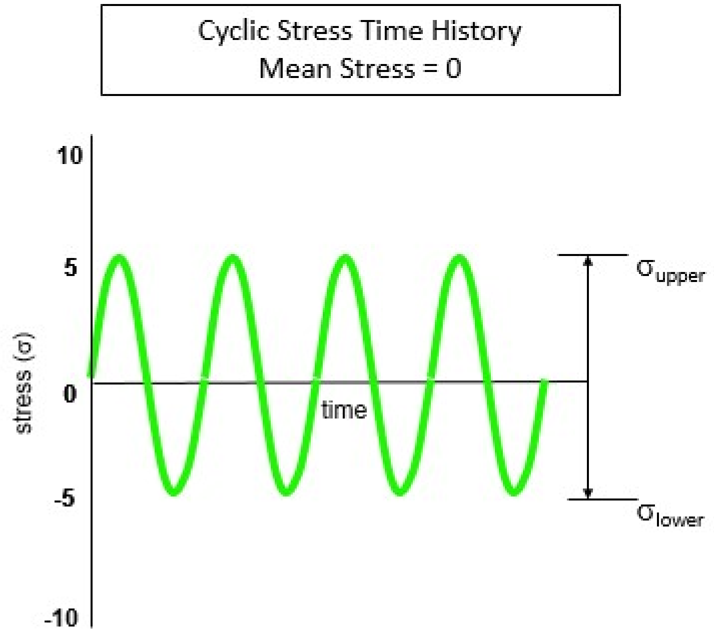
As a general rule of thumb, one can associate the following k-factors with the following:

- k-factor of 7: Aluminum
- k-factor of 5: Steel
- k-factor of 3: Welds

SN-Curve adjustments due to Mean Stress

When using SN-Curves, there can be extenuating circumstances where the SN-Curve must be adjusted to reflect certain situations.

Take the stress time history in *Picture 17*. The average or mean stress of the cycles is zero.

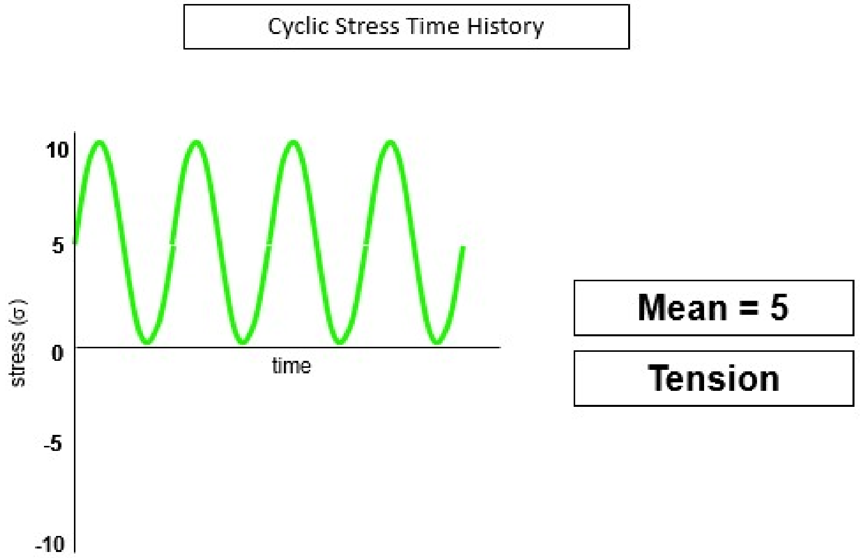


Picture 17: Cyclic stress cycles with mean stress of zero

Why track the mean stress? In real world loading situations, there could be a mean stress other than zero acting on the part. For example, the suspension system of a car has to carry the static weight (or load) of the car. As the car drives on the road, cyclic stresses/loads are applied by bumps in the road while the car weight is applying a mean stress (which is not zero).

There are two different types of mean stress that a part may encounter: tension and compression.

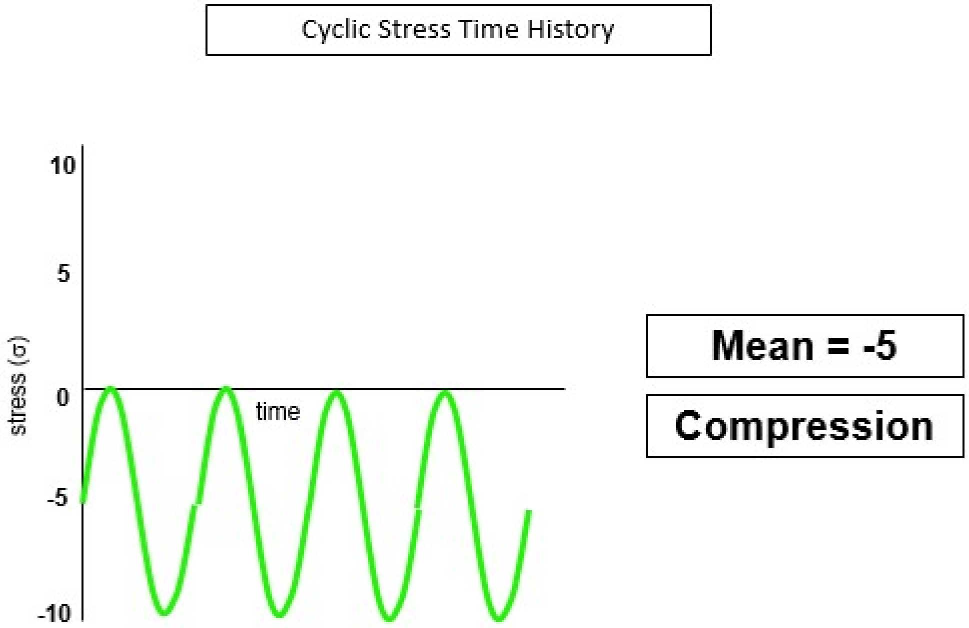
In the case of tension (*Picture 18*), there is a positive mean stress. In a metal coupon test, a static tensile mean stress creates a load that tries to pull the coupon apart.



Picture 18: Cyclic stress cycles with positive mean stress greater than zero (tension)

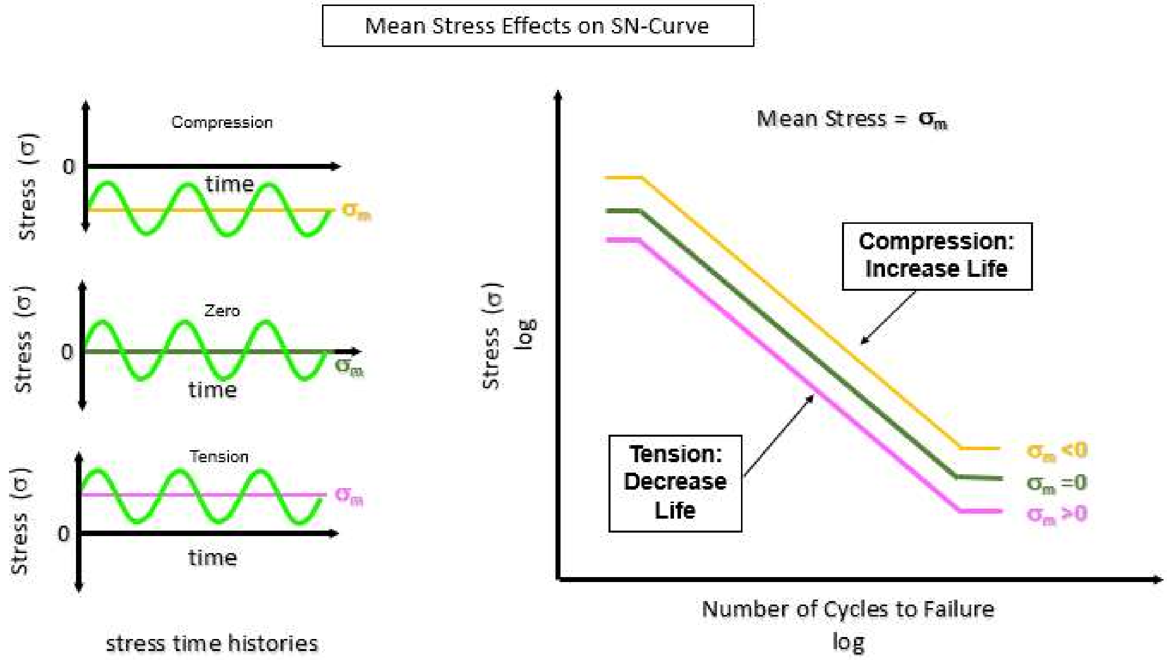
This additional tension reduces the number of cycles to failure. The part would fail sooner than the SN-Curve with mean stress of zero would predict.

The static mean stress could also be pushing the part together, creating compression (*Picture 19*). This compression would extend the life of the part, making it last longer than the zero mean stress SN-Curve would predict.



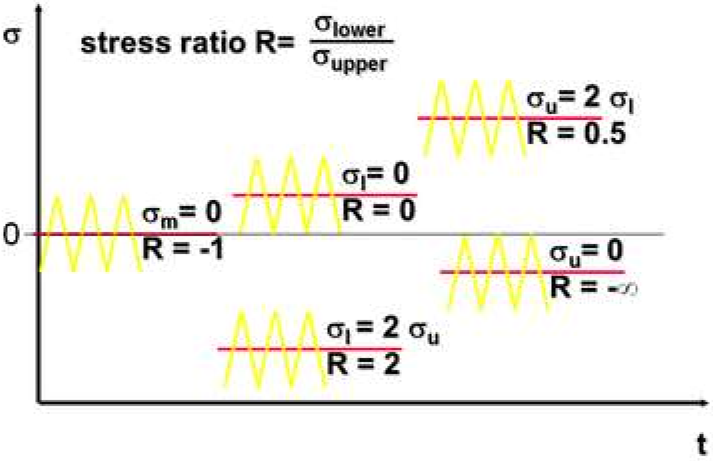
Picture 19: Cyclic stress cycles with negative mean stress greater than zero (compression)

Mean stress effectively shifts the SN-Curve up or down (*Picture 20*). A tensile mean stress in effect shifts the SN-Curve downward so it takes fewer number of cycles to fail. A compressive mean stress shifts the SN-Curve upward so the number of cycles to failure is higher.



Picture 20: SN-Curve adjustments due to mean stress

Typically, SN-Curves are developed for a specific “Stress Ratio”. The “stress ratio” called R is the lower value of the stress divided by upper value of the stress in cyclic stress time history. It is a convenient way to designate the conditions for a SN-Curve test. For example, in the aerospace industry, many components are tested with a stress ratio of 0.1, which ensures a net tension on the component.



Picture 21: Diagram of stress ratios

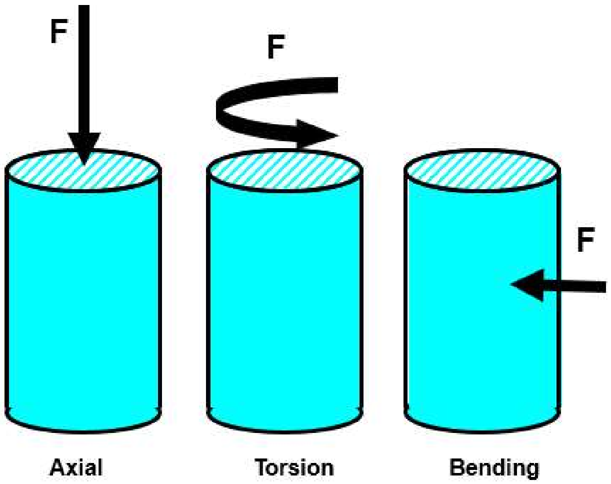
For fully-reversed loading conditions with mean stress of 0, R is equal to -1. For static loading, R is equal to 1. For a case where the mean stress is tensile and equal to the stress amplitude, R is equal to 0.

SN-Curve Adjustments due to Loading

How the load is applied to the structure makes a difference in the number of cycles to failure. The load can be applied in several ways: torsional, bending, axially, etc.

Load Factors, C_L

Type of Loading	C_L
Axial	70%
Bending	100%
Torsional	60%



Picture 22: Different types of loads/stresses

The load scaling correction factors (Cf) are different and depend on the material. The correction factors are used to scale the stress up or down based on the type of load being applied. In the case of bending vs Torsion for the material in *Picture 22*, the adjustment is 40%.

Other SN-Curve Adjustments

There are many other reasons why a SN-Curve may need to be adjusted. Other SN-Curve adjustments include part size, surface finishes, notches in the geometry, etc.

Rainflow Counting

'Rainflow Counting' is a method to determine the number of fatigue cycles present in a load-time history. A fatigue cycle is the loading and unloading of a part as shown in *Figure 1*. With enough repeated cycles, a part will weaken and eventually fail.

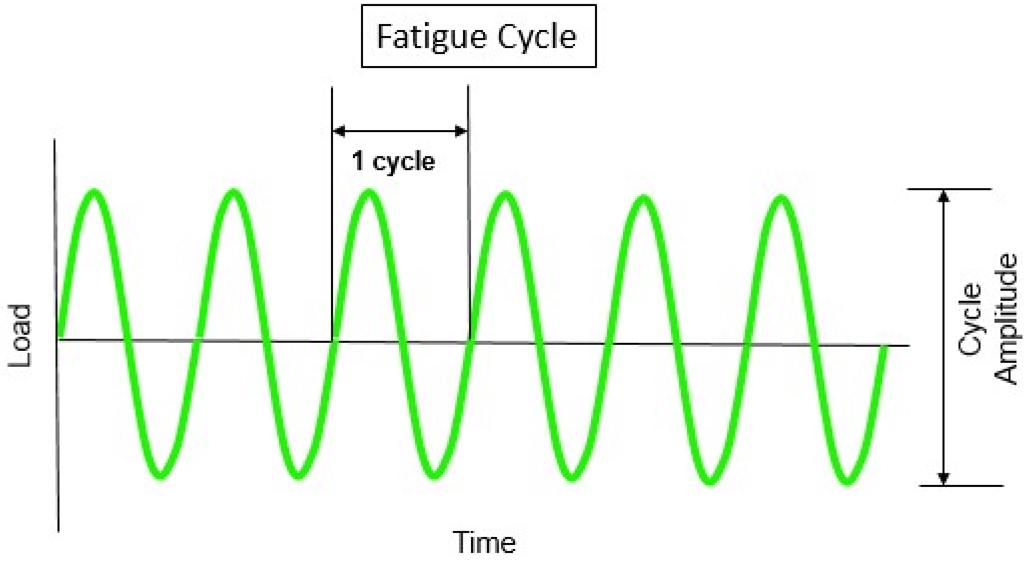


Figure 1: A load-time history with one fatigue cycle highlighted

It is easy to calculate the fatigue damage for a part subjected to a cyclical load of constant amplitude using the SN-Curve of the material and Miner's Rule. However, in a real-world load-time history, the number of cycles and their respective amplitudes is not easily determined as seen in *Figure 2*.

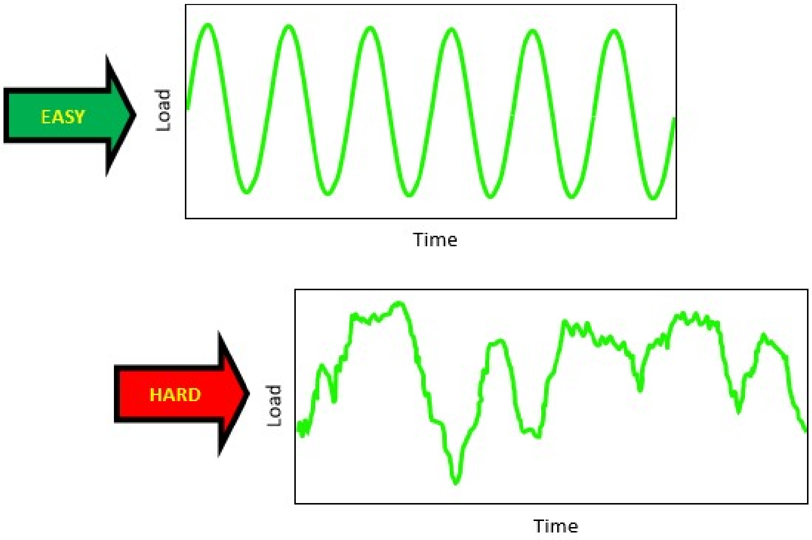


Figure 2: Top – Constant amplitude load-time history: number of cycles and their amplitude are easily determined, Bottom – Measured load-time history: number of cycles and amplitude are difficult to determine

In 1967, Tatsuo Endo, a visiting engineering professor from Japan at the University of Illinois, proposed a method called 'Rainflow Counting' to breakdown any load-time history into its constituent fatigue cycles.

A load-time history typically consists of force versus time, or strain versus time. If doing stress life, the force or strain time histories are converted into stress time histories. Rainflow counting is then used to extract the number of cycles, and their respective range and mean.

Real life loading is not necessarily cyclic and often appears to be random or transient in nature. Using rainflow counting, the fatigue damage of one load history could be compared to the fatigue damage of another load history as shown in *Figure 3*.

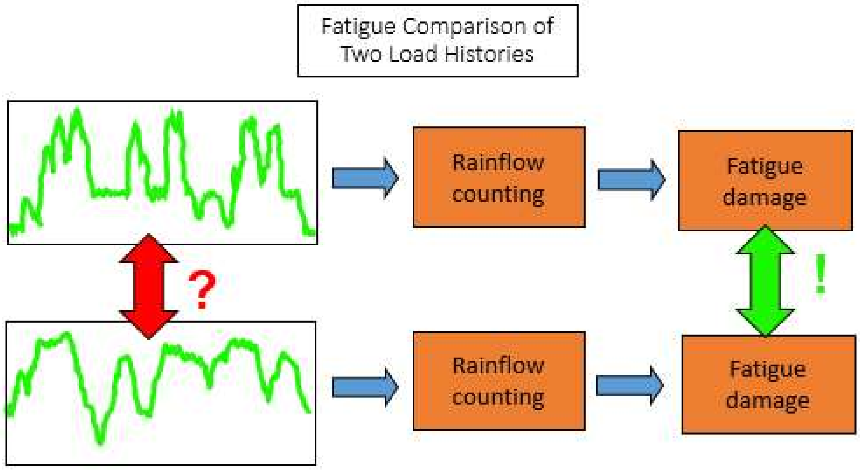


Figure 3: Using the time domain data to compare fatigue damage is not possible. Rainflow counting is used to make comparisons of fatigue damage possible.

Not only does 'Rainflow Counting' make it possible to determine the fatigue damage of a given load-time history, but it also reduces the time history to the minimal amount of data required to preserve the damage information. By reducing the time data size, the calculation speed for a durability fatigue analysis is decreased, and the amount of computer storage required is lowered.

In 1986, the first ASTM Rainflow Counting standard, E1049, was published.

Rainflow Counting Method

'Rainflow Counting' consists of four main steps:

1. Hysteresis Filtering
2. Peak-Valley Filtering
3. Discretization
4. Four Point Counting Method

These steps are fully documented in standards such as ASTM E1049 "Standard Practices for Cycle Counting in Fatigue Analysis".

Hysteresis Filtering

The first step in reducing the load-time history is to remove very small cycles from the load-time history that contribute a negligible amount of damage (*Figure 4*).

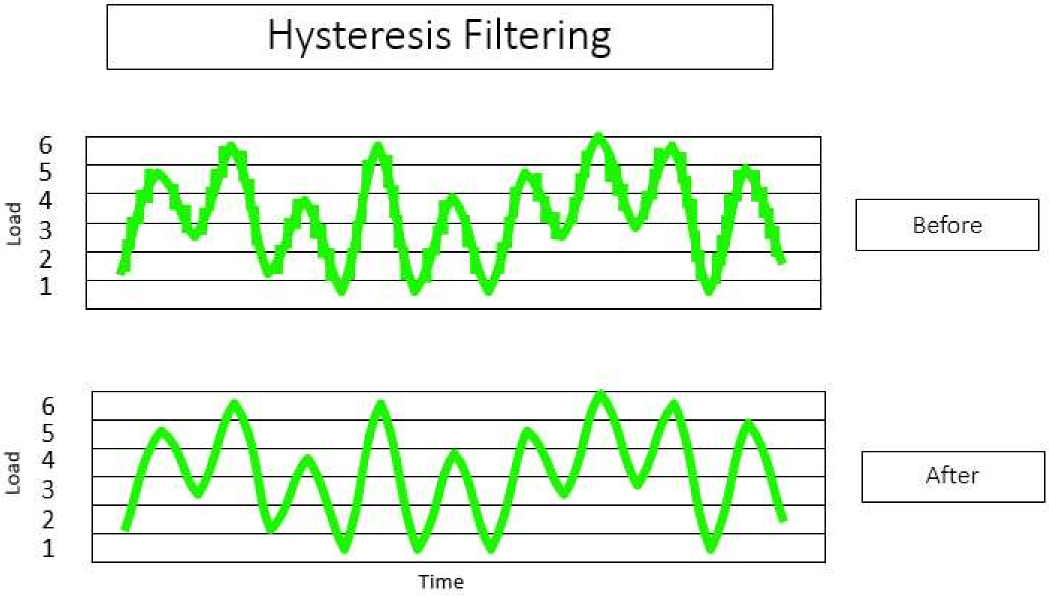


Figure 4: Top – Original load-time history, Bottom – Original load-time history with small cycles removed

This is done by defining a gate of a specific amplitude. Any cycle that has an amplitude smaller than the gate is removed from the load-time history. This is done by projecting the gate from left to right from each turning point in the time series. If a turning point is smaller than the gate, it is eliminated from the time history (*Figure 5*).

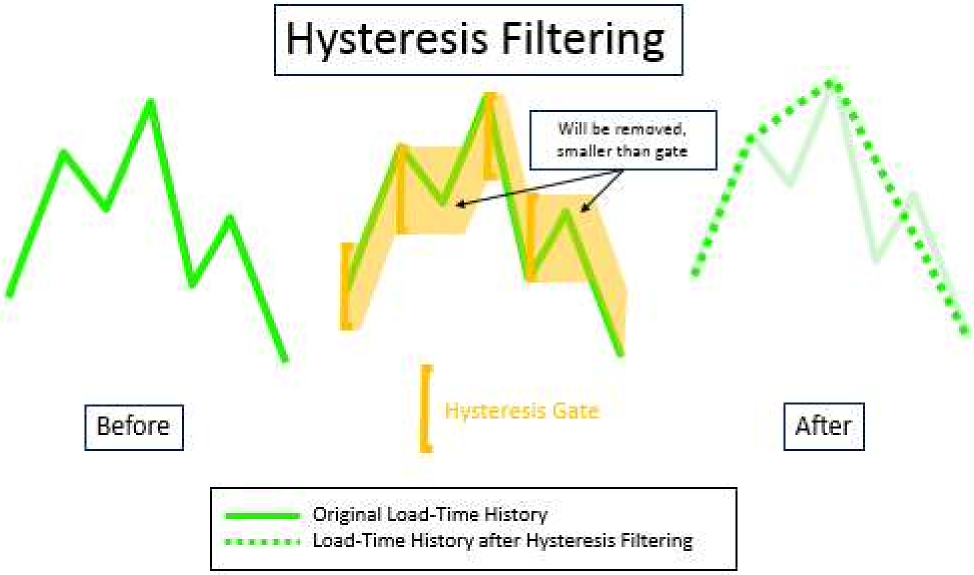


Figure 5: Removal of cycles smaller than amplitude of hysteresis gate from load history

Usually a percentage of the bin size (see rainflow counting discretization step #3) is used to define the gate size.

If a hysteresis gate of zero is used, this step is skipped.

Peak-Valley Filtering

The goal of Peak-Valley filtering is to only keep data points which are reversals in direction/slope as shown in *Figure 6*.

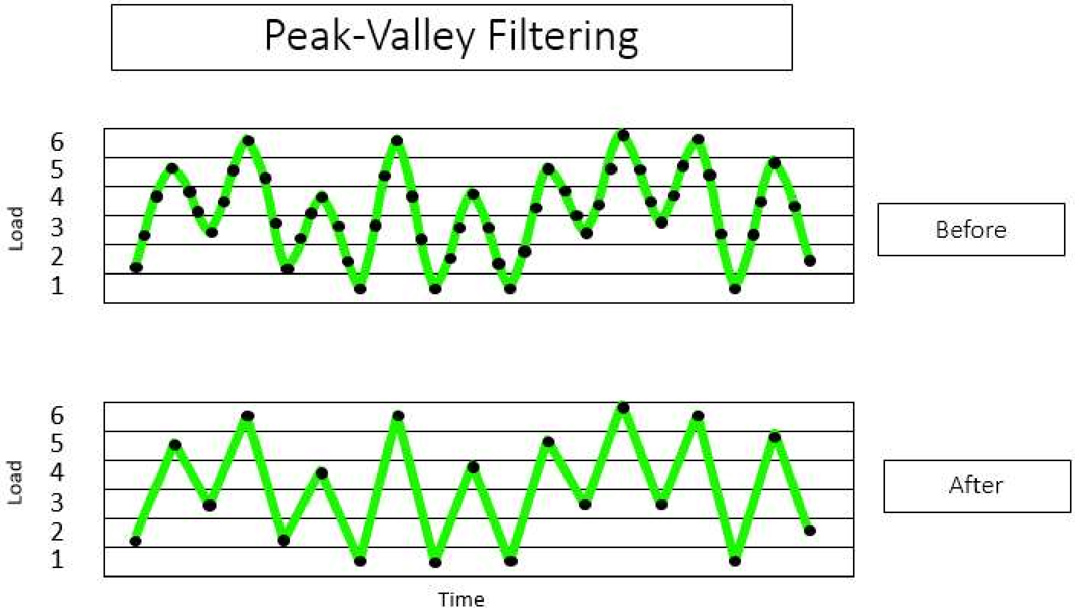


Figure 6: Peak-Valley Filtering keeps only data points (black dots) which represent reversals in slope

Within a cycle, only the maximum and minimum value of the cycle are important for fatigue life calculations. Any intermediate data points between the maximum and minimum values of a given cycle can be removed as they are not relevant for the fatigue calculation.

The result is sometimes called a 'turning point sequence'.

Discretization

Next, the Y axis is divided into discrete 'bins'. Each 'bin' is a fixed amplitude range that the data is mapped into as shown in *Figure 7*. In *Figure 7*, there are six discrete bins used to divide the amplitude range. In practice, many more bins are used.

The measured data points are mapped to the centers of their bin, which enables counting procedures.

For example, if a signal with a range of 128 was divided into 64 bins, each bin would have a range of 2.

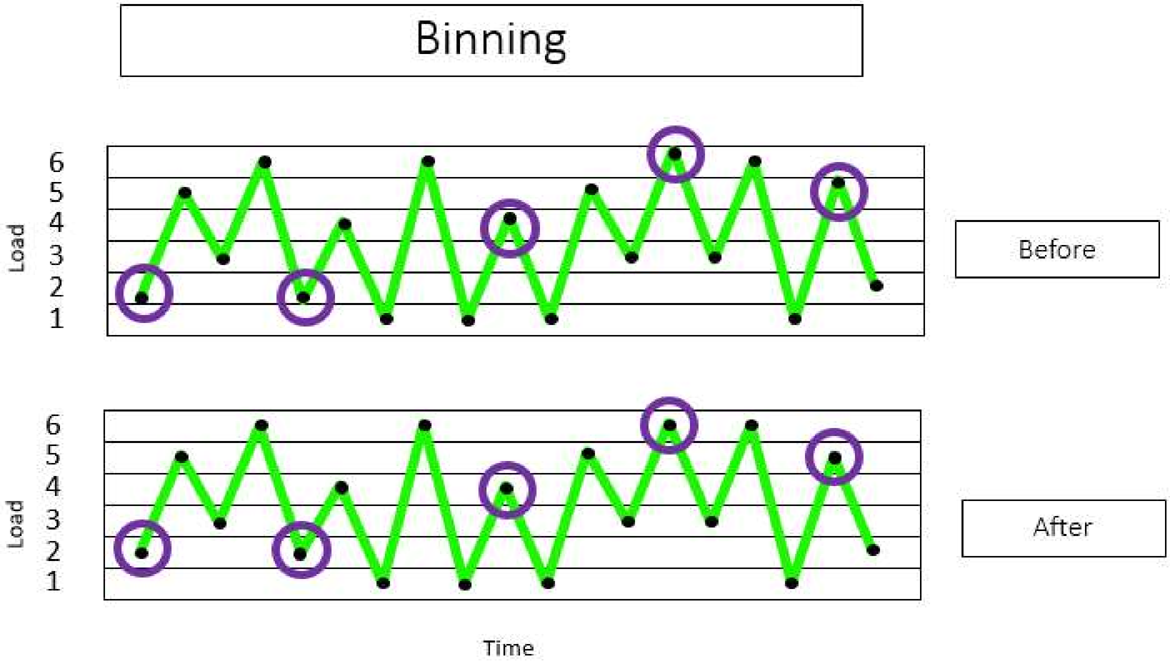


Figure 7: Data points (black dots) amplitudes are adjusted to the center of the bins. Data points whose amplitude is affected by binning are circled in purple.

The amplitude of the data samples is altered slightly by centering them in their respective bins. It is important to use a reasonably sufficient number of bins for the analysis, so the amplitudes are not altered greatly. Depending on the slope of the SN-Curve, a 15% change in load can result in a factor of two change in fatigue life.

According to most standards, the Y-axis scale is typically divided into a minimum of 64 bins. In most modern durability software, it is possible to use more bins in the rainflow count. Increased accuracy is achieved by using more bins, but the file size is larger and computational times are longer.

Four Point Counting Method

With hysteresis filtering, peak-valley filtering and discretization all finished, the cycles can be counted. When counting cycles for fatigue life calculations, not only is the amplitude and number of cycles important, but so is the mean of the cycle as well. Any counting method needs to preserve the mean.

The four point counting method meets these aforementioned criteria. In the method, the following steps are performed:

1. Chose four consecutive stress points S1, S2, S3, S4
2. Define inner Stress |S2 -S3|
3. Define outer Stress |S1 -S4|
4. If inner stress range <= to outer stress range and the points comprising the inner stress range are bounded by the outer, a cycle is counted.
5. If inner stress range >= to outer stress range and the points comprising the inner stress range are not bounded by the outer, a cycle is not counted

Evaluating the first four points in *Figure 7*, the range between S2 and S3 is less than the range between points S1 and S4. The inner stress, where S2=5 and S3=3, has a range of 2. The outer stress where S1=2 and S4=6 has a range of 4. The data points S2 and S3 are within the data points S1 and S4. A cycle is counted as shown in *Figure 8*.

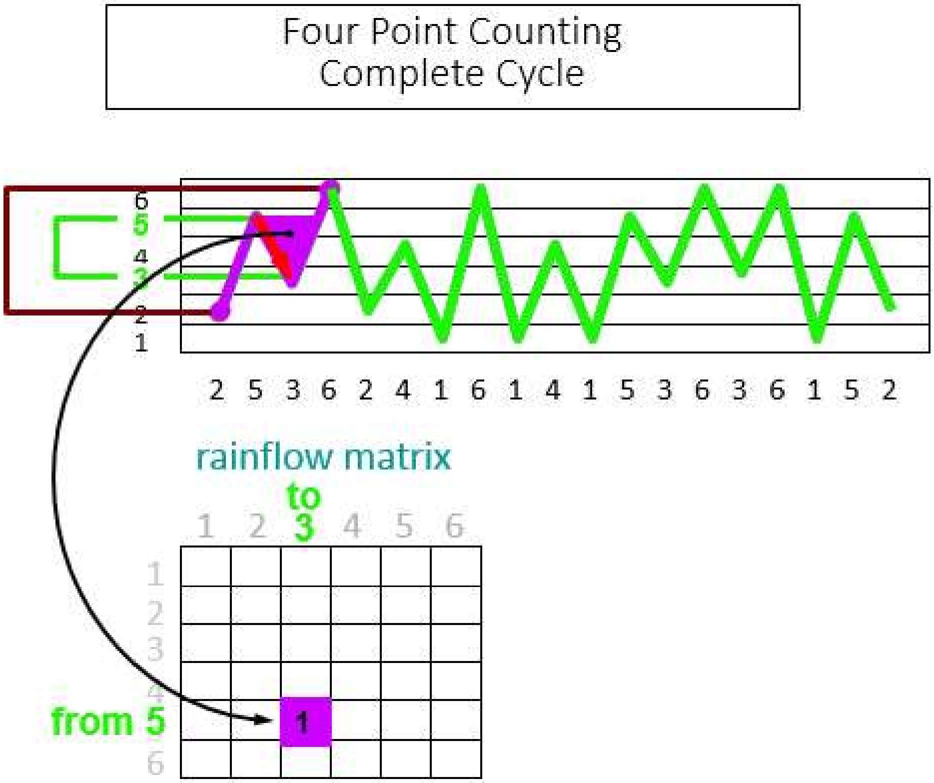


Figure 8: The first four points (purple) in the time history are evaluated. In this case, a complete cycle is identified

When a cycle has been identified, it is stored in a rainflow matrix. The rainflow matrix is an n x n matrix of data where n equals the number of bins. Each element in the matrix contains the number of cycles found in the time history corresponding to the 'From' and 'To' amplitudes.

The inner two stress points (S2 and S3) are now removed from the load-time history. The first four points in the *remaining* time history (new S1, S2, S3, S4 values) are evaluated again. This time, there is not a complete cycle within the four points connected by purple line as shown in *Figure 9*.

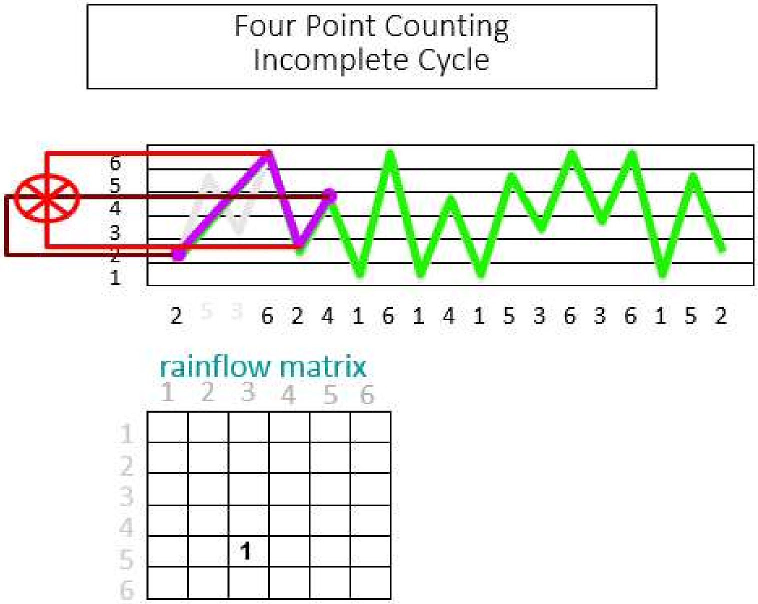


Figure 9: From the remaining time history, the first four points (connected by purple line) are evaluated. The inner two values (S2 and S3) are not bounded by the outer values (S1 and S4). Therefore, there is not a complete cycle.

The inner stress, where S2=6 and S3=2, has a range of 4. The outer stress, where S1=2 and S4=4, has a range of 2. The points S2 and S3 are not within the points S1 and S4.
In this case the cycle is not complete. The next four points in the time series will be evaluated as shown in *Figure 9* by the connecting light purple line.

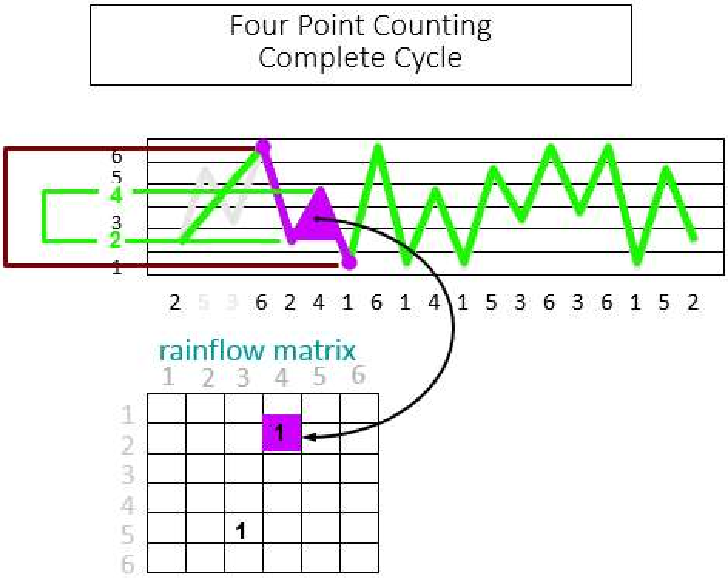


Figure 9: Because the first four points did not yield a complete cycle, the next four points are evaluated. Now there is a complete cycle.

For the four points in *Figure 9*, there is a complete cycle. Like the first cycle identified, it also has a range of 2. In this case, however, the cycle goes from 2 to 4, and not from 5 to 3. These two cycles have a different mean and different direction, which is preserved in the rainflow matrix.

The process is continued until all identifiable cycles are removed and counted from the time history as shown in *Figure 10*.

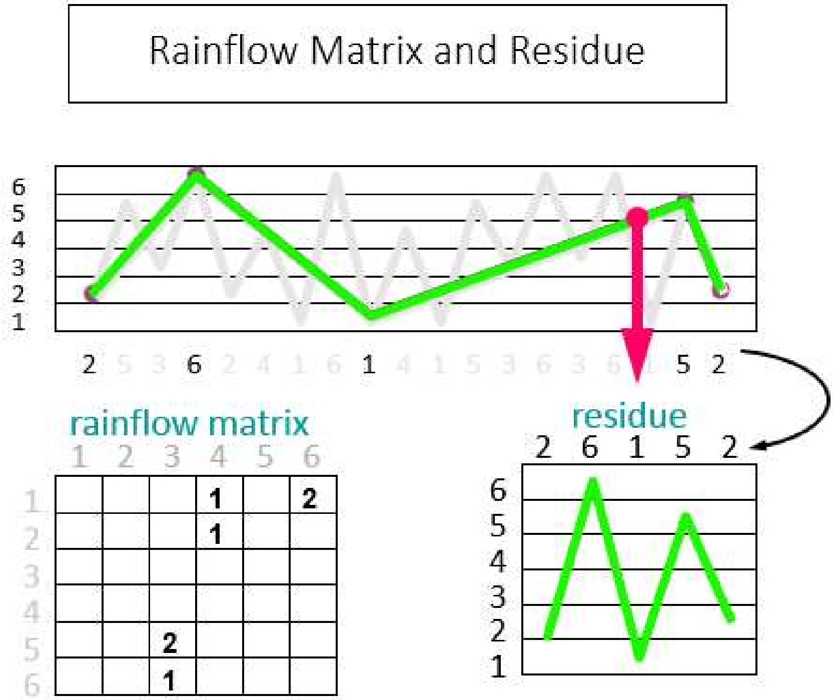


Figure 10: Rainflow matrix and Residue

Inevitably, there are some cycles that do not close (i.e., are not complete). These unclosed cycles are preserved and called the 'residue' of the rainflow matrix.

The residue contains the largest unclosed cycles present in the time history. If the time history was for one lap of a durability proving ground, to calculate the damage for 1000 laps, every element of the matrix would be multiplied by 1000. The residue would be appended 1000 times over and the unclosed cycles then counted and added to the rainflow matrix.

Rainflow Matrix

The 'Rainflow Matrix' and 'Residue' are the end results of the rainflow counting process. They contain the following information:

1. Cycle amplitude – Across the top of the display is the "To" stress level for the cycle. Across the side is the "From" stress level for the cycles. The range or amplitude of the cycle is |To-From|.
2. Cycle mean – The mean of the cycle is (To+From)/2. The mean stress determines if the cycle is compressive or tensile, which affects the accumulated damage.
3. Number of cycles – The number of the cycles is indicated, sometime with colors dictating specific number of cycle thresholds

A 'From-To' rainflow matrix has three dimensions (Figure 11):

1. From – Stress level bin that the cycle originates from
2. To – Stress level bin that the cycle finishes at
3. Number – Number of times a particular From-To cycle occurs

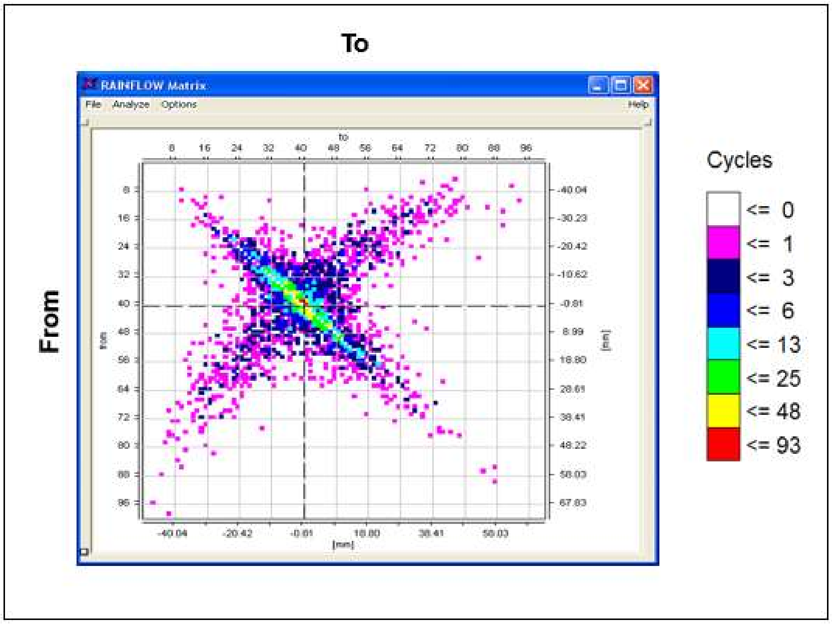


Figure 11: Rainflow matrix has from and to, color indicates number of cycles

In the From-To representation (*Figure 12*) of the rainflow matrix, cycles of compression are located in the upper left, while tensile cycles are located in lower right. The mean of the cycle effects the fatigue life of the part.

Compressive cycles have a negative mean, which pushes the part together despite the cycling of the material. These compressive cycles will not reduce the fatigue life as much as similar amplitude tensile cycles. In a tensile cycle there is a positive mean, which creates forces that try to pull apart the object in addition to cycling. The diagonal from upper left to lower right is very small amplitude cycles, e.g., with a range close to 0.

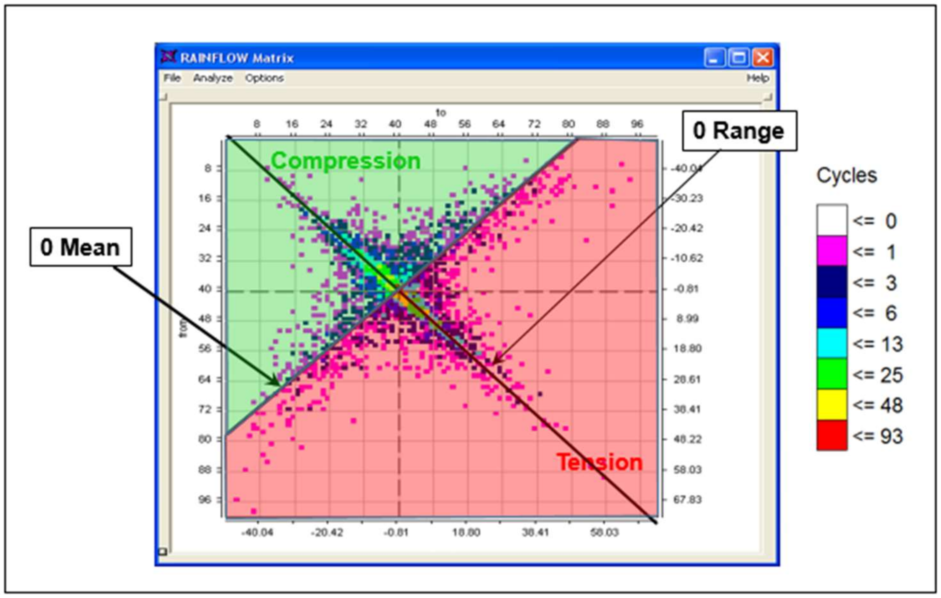


Figure 12: Rainflow Matrix indicating Compressive versus Tensile cycles, Zero Mean cycles, and Zero Range cycles

The most damaging cycles are located in the upper right and lower left due to their very large range. These are the largest amplitude cycles and create the most damage (*Figure 13*). It is typical that the highest number of cycles fall along the diagonal of the rainflow matrix close to the zero range line.

When looking to accelerate a fatigue test or analysis, these low damage, but high occurrence, cycles are removed from the test recreation or analysis to save time in performing the failure analysis.

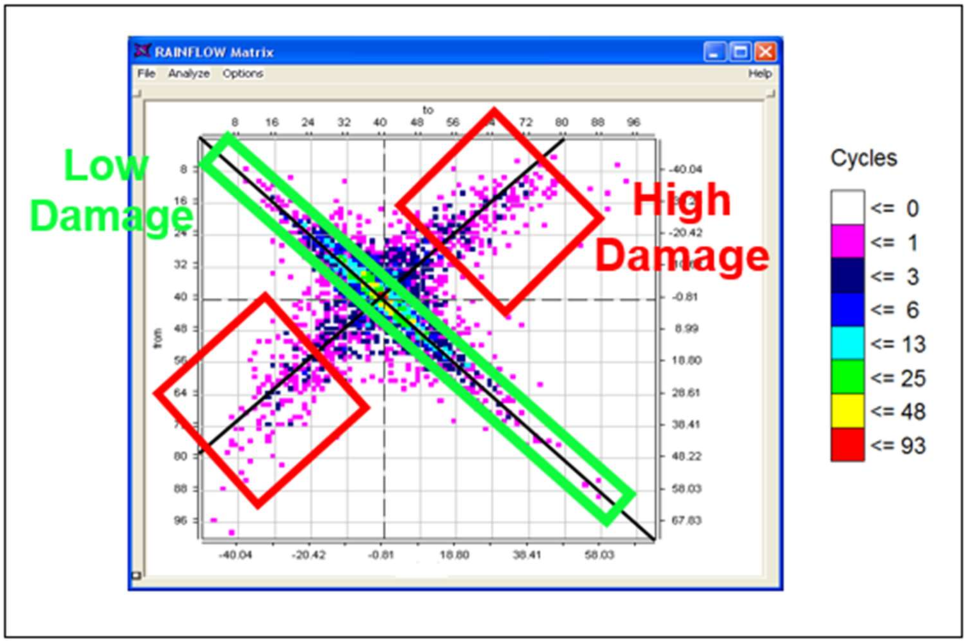


Figure 13: Rainflow Matrix with most damaging and least damaging cycles indicated

Using Miner’s Rule and a SN-Curve of the material, the rainflow matrix cycles can then be used to calculate the fatigue damage. This enables predicting when fatigue failures would occur (when damage = 1) and compare different complex time histories and understand the damage associated with each.

Conclusion

The 'Rainflow Counting' method extracts fatigue cycles from any load-time history. The result is a rainflow matrix and residue. The following information is preserved from the time history:

- Number of cycles
- Range of cycles
- Mean of cycles

This cycle information is in a much more compact and manageable form than the original time history data. Only the sequence, or order, in which the cycles are applied over time are not kept.

Difference between “Range-Mean” and “From-To” cycle counting

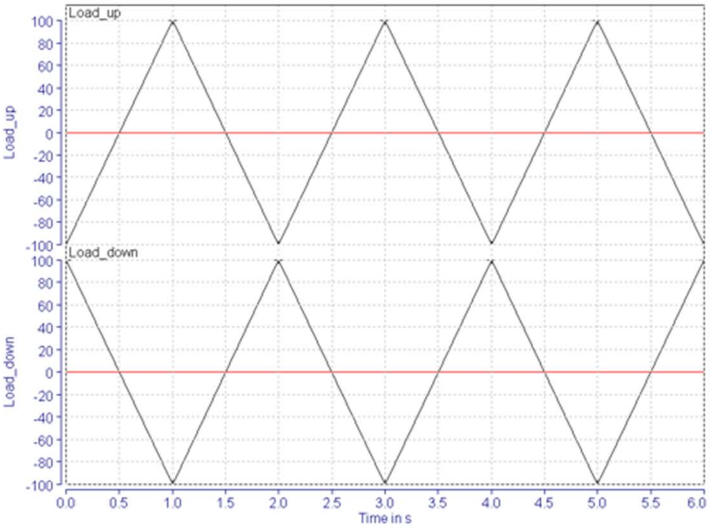
The unsymmetrical From-To cycle counting keeps more information about the loading cycles than Range-Mean counting does, because it also stores the "orientation" of each load cycle. This is important information if you want to reconstruct a time history from a Rainflow matrix.

The Rainflow counting of Simcenter Tecware is a From-To cycle counting, and thus the default representation of the Rainflow matrices are also in From-To form.

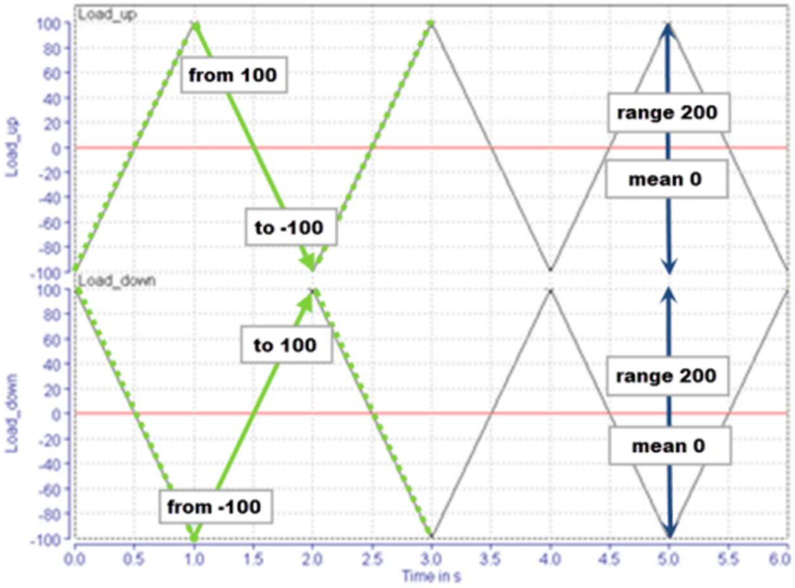
However, Simcenter Tecware also allows changing the representation to Range-Mean matrices. In fact, a Range-Mean histogram can always be derived from a From-To histogram, but not vice versa. This is because the From-To representation includes additional information (as mentioned above).

Example

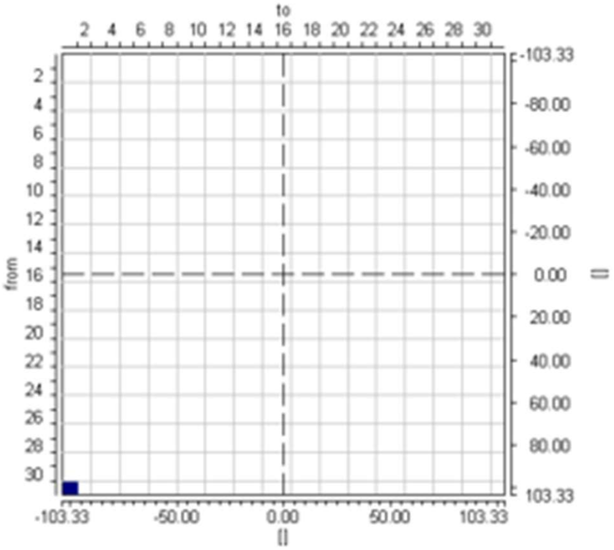
Look at the two load histories below:

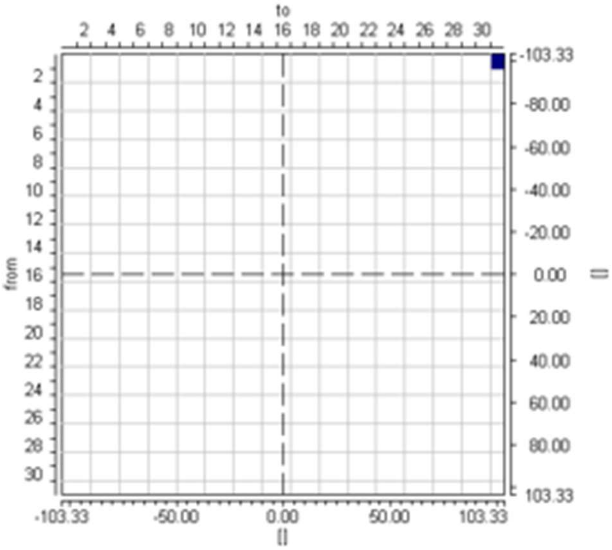


They both have the same mean level and the same number of cycles, and the cycles' amplitudes are identical. The only distinctive property is the opposite polarity.



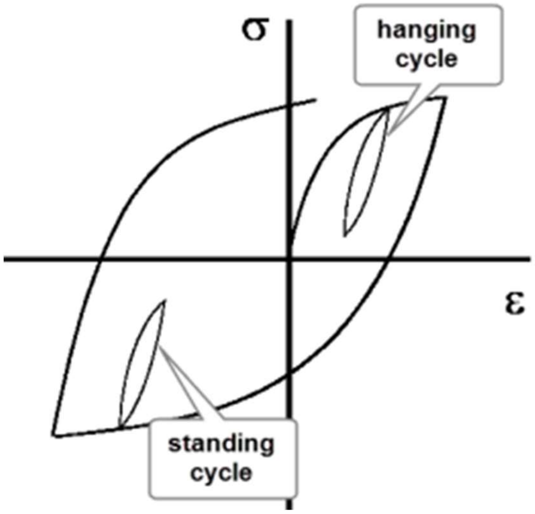
Looking at the Rainflow matrices of the two load histories, we get in the From-To representation:



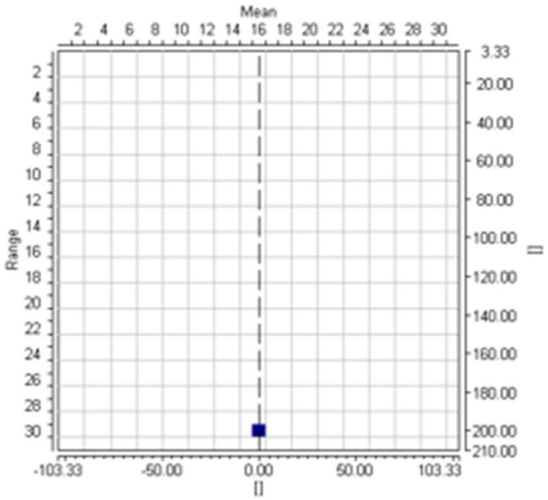


The Rainflow matrix of "Load_up" shows *hanging* cycles, whereas the corresponding Rainflow matrix of "Load_down" shows *standing* cycles.

The denotation *hanging* and *standing* is motivated from the stress-strain-path. There, a *hanging* event is connected to the superior hysteresis branch at its upper reversal point, but a *standing* event is connected at its lower reversal point.

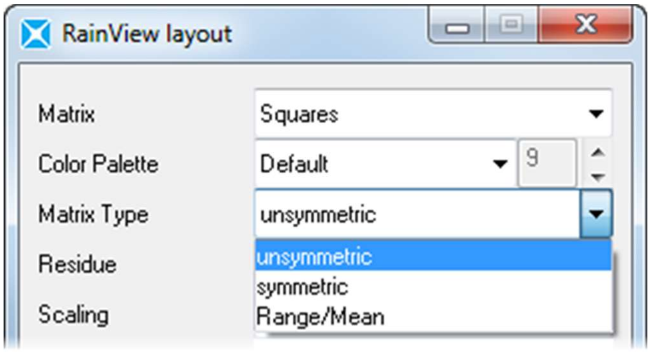


When a load cycle is just represented by its **range** and **mean**, the distinction between *hanging* and *standing* is not possible. Thus, the **Range-Mean** representation for both of the signals looks like this:



Remarks

The desired representation of a Rainflow matrix can be set in the "RainView layout" window, which is available via the menu Options à Layout within the Rainflow matrix display.



Matrix: Squares
Color Palette: Default 9
Matrix Type: unsymmetric
Residue
Scaling

Rainflow matrices can only be edited in the From-To representation.

The Goodman-Haigh Diagram for Infinite Life

Infinite life is often used in designing critical components of products with demanding use. Examples include crankshafts of an engines, vehicles for public transportation, spacecraft, etc.

What is meant by infinite life? Ferrous materials have an 'infinite life' region defined by an 'endurance limit'. The endurance limit is a specific stress level for a material, where stress cycles below a certain amplitude and mean will not accumulate fatigue damage.

The Goodman-Haigh diagram is used to check if a cyclic stress time history is within the infinite life region for a product made of a given material (*Figure 1*).

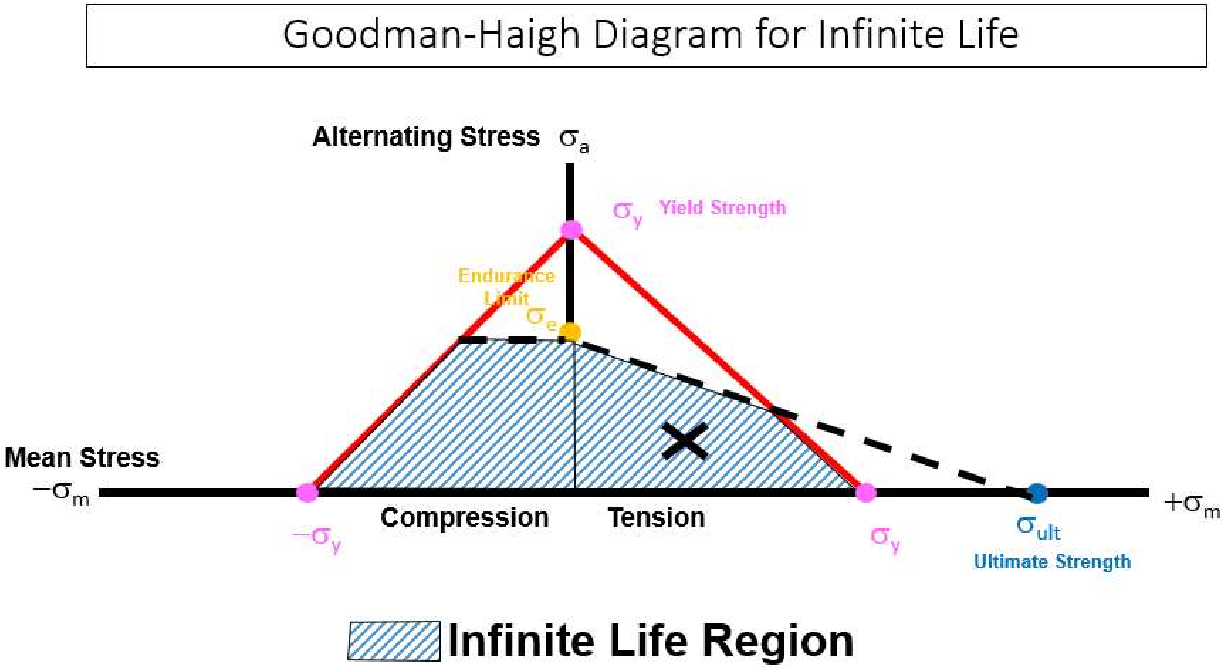


Figure 1: Goodman-Haigh diagram

It is important that none of the stress cycles in a load history exceed the infinite life endurance limit. If they do, the material will behave as if the infinite life region does not exist, and failure will occur given enough additional cycles, even if they are below the endurance limit.

Goodman published his original diagram in 1899. Haigh added alternating and mean stress in 1917. The combination of these two is referred to as the 'Goodman-Haigh Diagram'.

Goodman-Haigh Diagram

Two major pieces of information are needed to use a Goodman-Haigh diagram:

- Stress cycles: A stress cycle time history of the expected loading that includes both alternating and mean stress information
- Material Information: The yield strength, ultimate strength, and endurance limit of the part material

The material information is used to define an infinite life region. The stress cycles are plotted against this region to see if they are contained within it.

Stress Cycles

A stress time history can be broken down into individual cycles. A cycle has an alternating component as shown in *Figure 2.*

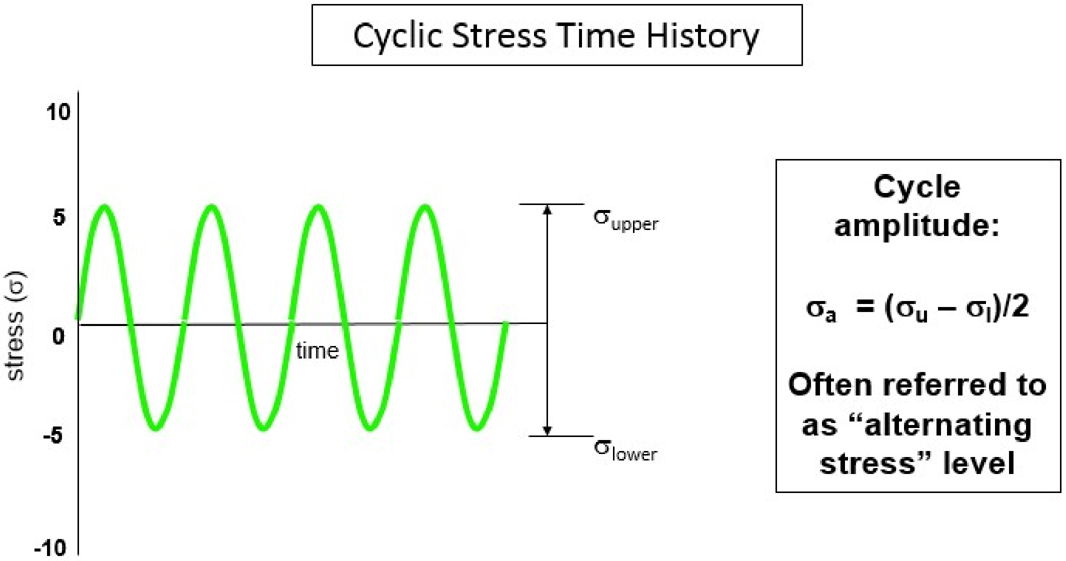


Figure 2:

Alternating stress levels

A stress cycle can also have a mean stress. This mean stress puts the part in either net compression or tension as shown in *Figure 3*.

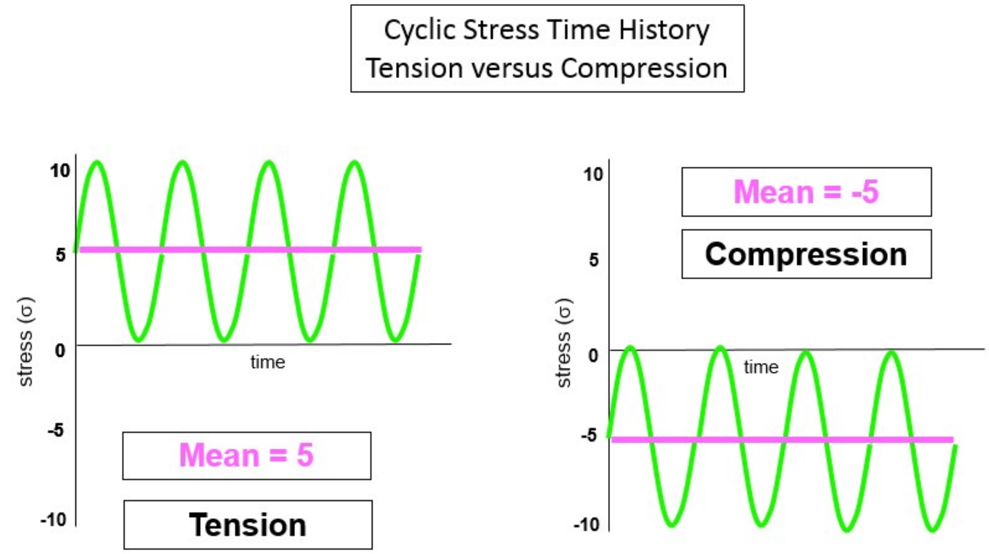


Figure 3: Mean stress: compression versus tension

The mean stress is very important factor in governing the fatigue life. Net tension on a part tries to pull it apart, which significantly reduces its life. Net compression pushes a part together, which is not as damaging.

In the Haigh diagram, the alternating and mean stress of the cycles will be plotted against each other as shown in *Figure 4*.

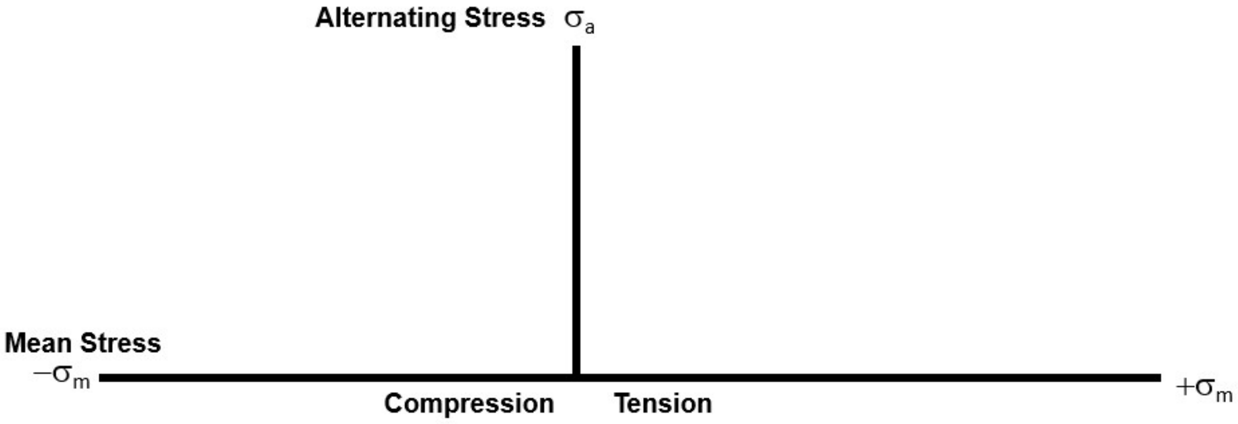


Figure 4: Alternating versus mean stress

The alternating stress level is plotted on the Y axis. The mean stress level is plotted on the X axis. Negative mean stress is compression, and positive mean stress is tension.

Material Information

Using a static stress-strain test on a material, the following material properties can be determined:

- Yield Strength – Stress level at which there is a transition between the elastic region and plastic region of the material, where the relationship between stress and strain ceases to be linear
- Ultimate Strength – Stress level where the material starts to fail

These material properties are determined via applying static loads to the material and plotting the relationship of stress and strain as shown in *Figure 5*.

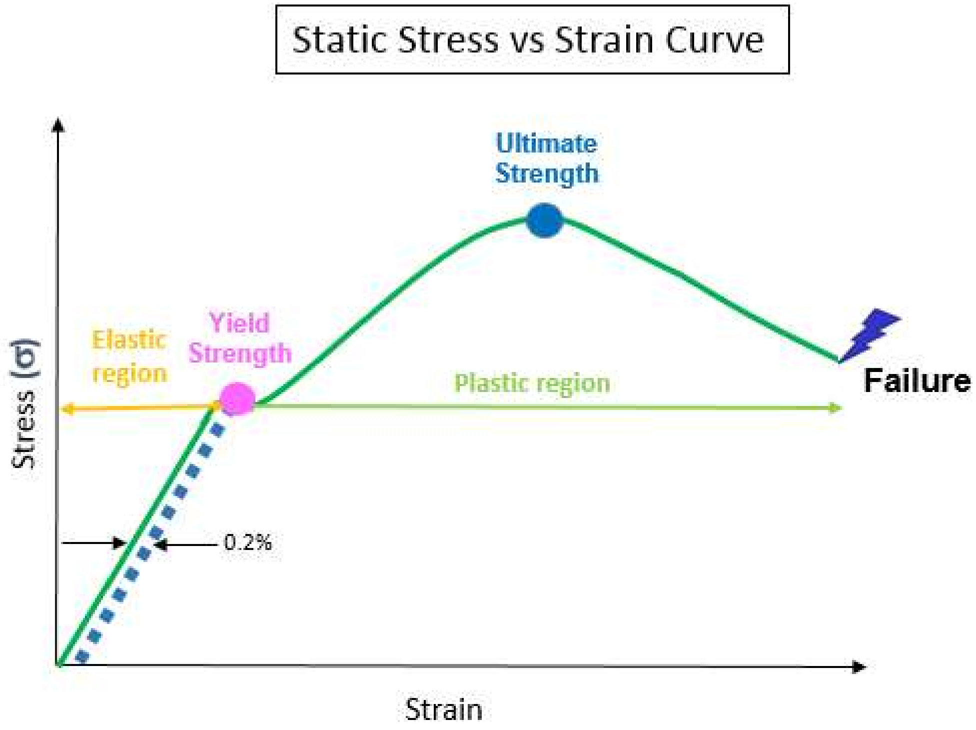


Figure 5: Yield and Ultimate strength are determined from static stress-strain test

The Yield strength and Ultimate strength are plotted on the Goodman-Haigh diagram as shown in *Figure 6*.

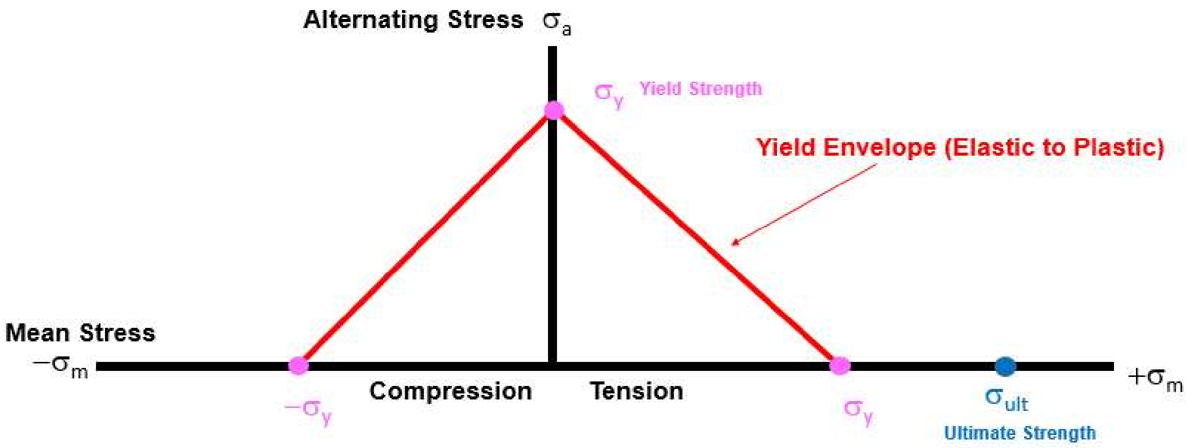


Figure 6: Ultimate strength and yield strength are plotted on diagram

A yield envelope is created by connecting the yield strength points. However, this yield envelope is symmetric around the Y-axis, and does not distinguish between compression and tension.

Additional material information is needed from a dynamic/cyclic stress test. The result of a dynamic stress test can be found in a SN-curve as shown as shown in *Figure 7*.

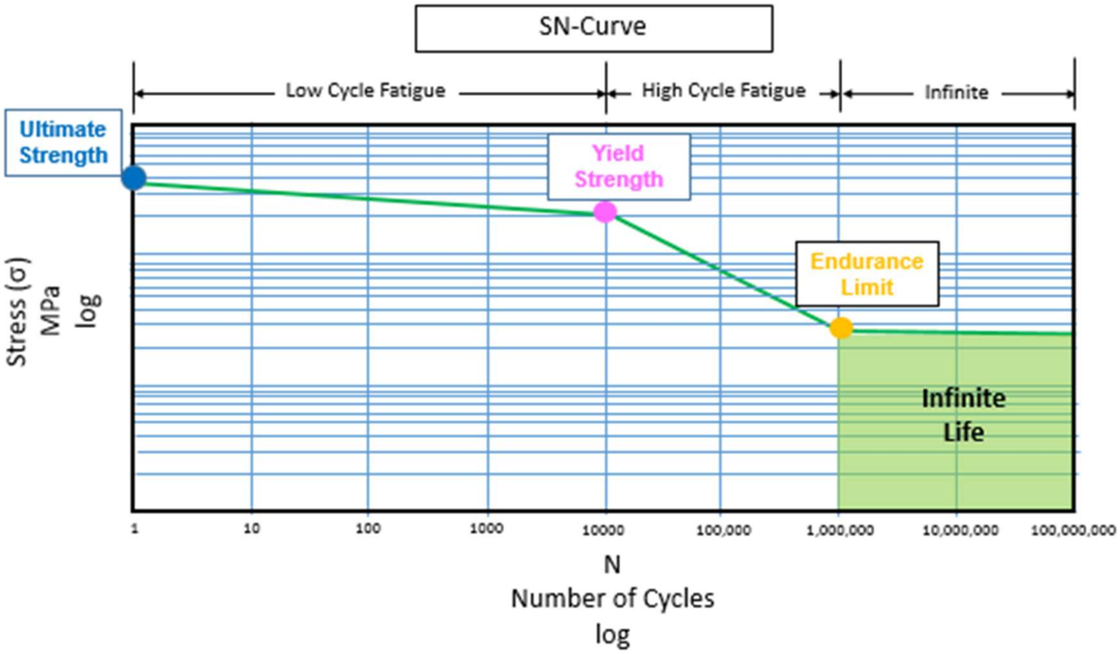


Figure 7: SN-Curve with Infinite Life

The endurance limit is determined from the SN-Curve. The endurance limit is then plotted on the Goodman-Haigh diagram as shown in *Figure 8*.

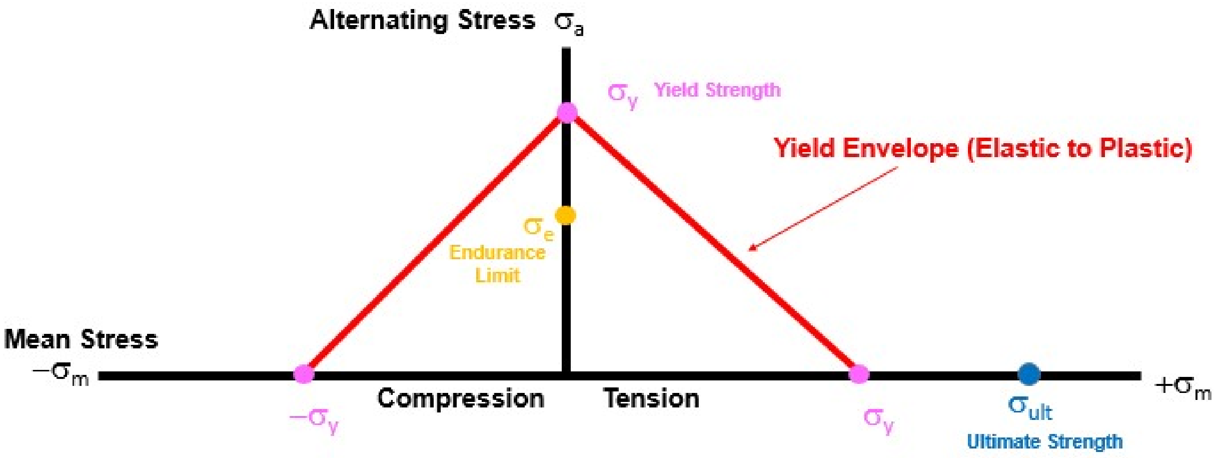


Figure 8: Goodman-Haigh diagram with Endurance limit

An infinite life region can then be created by:

- Connecting the endurance limit to the ultimate strength on the tension side (called the Modified Goodman line)
- Project the endurance limit on the compression side

This infinite life region defined by these connections and projections are shown in *Figure 9*.

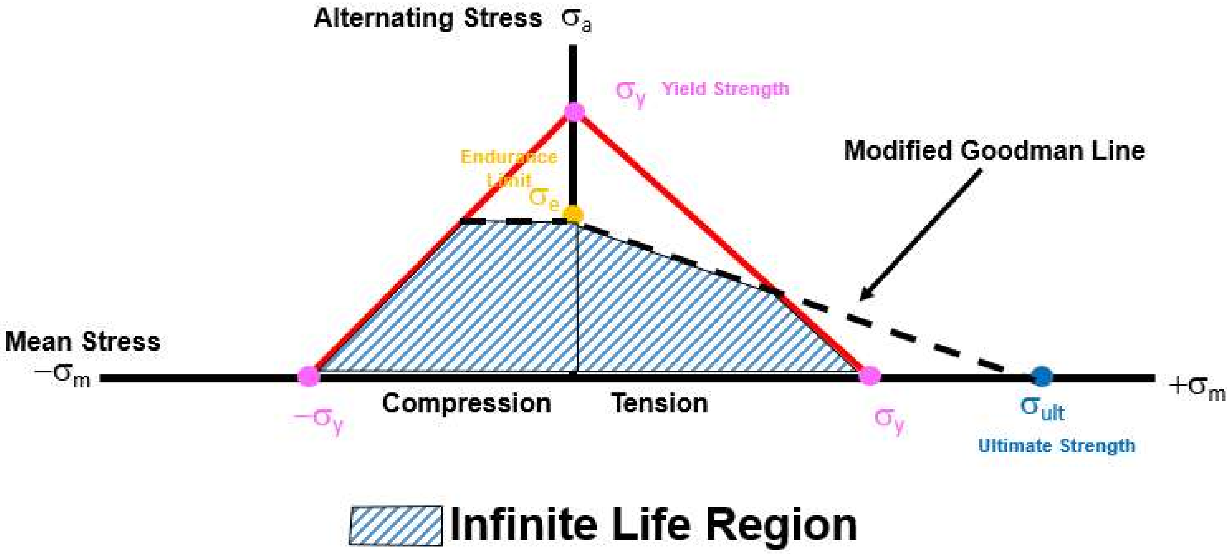


Figure 9: Infinite life region defined by Modified Goodman line

This infinite life region has a smaller region for tension versus compression, as would be expected. A stress time history can then be evaluated against the infinite life region.

Using the Goodman-Haigh diagram

The mean and alternating stress of a stress time history is plotted on the Goodman-Haigh diagram as shown in *Figure 10*.

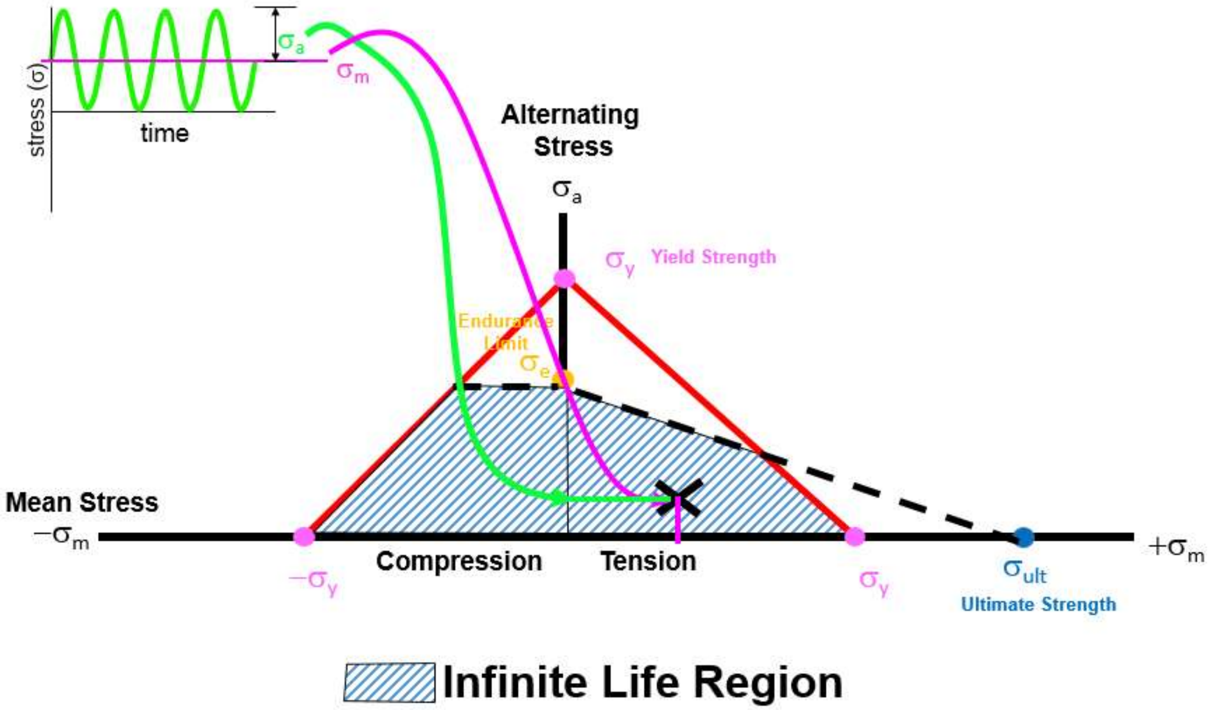


Figure 10: Mean and alternating stress plotted against Infinite life region

This is done for each cycle in the time history. Each cycle is evaluated as to whether it falls in the infinite life region. In *Figure 10*, the stress cycles are contained entirely in the infinite life region.

Any stress time history, no matter how complicated, can be broken into individual cycles via the rainflow counting process. These cycles produced by the rainflow counting process include a mean and alternating stress.

Projecting from the origin to the cycle versus the region, a factor of safety can be calculated (*Figure 11*).

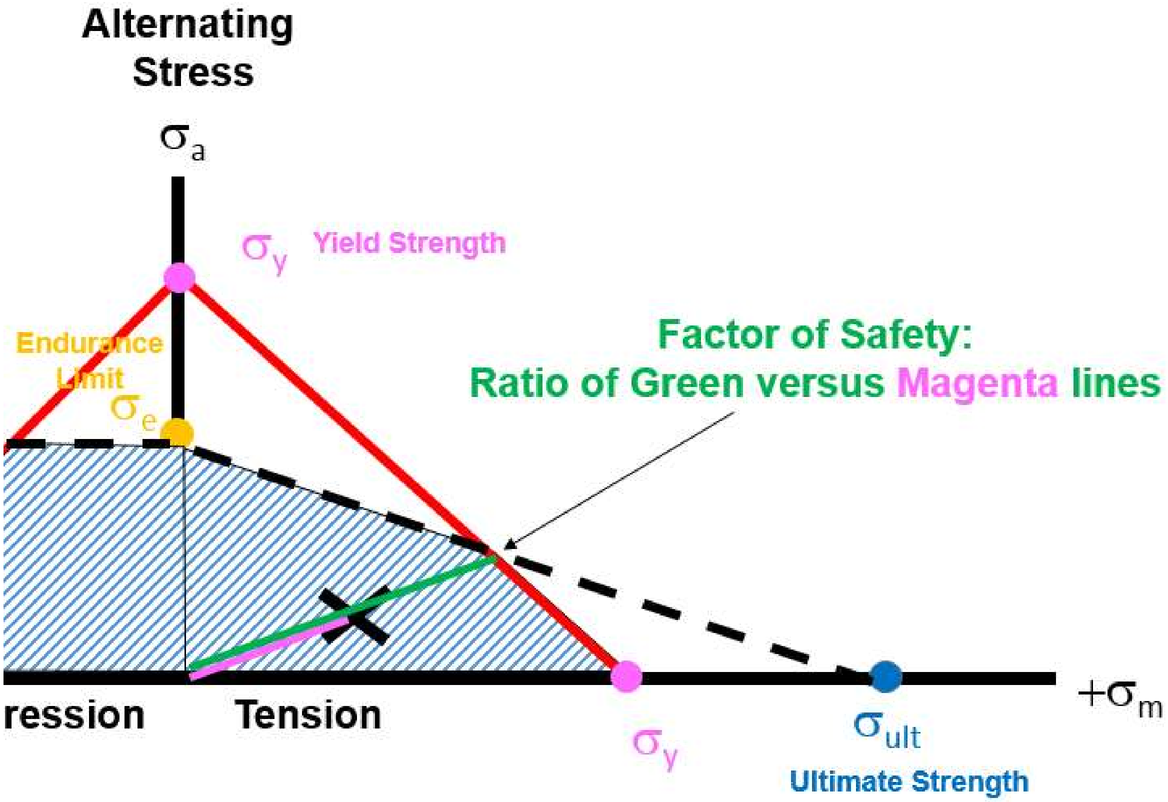


Figure 11: Factor of Safety

In this case, the factor of safety is approximately two: the ratio of the magenta and green lines. In many engineering applications, a factor of safety of three or higher is often desired. This would ensure that the part would survive with three times higher than expected loads.

Simcenter Tecware

Using Simcenter Tecware, infinite life calculations can be made using the Simcenter Tecware Processbuilder and the files attached to this article (*Figure 12*). They include an Installation and Instructions (*.docx), a ProcessBuilder file (*.pb), and other additional files.

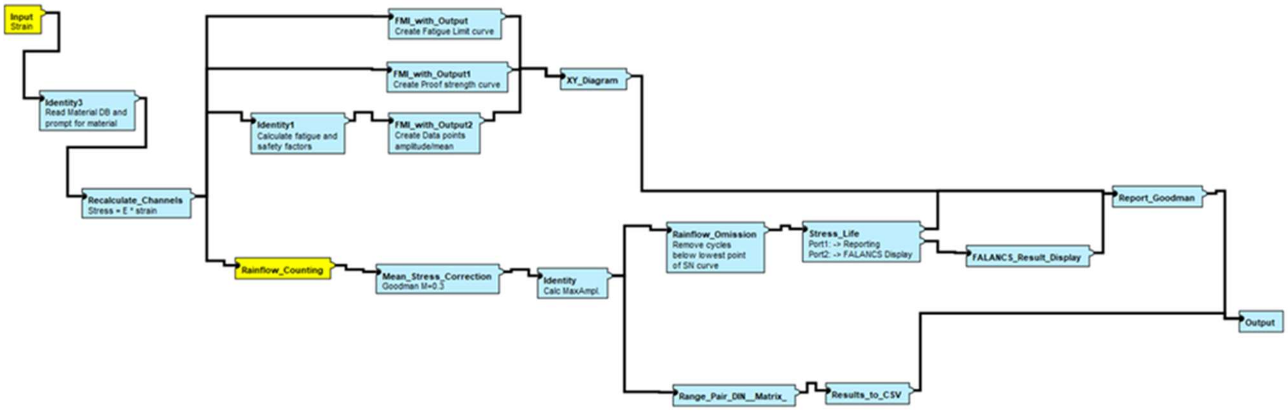
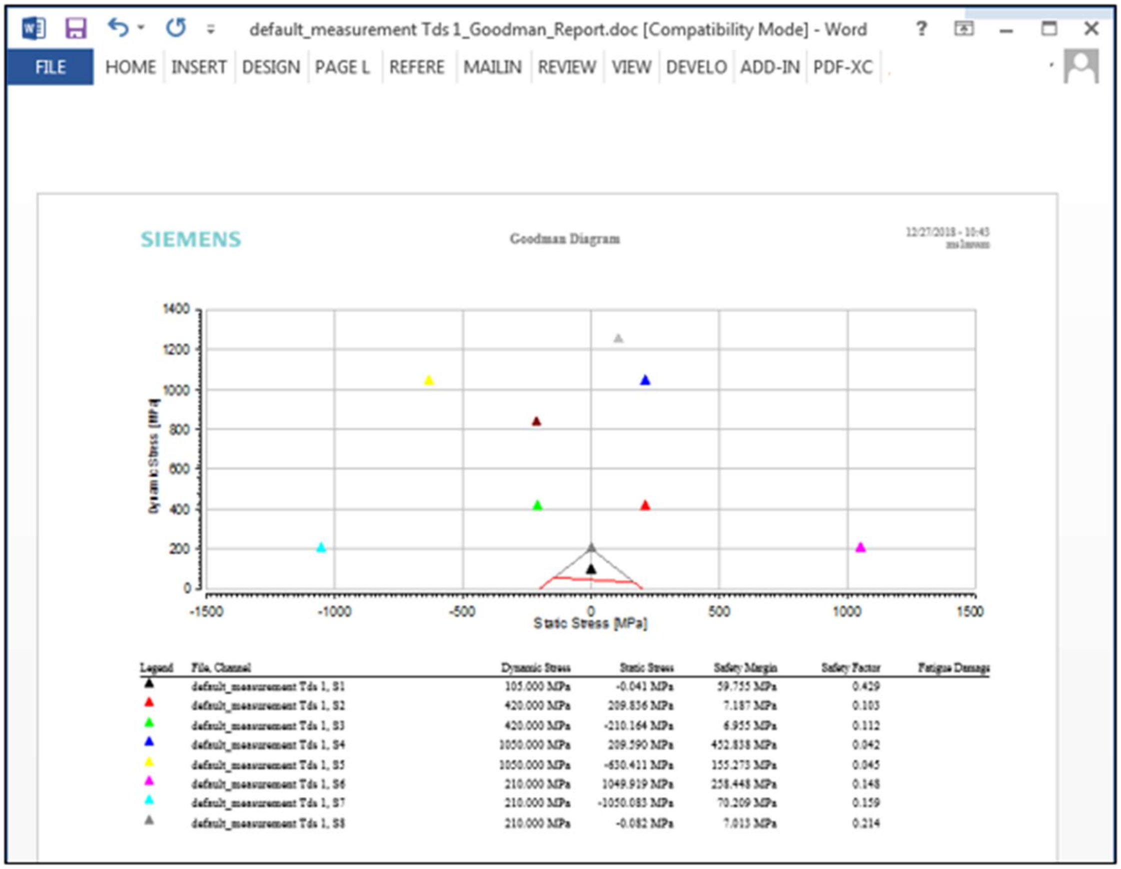


Figure 12: Simcenter Tecware ProcessBuilder diagram for Goodman Infinite Life calculation.

Simcenter Tecware ProcessBuilder can be run with Simcenter Testlab Token licensing.



Legend	File, Channel	Dynamic Stress	Static Stress	Safety Margin	Safety Factor	Fatigue Damage
▲	default_measurement Tds 1, S1	105.000 MPa	-0.041 MPa	59.755 MPa	0.429	
▲	default_measurement Tds 1, S2	420.000 MPa	209.836 MPa	7.187 MPa	0.103	
▲	default_measurement Tds 1, S3	420.000 MPa	-210.164 MPa	6.955 MPa	0.112	
▲	default_measurement Tds 1, S4	1050.000 MPa	209.590 MPa	452.838 MPa	0.042	
▲	default_measurement Tds 1, S5	1050.000 MPa	-630.411 MPa	155.273 MPa	0.045	
▲	default_measurement Tds 1, S6	210.000 MPa	1049.919 MPa	258.448 MPa	0.148	
▲	default_measurement Tds 1, S7	210.000 MPa	-1050.083 MPa	70.209 MPa	0.159	
▲	default_measurement Tds 1, S8	210.000 MPa	-0.082 MPa	7.013 MPa	0.214	

Figure 13: Goodman Infinite Fatigue Life report from Simcenter Tecware

If all cycles (indicated by triangles) fall within the Goodman triangle area, then infinite life is achieved. If the cycles are outside the triangle, as shown in *Figure 13*, infinite life is not possible.

What is a Power Spectral Density (PSD)? How is it different than an autopower?

A Power Spectral Density (PSD) is the measure of signal's power content versus frequency. A PSD is typically used to characterize broadband random signals. The amplitude of the PSD is normalized by the spectral resolution employed to digitize the signal.

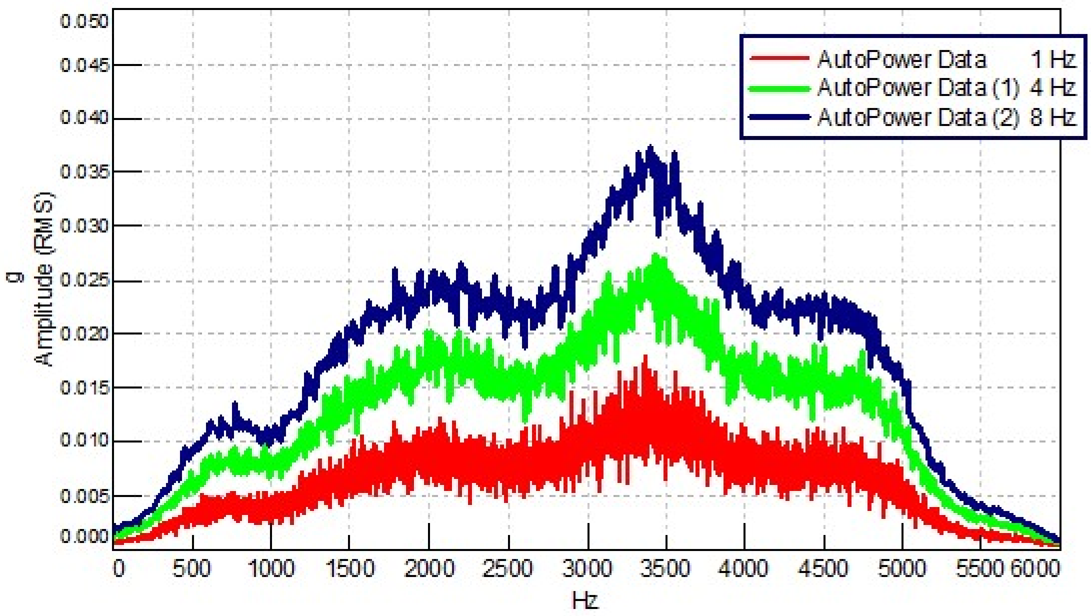
For vibration data, a PSD has amplitude units of g2/Hz. While this unit may not seem intuitive at first, it helps ensure that random data can be overlaid and compared independently of the spectral resolution used to measure the data. This article explains how this is done.

To understand a Power Spectral Density (PSD), it is helpful to understand some limitations of an autopower function when analyzing data with differing spectral resolutions:

Scenario

Identical broad band data was measured three different times. For each measurement, *only* the frequency resolution was changed. It was acquired with a 1 Hz frequency resolution, then a 4 Hz frequency resolution, and finally an 8 Hz frequency resolution.

The resulting autopower data has very different amplitudes (*Picture 1*). Why? Which one is correct?



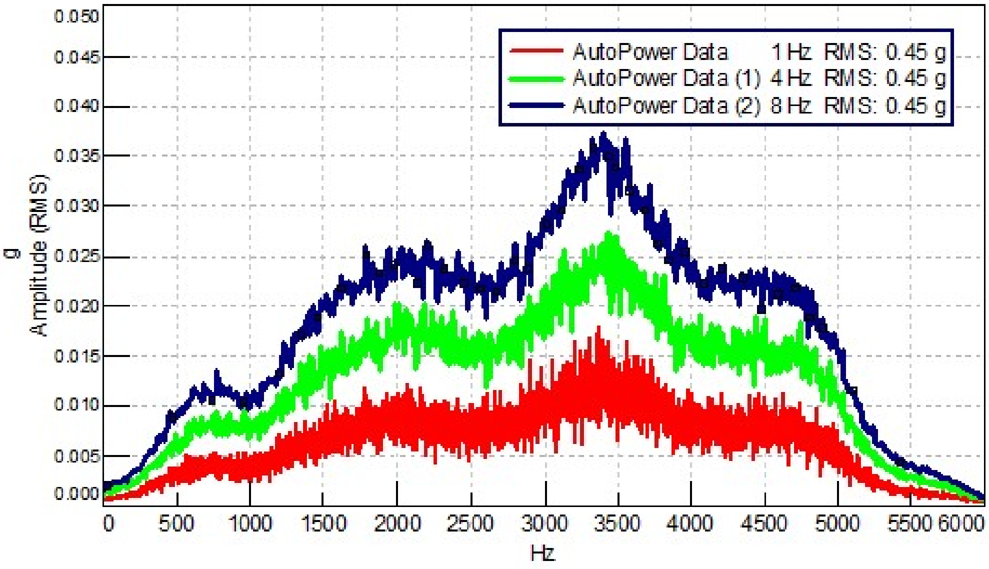
Picture 1: Autopowers of identical broadband data measured with 1 Hz spectral resolution (red), 4 Hz spectral resolution (green) and 8 Hz spectral resolution (blue)

Answer

All of the autopowers are correct! They appear visually to have different amplitudes however, which is confusing.

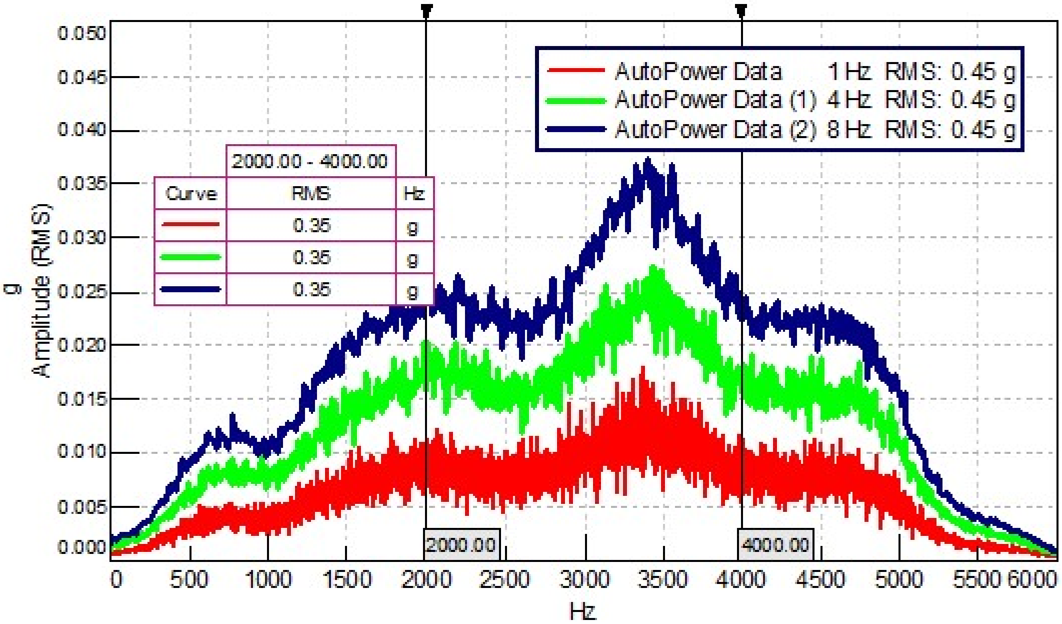
As the frequency resolution (sometimes referred to as spectral resolution) gets finer (starting with 8 Hz, then 4 Hz, then 1 Hz), more data points are being used to measure the signal. The same signal is being divided up into smaller parts, but the total remains the same.

While the amplitude at *individual* frequencies appears to be different, the *total summation* of data across the frequency range is identical.



Picture 2: Overall RMS summation value displayed in legend (upper right) is identical for all three autopowers

The “total” of the signal is reflected in the RMS summation of the entire spectrum as shown in *Picture 2*. The RMS summation is identical for all three autopower spectrums.



Picture 3: Partial RMS value for 2000 to 4000 Hz is identical for all three autopowers. Partial RMS displayed on left

Even a partial RMS summation of the data (*Picture 3*), based on a smaller frequency range, is identical for all three measurements.

Spectral Lines

Spectral lines are the key to understanding why the plotted amplitudes for these identical signals looks to different, but sum to the same amount.

An autopower spectrum, measured with a 1 Hz resolution and a bandwidth of 6000 Hz, would have 6000 data points or spectral lines as shown in *Equation 1*.

$$\frac{bandwidth}{\Delta f} = \#\, spectral\ lines$$

Equation 1: The number of spectral lines is determined by dividing the bandwidth by the frequency resolution.

Spectral lines are discrete points in the frequency domain used to digitize the spectrum (remember that a computer cannot store a continuous analog function, it must break any data into discrete points). The entire signal is divided up among these 6000 data points (i.e., spectral lines).

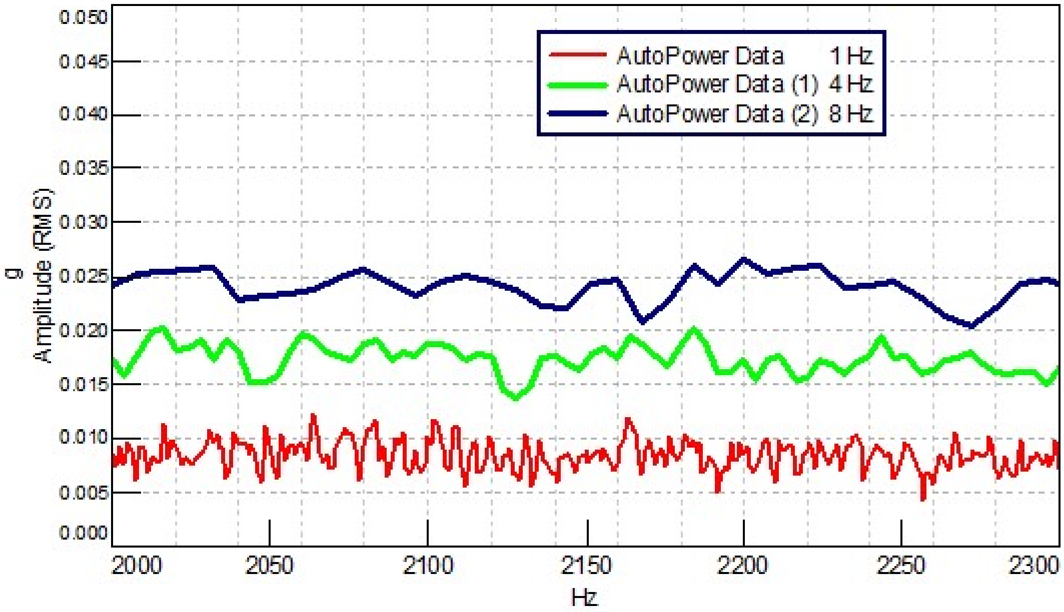
For the three separate measurements (each with a max frequency of 6000 Hz), the following is observed:

- 1 Hz frequency resolution -> 6000 spectral lines -> lowest apparent amplitude
- 4 Hz frequency resolution -> 1500 spectral lines -> mid-range apparent amplitude

- 8 Hz frequency resolution -> 750 spectral lines -> highest apparent amplitude

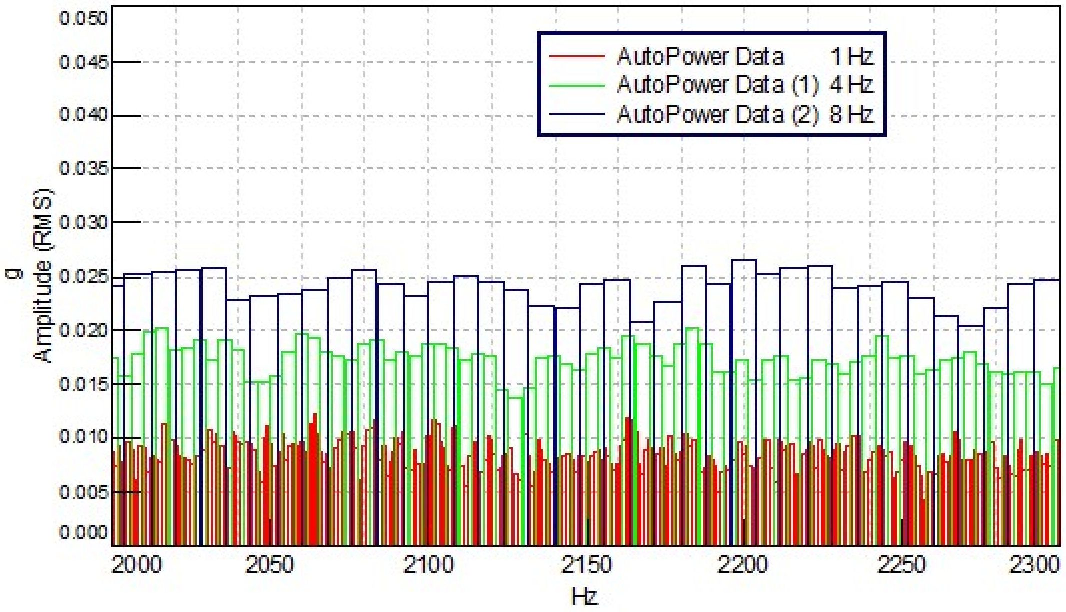
Note that the amplitude is really a function of the number of spectral lines. The more spectral lines, the lower the amplitude of each spectral line.

The results are correct for a given frequency resolution, although this is not readily apparent when viewing the spectrum. By zooming into a narrower frequency range (*Picture 4*), the different frequency resolutions between the three measurements start to become more obvious. One can see that the blue line (8 Hz resolution) has less data points than the red line (1 Hz resolution).



Picture 4: Zoomed in frequency range of 2000 to 2300 for three autopowers (red=1 Hz, green=4 Hz, blue=8 Hz frequency resolution)

The manner in which the data is presented disguises the differences between the data curves. By default, most FFT analyzers display data with lines connecting the data points. Instead of connecting with the data with lines as in *Picture 4,* the same data can instead be viewed as block outlines (*Picture 5*). Block outlines allow the individual spectral lines to be seen.



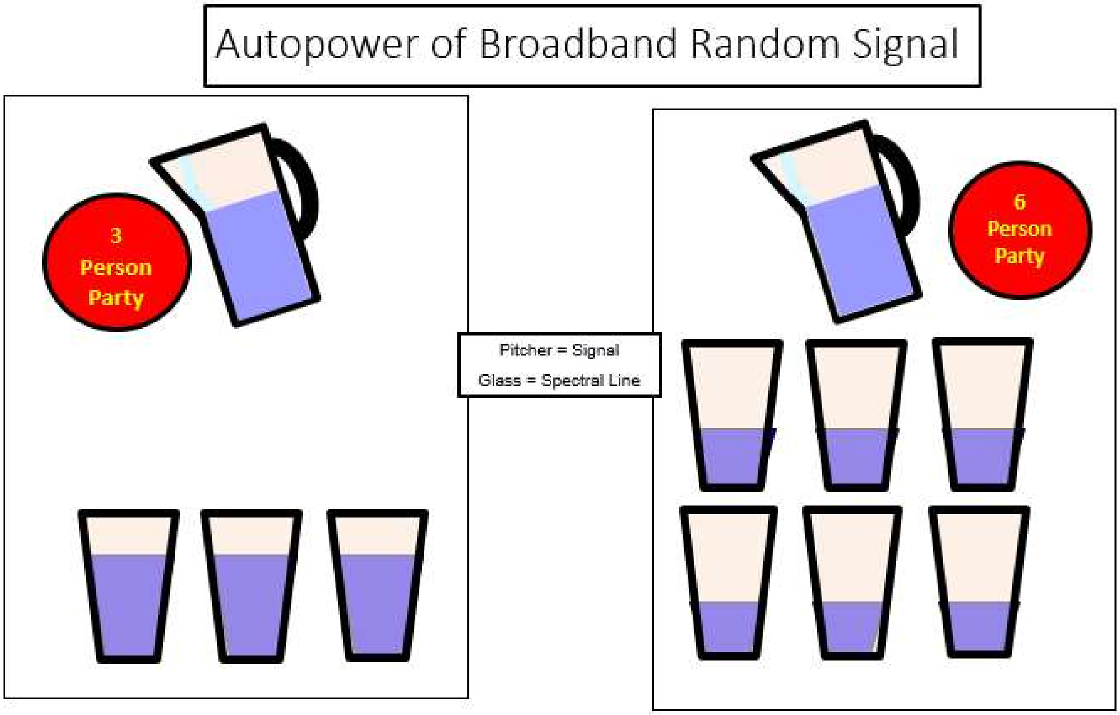
Picture 5: Data block presentation of frequency range of 2000 to 2300 for three autopowers (red=1 Hz, green=4 Hz, blue=8 Hz frequency resolution)

Using the block outlines, the differences in the three measurements is more obvious (*Picture 5)*. One can see that in the blue curve, measured with 8 Hz frequency resolution, that the levels of each spectral line are higher, but there are fewer data points over the frequency range. In the red curve, there are more data points, but each point/line is lower in amplitude. The green curve is in the middle.

Party Analogy

A party where beverages are being served can be used as an analogy (*Picture 6*) to explain this relationship between frequency resolution and amplitude in the autopower.

Imagine that the signal being measured is a fixed quantity of beverage to be served. The number of glasses held by attendees is analogous to the number of spectral lines.



Picture 6: Party analogy for amplitude versus frequency resolution of broadband random signal. The amplitude levels in each glass decrease as the number of glasses increase

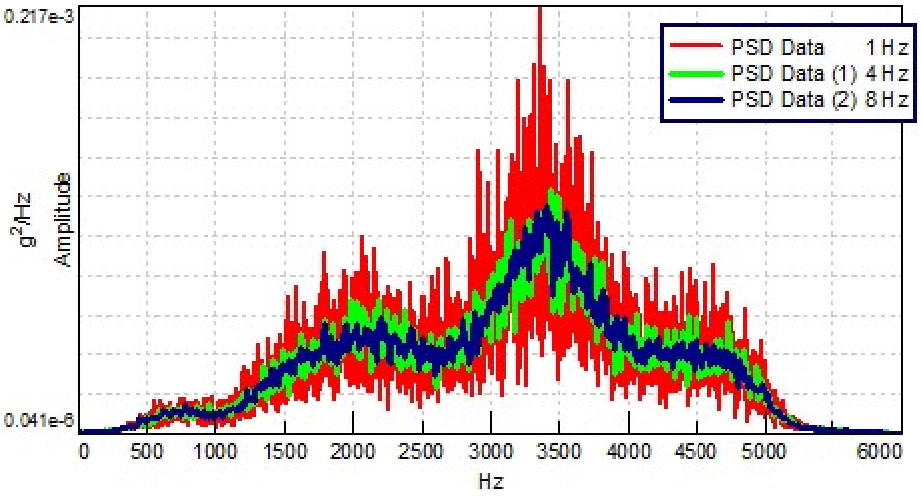
To simulate a broadband signal, the beverage is distributed evenly among the glasses. The more glasses (i.e., spectral lines) for distribution, the lower the amount in each glass. The total amount of beverage (i.e., RMS) served remains the same.

The Power Spectral Density function will now be used to remove/reduce the apparent difference in the three autopower spectrums. Remember, the Autopower and Power Spectral Density are both correct, only the representation of the data is being changed by switching functions.

Power Spectral Density

Despite the fact that the total amount of signal (as shown by the RMS) is identical, it is often desired that the amplitudes shown in the autopower graph also look similar.

Power Spectral Density (PSD) normalizes the amplitudes by the frequency resolution to give the amplitudes a similar appearance (*Picture 7*).



Picture 7: Power Spectral Density (PSDs) of identical broadband data measured with 1 Hz spectral resolution (red), 4 Hz spectral resolution (green) and 8 Hz spectral resolution (blue)

The term "normalizing" by the frequency resolution means dividing the amplitude of each spectral line by the frequency resolution.

- In the case of a 1 Hz frequency resolution, the amplitude would remain unchanged.
- For a 4 Hz frequency resolution, the amplitude is divided by 4 at each frequency.
- For an 8 Hz resolution, the amplitude is divided by 8 at each frequency.

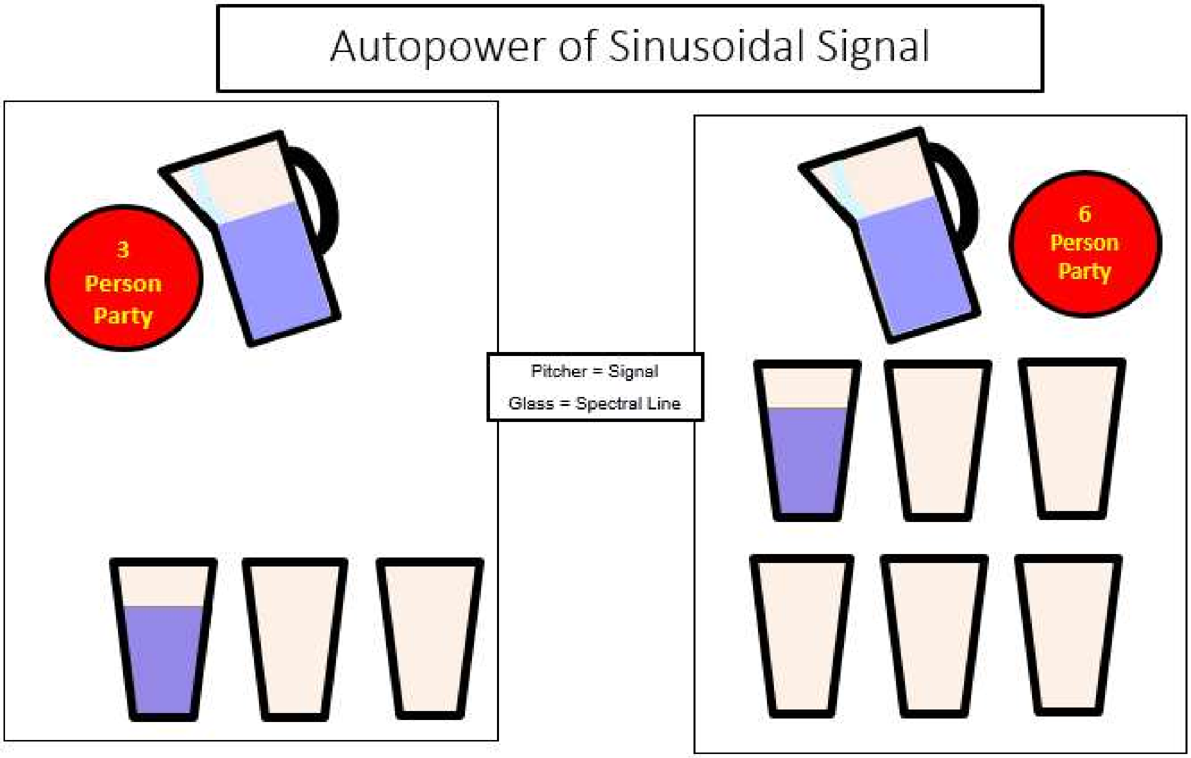
The amplitude is always shown divided by Hertz as result, as in 25 g^2/Hz.

By convention, the amplitude of the data in a Power Spectral Density is squared. For example, if one were measuring a 5 g amplitude (rms) sine wave, the amplitude shown in a PSD would be 25 g^2/Hz.

Sinusoidal Data

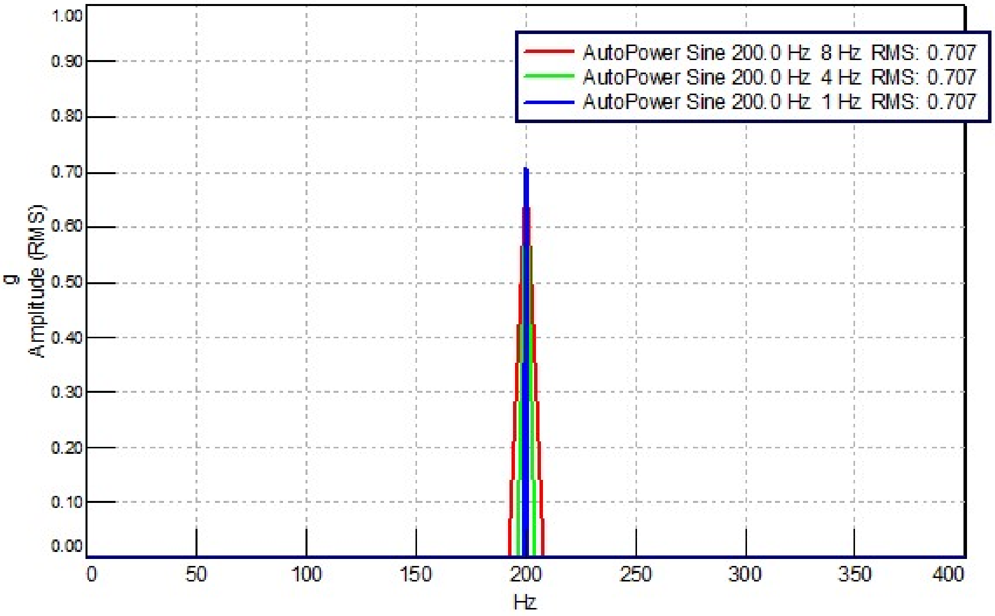
Everything is the opposite for sinusoidal data!

Going back to our party analogy, in the case of a sinusoid, all the signal in the pitcher is put into a single glass (spectral line). For example, a 200 Hz sine wave acquired with a 1 Hz, 4 Hz, or 8 Hz frequency resolution puts all the signal in a single spectral line (200 is evenly divisible by 1, 4, and 8).



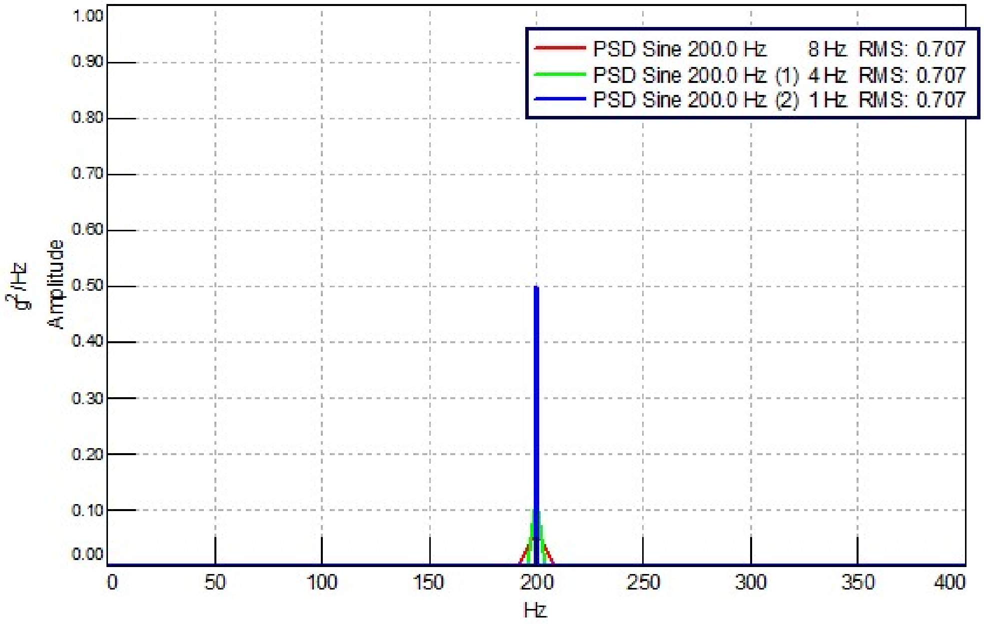
Picture 8: Party analogy for amplitude versus frequency resolution of sinusoidal signal. The amplitude levels in an individual glass do not change with more glasses (i.e., spectral lines)

For a sinusoid, the amplitude will not vary greatly with changes in the number of spectral lines. Because the signal is always placed in one “glass” (ie, spectral line), the amplitude in the glass does not change as more glasses are added.



Picture 9: Autopowers of a 200 Hz sine wave measured with an 8 Hz frequency resolution (red), 4 Hz frequency resolution (green), and 1 Hz frequency resolution (blue). RMS values are identical as shown in legend in upper right.

In fact, a Power Spectral Density (PSD) of a sinusoidal signal would actually change the apparent amplitude of a sine wave drastically as in *Picture 10*.



Picture 10: Power Spectral Density functions of a 200 Hz sine wave measured with an 8 Hz frequency resolution (red), 4 Hz frequency resolution (green), and 1 Hz frequency resolution (blue). RMS values are identical as shown in legend in upper right.

This is because the amplitudes of the sine waves are being divided by their respective frequency resolutions (delta f). Taking the same amplitude and dividing it by different frequency resolution (delta f) values makes the amplitudes different.

The PSD in which we divided the amplitude value by largest frequency resolution (in this case 8 Hz), results in the lowest amplitude.

The RMS summation of the PSD of the sine waves remains the same. This is because the RMS summation functionality adjusts for the frequency resolution division automatically to get the correct value.

Conclusion

Because computers digitize signals into discrete points, some interesting digital signal processing phenomenon are created.

Broadband (random) signals:

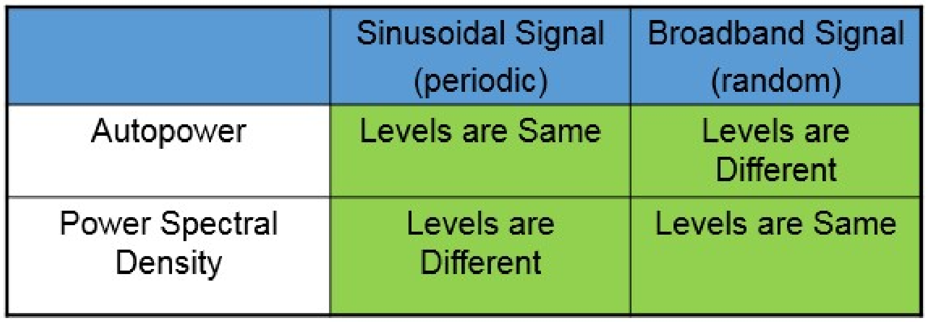
- Autopower spectra with *different* frequency resolutions will have *different* amplitude levels.
- Power Spectral Densities with *different* frequency resolutions will have the *same* amplitude levels.

Sinusoidal (periodic) signals:

- Autopower spectra with *different* frequency resolutions will have the *same* amplitude levels.

- Power Spectral Densities with *different* frequency resolutions will have *different* amplitude levels.

Table 1 summarizes these observations about Autopowers versus Power Spectral Densities.



	Sinusoidal Signal (periodic)	Broadband Signal (random)
Autopower	Levels are Same	Levels are Different
Power Spectral Density	Levels are Different	Levels are Same

Table 1: Summary of Autopower versus Autopower PSD

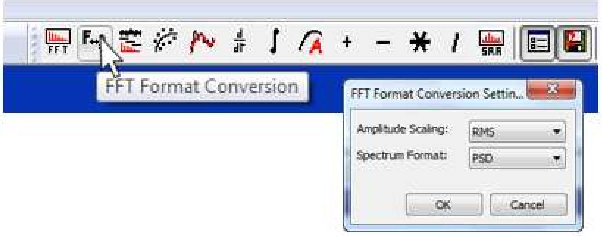
In all cases, the RMS summation of data over the frequency range is the same in all cases. When evaluating a spectral function, it is best practice to uses a RMS for comparison purposes, since the RMS amplitudes take into account frequency resolution and other adjustments to produce consistent and useable values.

In practice, typically one finds in industry:

- Power Spectral Density – Used to quantify random vibration fatigue
- Autopower – Used to quantify sinusoidal data, for example, harmonics generated by engines, pumps, gears, etc.

Simcenter Testlab Format Conversion

In Simcenter Testlab (formerly LMS Test.Lab), an autopower can be converted to a PSD and vice versa.



Amplitude Scaling: RMS
Spectrum Format: PSD

Picture 11: "FFT Format Conversion" button in Navigator worksheet to convert to a PSD

In the menu, the following can be changed:

- 'Amplitude Scaling' - Select the amplitude mode between RMS and Peak.
- 'Spectrum Format' - Select between Linear, Power, PSD and ESD

While the mode and format can be changed, the spectral resolution cannot. To change the spectral resolution, the data must be reprocessed from the original time history.

Some Thoughts on Accelerated Durability Testing

Suppose the fatigue damage target for your part or product has been determined. The test loads and number of cycles perfectly match how the product will be used in real life. Now it is time to test it and make sure the product will last the desired amount of time and usage.

One big problem – who has time to wait hundreds of hours for the fatigue damage cycles to accumulate while the test is running? The pressure is on! We want to know, will it last or not? And we want to know now, not later!

Fortunately, there exists several methods to accelerate a fatigue test. The most common options (*Figure 1*) include:

1. Increase the load level
2. Apply cycles more quickly
3. Omit non/low damaging events from the test profile

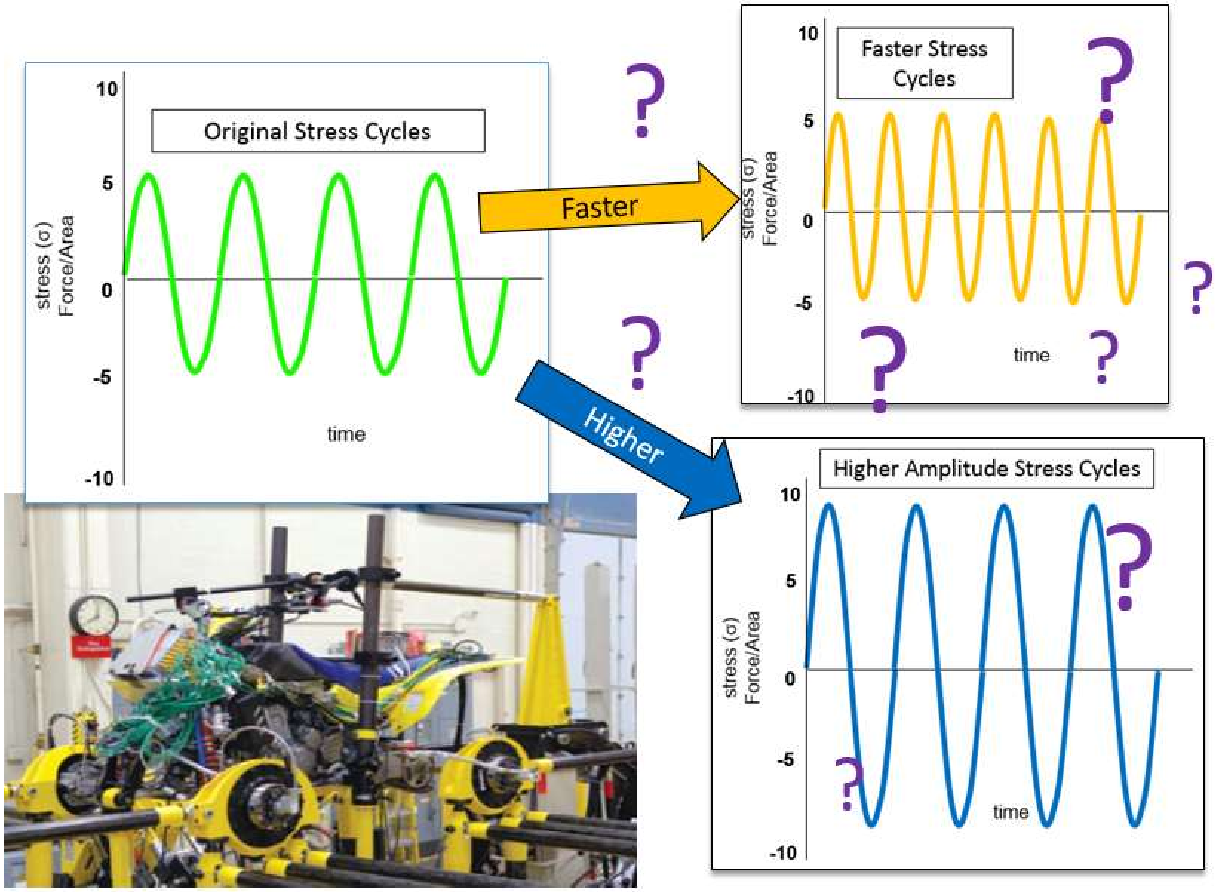


Figure 1: How can I make my durability test go faster? Increase the speed? Increase the amplitude? Something else?

Great! But which option should be used to accelerate the test? Each option is discussed in more detail in the following sections.

Load Level

Perhaps to make the test finish quicker, all I have to do is turn up the amplifier to the shaker a little bit! Or maybe a lot? The higher the shaking forces, the quicker the test, right?

Unfortunately, it is not that easy. Increase the shaking force level too much, and it will break in a way that it would never fail during actual customer usage. How much of an increase is too much? How much can the test time be reduced?

For many materials, there is a logarithmic relationship between load and the number of fatigue cycles (see material curve in *Figure 2*). Increase the test level a small amount, for example 15%, and the fatigue life will be reduced by 50%.

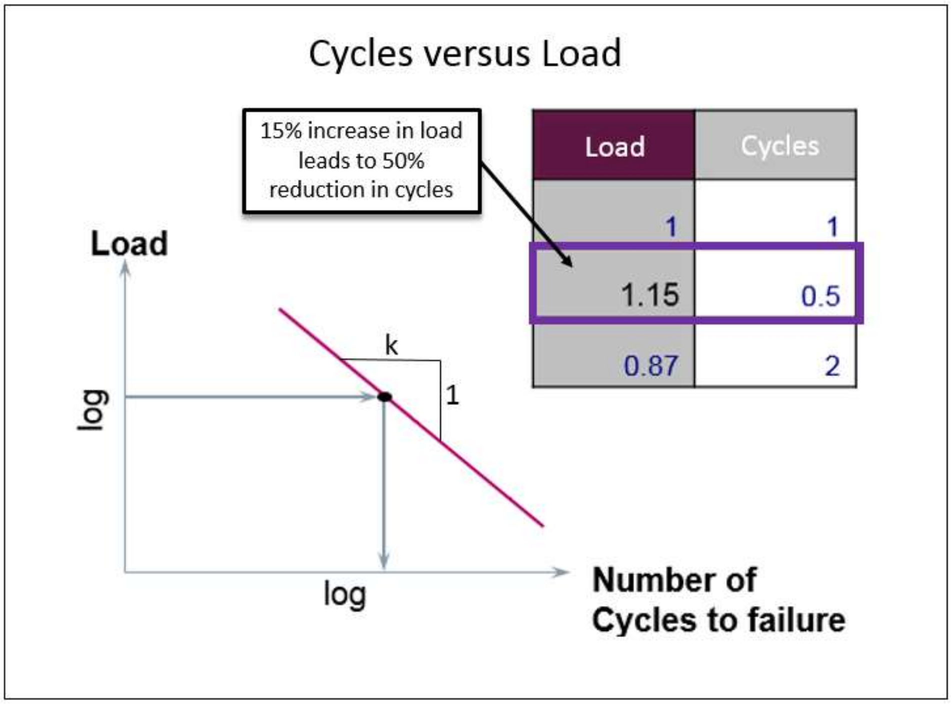


Figure 2: For a material curve with a slope of k=5, a 15% change in load level changes the test time by 50%.

This means a relatively small increase in load can reduce the test time significantly. To learn more about a material property curve, see the SN-Curve knowledge base article.

The slope of the SN-Curve is different depending on the material used to make the product. The slope, expressed as a k-factor, is typically 5 for many steels. However, the k-factor can differ depending on the material used. For example, most aluminums have a k-factor of 7, which leads to a 60% reduction in life (versus 50% for steel) for a 15% increase in load.

When accelerating a test, load levels can be increased slightly (~15%) to decrease test time significantly (~x2).

Why not double the load level, rather than increasing it by a measly 15%? Consider the classic SN curve (Stress versus Number of Cycles) shown in *Figure 3*:

- The *ultimate tensile strength* point is the load where one cycle fails the material.
- The *yield strength* separates the plastic and elastic region (see *Figure 3*) of the material. The failure mechanisms are different in the two regions.
- If all loads are in the infinite life region (see *Figure 3*), below the *endurance limit,* no failure can occur.

For many steels, the ratio of the *ultimate tensile strength* and the *endurance limit* is about 2 to 1.

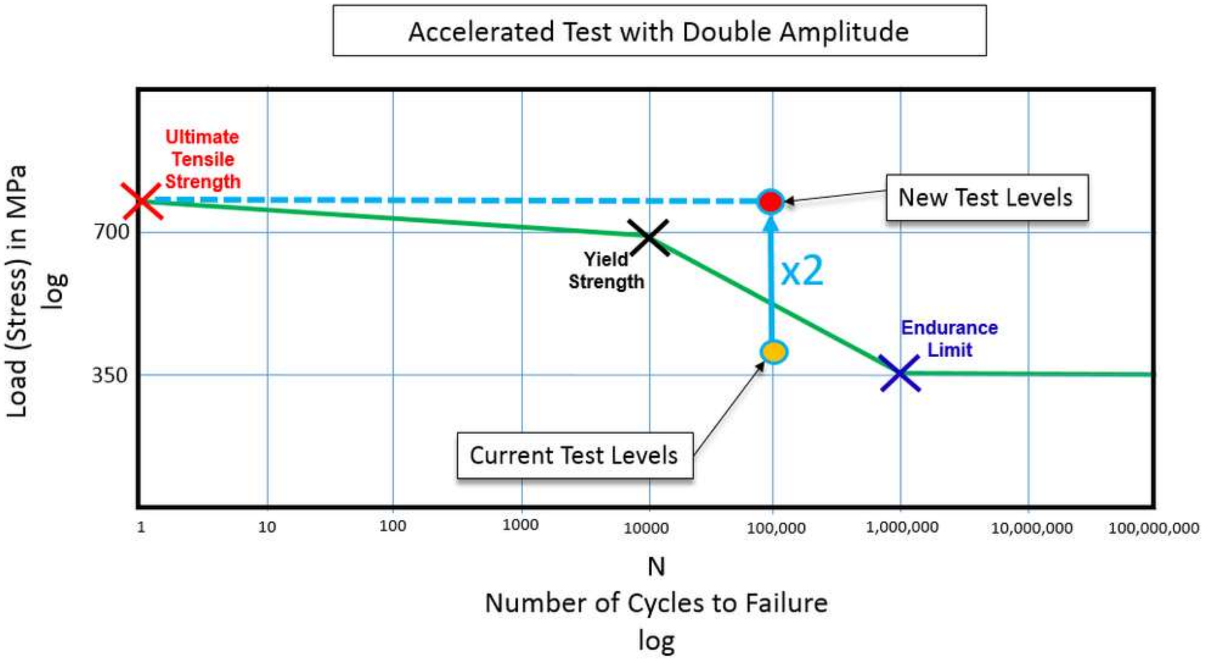


Figure 3 – The ultimate strength of a typical SN curve for steel is two times the endurance limit. Unwisely doubling the stress levels can lead to unrepresentative failures in the fatigue life verification test.

The red and orange dots in *Figure 3* shows a very simplified example of how to *not* accelerate a fatigue test.

The current test, represented by the orange dot, takes 100,000 cycles to complete. Perhaps that is a long time to wait to verify that the current product design will live up to the expected life. So your manager may say “Hey, crank up the amplitude of that test! Double it!” in order to not have to wait for all 100,000 cycles to complete.

Unbeknownst to the manager, by doubling the stress level, the product will fail in one cycle (red dot)! This would not be the best way to accelerate the test!

When accelerating a test, increasing load levels by a factor of 2 or more is likely to cause unrepresentative failures to occur in the test.

When increasing the load levels of the test, it is desirable to keep the amplitude of the stress cycles within the same region of the SN-curve as shown in *Figure 4*.

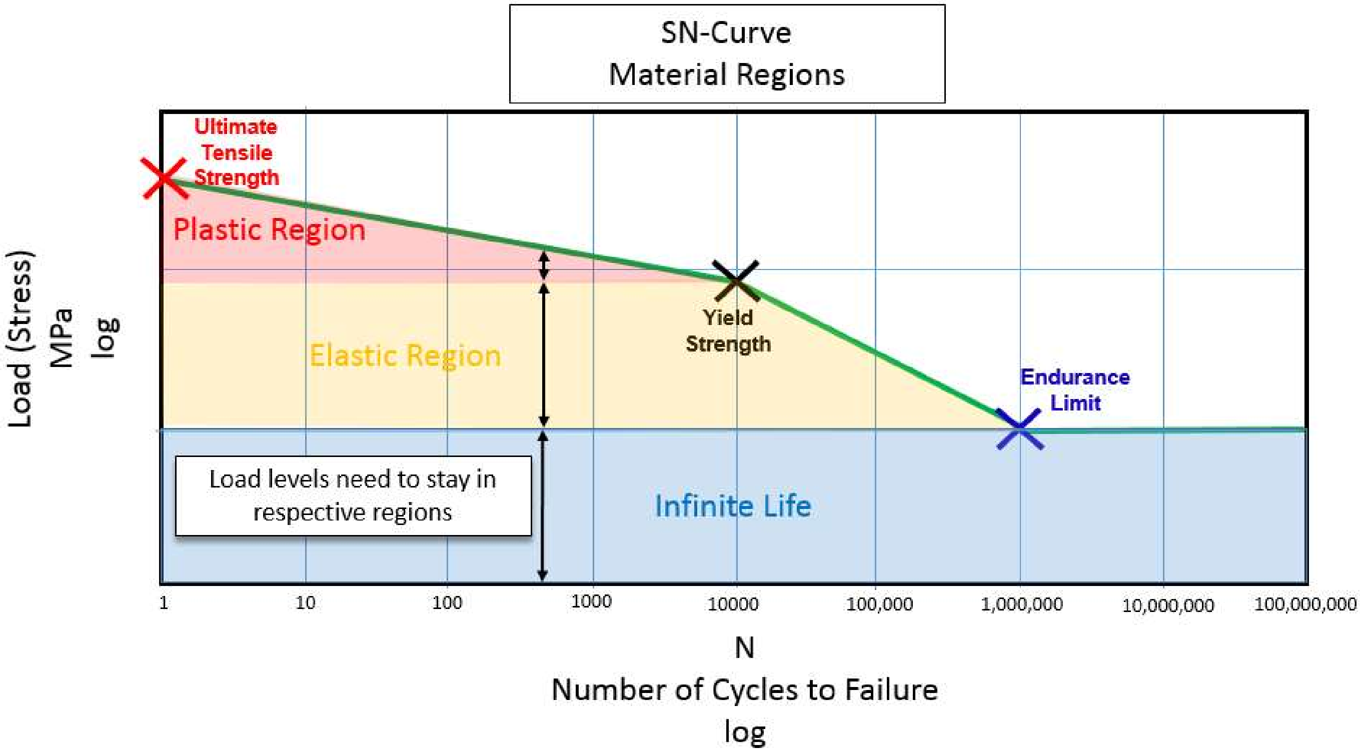


Figure 4 – The SN curve of a typical metal has three regions: plastic, elastic, and infinite life. Load levels in an accelerated test should not change regions in which they operate.

The fatigue failure mechanism in the elastic region is different than that of the plastic region. If the loads were increased in level from the elastic region to the plastic region, a different type of failure is induced. This failure would not occur in real product usage where the loads operate only in the elastic region.

When accelerating a test, load levels ***should not be*** increased into a different region of the SN-Curve.

If loads for a test only occurred in the infinite life region (which is a pretty long test!), increasing the levels into the elastic region would cause failures, whereas none would occur on the original test.

Note: It is always a good practice to understand the maximum load relative to the endurance limit and where it will be after the scaling operation. The level of the cycles in an endurance test can be determined by using the rainflow counting method to analyze the loads.

If the load levels and SN-curve material properties are already known, why run the test at all? The material property is not the only factor governing the fatigue life of a product. The geometry of the part is also an influence, so the test needs to be run to ensure the part will last. For example, a part made with sharp corners creates 'stress concentration' areas that can lead to shorter fatigue life. These stress concentrations can be reduced by making the part with rounded corners.

Apply Cycles More Quickly

Faster! Faster!

Can’t the speed of the test be increased simply by applying the cycles more quickly? Fatigue is not a frequency dependent phenomenon, correct?

For example, if the test machine applies 8 cycles per second, I can just increase it to 16 cycles per second to halve my test time. Right?

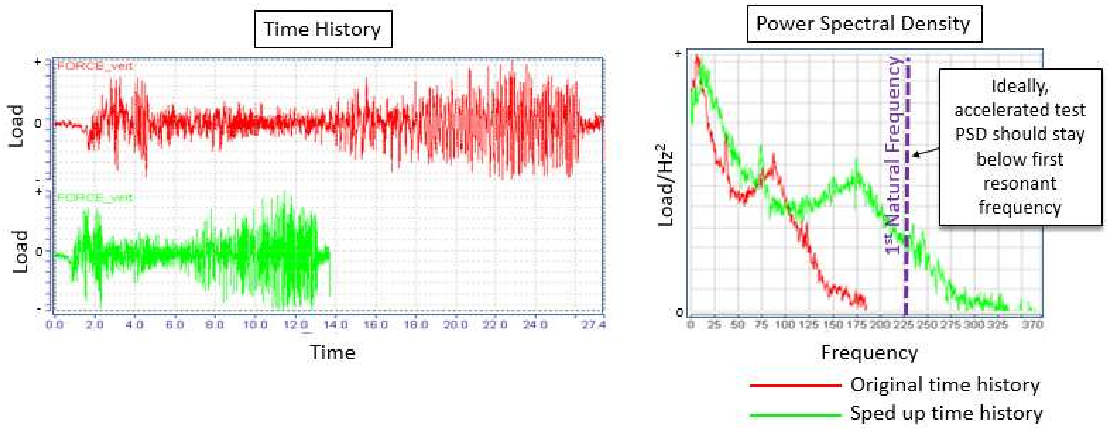
There are two factors that should be considered before running a test faster: *heat buildup* and *natural frequency* behavior.

Heat

A test can be sped up, but if it goes too fast, heat will build up in the part which cannot be dissipated quickly. This heat would cause a pre-mature failure that would not occur during the original test. A general rule of thumb is that the temperature of the part should not increase by more than 10 degrees Fahrenheit (~6 degrees Celsius) from the original test.

Natural Frequency

The frequency content is a consideration, especially in a test where exciting a resonant frequency could create higher than expected deformations (see *Figure 5*).



Ideally, accelerated test PSD should stay below first resonant frequency

Figure 5 – Comparison of load time history and power spectral density of original test (red) and increased speed test (green). Increasing the speed of the test (left graph) causes the test to excite a natural frequency which was not excited previously (right graph).

In particular, the frequency content of the loads should *not be* increased so that it excites a resonance of the part or product that was not previously being excited. In *Figure 5*, the spectrum (original in red, accelerated in green) is shifted in frequency by performing the same test schedule (left graph) at a faster rate.

The shape in the frequency domain *is the same* (red and green curves in right graph). Looking at the power spectral density spectrums, notice the shape of both curves are identical. The green curve is just stretched over a wider frequency range than the red curve. Think of a recording of a voice that is played back at triple speed – you can still make out the words, but the voice has a much higher pitch!

If there was a resonance in the product (represented by the purple line), it would not be excited in the original test (red spectrum), but would be excited by the accelerated test (green spectrum).

The speed of a durability test should not be increased so that a resonant condition is created that is not in the original test.

This will cause the structure to experience higher deformations in the accelerated test, which can cause the part to fail earlier than it would on the original test.

Omit Non-Damaging or Low Damage Cycles

Many cyclic fatigue tests consist of a variety of cycles, differing in amplitude and number of occurrences.

The cycle information is typically contained in a rainflow matrix (*Figure 6*) which shows:

- Cycle Amplitudes: The cycle amplitude is the difference of the *from load level* and *to load level* values on the X and Y axis.
- Number of Cycles: The number of cycles (indicated by the color key) at a given from and to value.

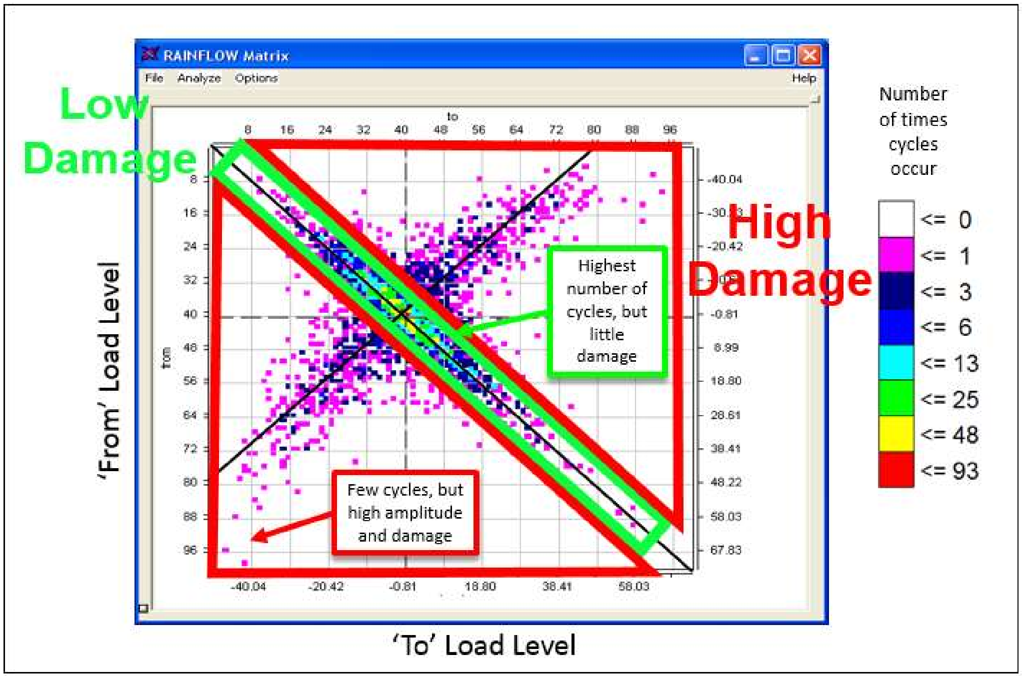


Figure 6 – The rainflow diagram contains the number of fatigue cycles and their amplitudes for a fatigue test. Some cycles create little damage (denoted in green) while others create higher damage (denoted in red).

The cycles contained along the diagonal area of the rainflow diagram are of low amplitude, and do not create much damage. These cycles go *to and from* very similar load levels, hence the cycles appear on the diagonal of the rainflow matrix.

The highest amplitude load cycles go *to and from* very different load levels, and are indicated in red on the rainflow diagram.

In this fatigue test, indicated by the rainflow diagram, 7% of the cycles (outlined in red) account for 99.5% of the fatigue damage.

To accelerate the test, the low damage cycles can be removed from the diagonal area of the rainflow diagram. An equivalent reduced time history can then be written out from the modified rainflow data (*Figure 7*).

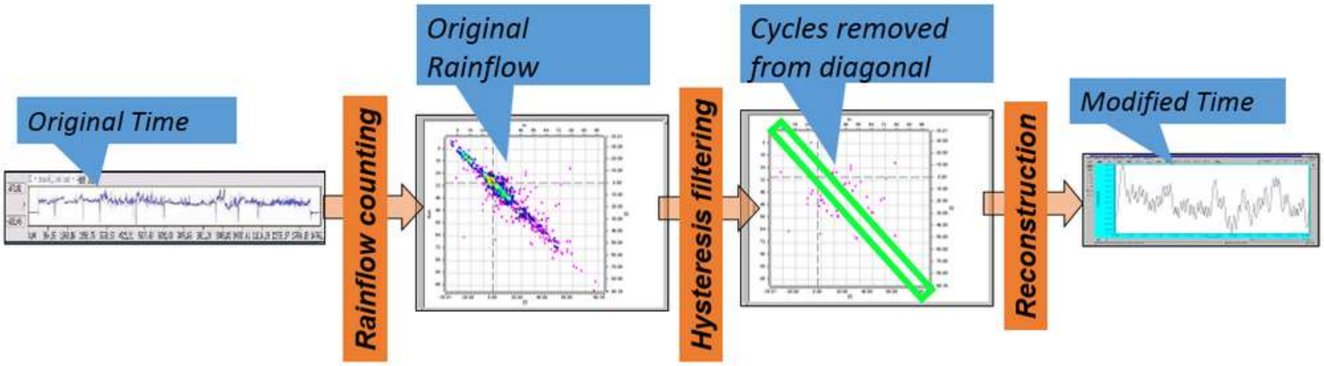


Figure 7: A reduced time history with 99.5% of the damage of the original test is created by removing the appropriate cycles along the diagonal of the rainflow diagram.

This reduced time history is shorter than the original time history. The amount of reduction depends on the number of cycles removed.

This reduction method can be done while still preserving key attributes of the original test durability. For example, the frequency content can be preserved, and not altered, as shown in *Figure 8*.

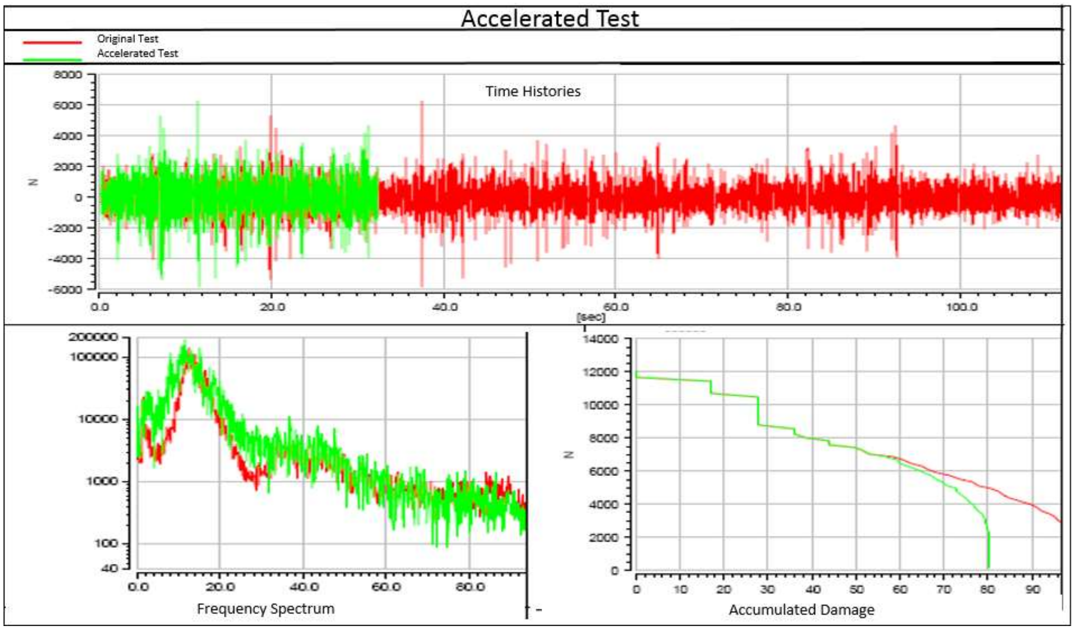


Figure 8 – Time data is reduced (red – original, green – reduced) in the test (upper graph), but frequency content (bottom left) and damage content (bottom right) are preserved.

Another important aspect when doing a durability test reduction is to preserve any multi-axial loading relationships. Data can exist on multiple load measurement channels that have related phase as shown in *Figure 9*.

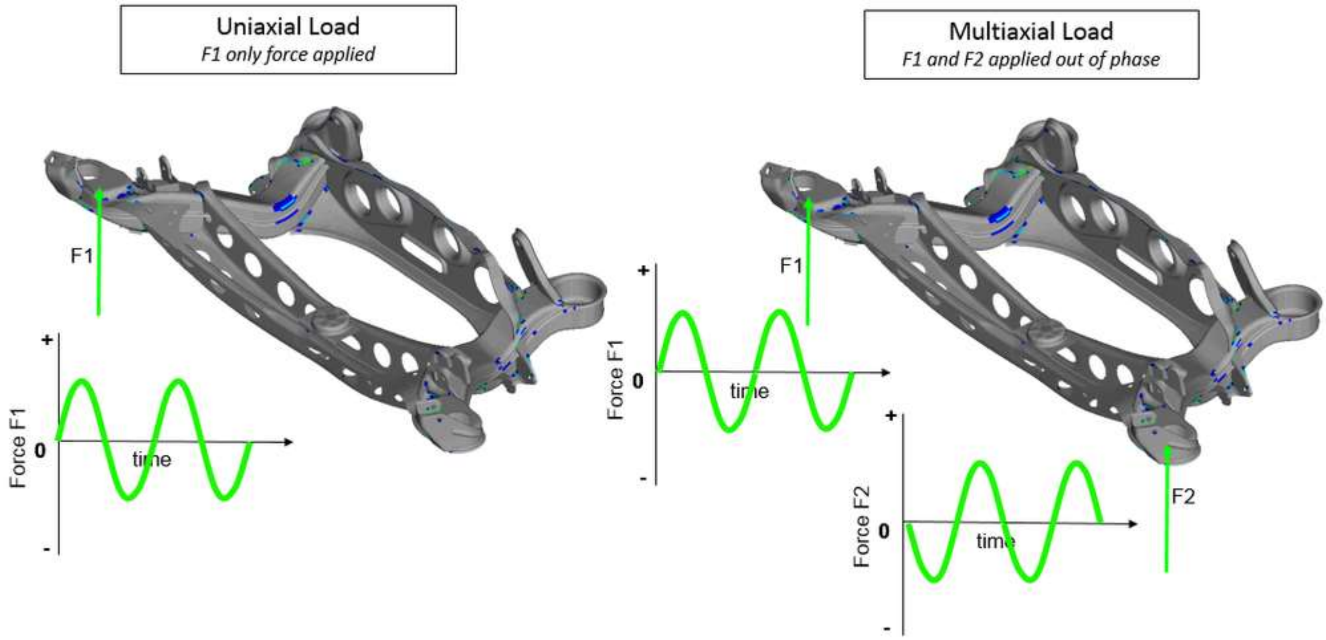


Figure 9: Left – Uniaxial load time history can be compressed without phase concerns, Right – Multiaxial loading must take phasing into account when doing compression.

Sometimes the phasing of multiple channels should be kept intact when the durability test time is reduced. To preserve multiaxial phasing, common time segments are kept across different channels. As a result, the reduction in test time will not be as large as if the phase preservation was not required.

By removing non or low damaging cycles from the test, the test duration can be reduced, without increasing loads and risking unrepresentative failure.

One benefit of removing low or non-damaging events to reduce test times is that the amplitude does not need to be increased. Increasing the amplitude can lead to causing unrepresentative failures in the accelerated tests, as previously discussed.

Conclusion

When looking to accelerate a durability test, there are several key items to keep in mind:

- Load levels should not be increased such that they create un-representative failures by moving into different region of material curve.
- The rate at which loads are applied should not be increased such that temperature is raised too much, or a natural frequency is excited that would not normally.
- Low damage cycles can be omitted to accelerate a test without increasing load level. This can be done with regard to frequency content preservation and/or multi-axial loading considerations.

There are many other considerations and methods for accelerating tests which were not covered in this article, including frequency-based fatigue using Power Spectral Density functions (through mission synthesis) and block cycle testing.

Need to accelerate your durability test? Tools like Simcenter Testlab Neo from Siemens can be used to acquire, analyze, and design your test.

Measuring Strain Gauges with Simcenter Testlab

Want to use Simcenter Testlab to measure with strain gauges? Here is how to do it:

Supported Scenarios

Strain gauges can be hooked up directly to the Simcenter SCADAS frontend. The SCADAS will provide all the needed signal conditioning.

Supported scenarios include:

- Direct connection between gauge and SCADAS
- Connection thru a slip ring to a strain gauge installed on a rotating part

VB8-II Cards

First, you will need a VB8-II card in your Simcenter SCADAS Mobile or Simcenter SCADAS Lab. The VB8-II card has strain gauge conditioning capabilities: supply voltages, completion resistors, shunt resistors, sense line support, etc.

A VB8-II card also support other types of transducers in addition to strain gauges: potentiometers, ICP/IEPE devices, as well as voltage inputs.

The cards have 8 channels with software selectable signal conditioning, which can be set independently per channel. Users can select from: ICP, Voltage, Bridges (Quarter, Half, Full), Potentiometer, and Active Sensors.

Picture 1: VB8-II card and with Open Wire (other end is LEMO) cable and BNC wire (other end is LEMO) cable

The card can be installed in any Simcenter SCADAS Mobile or Simcenter SCADAS Lab frame. The card can be mixed with other signal condition cards (like V-24, V8-E, etc).

Wiring

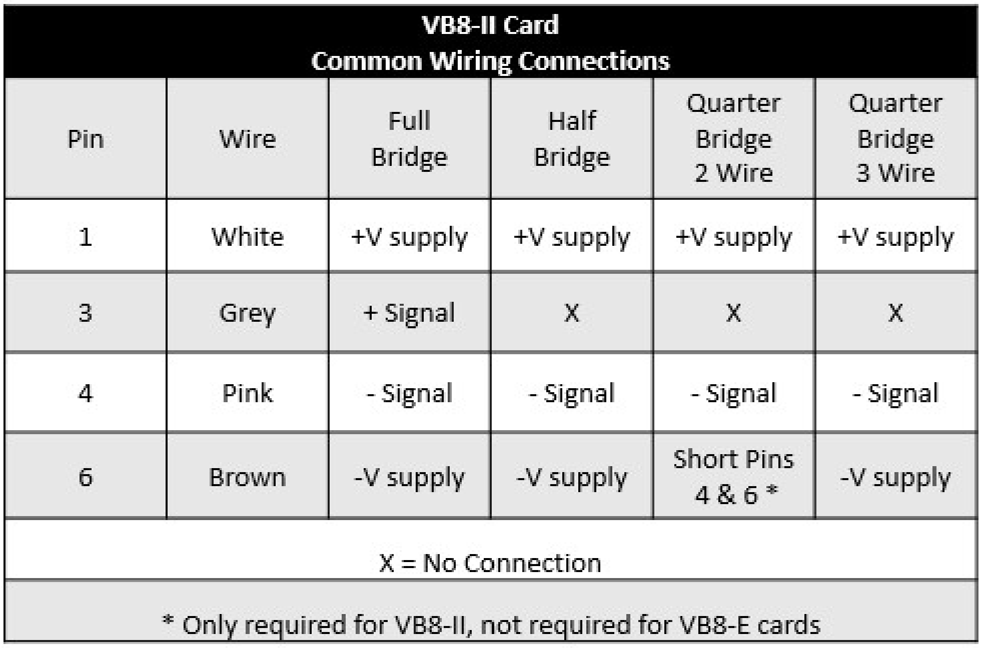
The VB8-II card has 7 pin LEMO-FGB.08.307 connections to accommodate power supplies, signal wires, ICP/IEPE and sense lines. The card comes with two sets of cables to accommodate BNC and any other types of connectors: a LEMO to BNC pigtail cables, and a LEMO to open wire.

There are 16 cables total delivered with each card, 8 cables of each type: 7-pin LEMO to BNC cable (for ICP/IEPE and Voltage inputs) and 7-pin LEMO to Open Wire (for strain gauges, bridges, active sensors, etc.).

1:	+Voltage Supply	White
2:	+Voltage Sense Line	Green
3:	+Signal	Grey
4:	-Signal	Pink
5:	-Voltage Sense Line	Yellow
6:	-Voltage Supply	Brown
7:	V/ICP/TEDS	Blue

Picture 2: LEMO-FGB.08.307 Pinout for VB8-II card

It is necessary to wire the strain gauge to the open wire provided with the VB8-II card. The most common connections to make are:



VB8-II Card
Common Wiring Connections

Pin	Wire	Full Bridge	Half Bridge	Quarter Bridge 2 Wire	Quarter Bridge 3 Wire
1	White	+V supply	+V supply	+V supply	+V supply
3	Grey	+ Signal	X	X	X
4	Pink	- Signal	- Signal	- Signal	- Signal
6	Brown	-V supply	-V supply	Short Pins 4 & 6 *	-V supply

X = No Connection

* Only required for VB8-II, not required for VB8-E cards

Picture 3: Common strain gauge wiring connections for VB8-II card

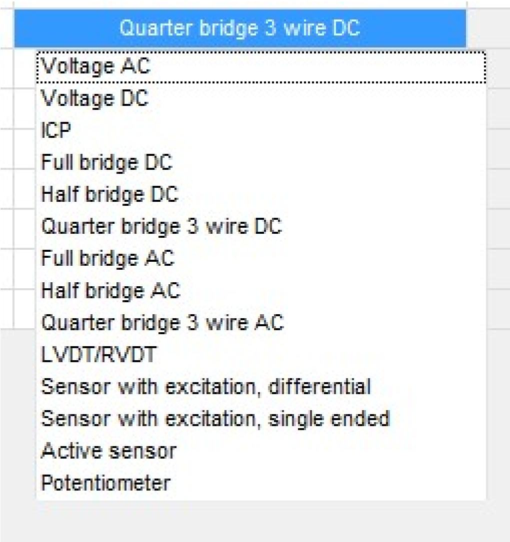
Quarter, half and full bridges are all supported. Generally, when using strain gauges, the more wires, the better the quality of the signal. In a full gauge, the signal is carried on two wires (a differential input), allowing common mode rejection to be employed to reject noise and Electro-Magnetic Field (EMF) interference.

On quarter and half bridges, the signal is only carried on single wire (a single-ended input) which makes common mode rejection not possible, creating more susceptibility to EMF. Strain gauges, with their long wires and low voltage levels are particularly susceptible to EMF.

Software: Channel Setup

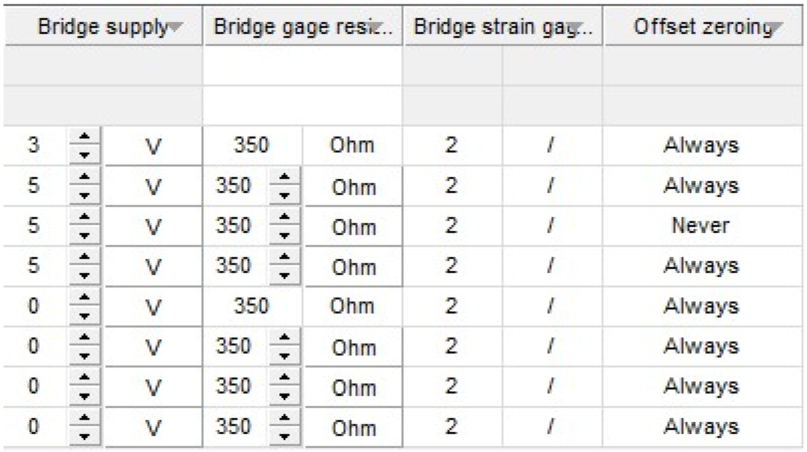
In Simcenter Testlab Signature Channel Setup worksheet, set the following to use the strain gauge (Note: If some fields are not showing, make them visible under “Tools -> Channel Setup Visibility”):

- Input Mode: Select Quarter, Half, or Full Bridge as desired. Note that AC or DC coupling is also part of this selection. If in doubt, select DC.



Picture 4: Simcenter Testlab pulldown menu choices for input mode

- Measure Quantity: Strain or Force as desired.
- Bridge supply: Set the voltage supply level. Lower voltages make the signal levels low and susceptible to EMF interference, while high voltage supplies may cause thermal drift. Note that the voltage level is set to zero by default to avoid unintended damage to the gauges. Use the strain gauge excitation guide if uncertain.
- Bridge gage resistance: This is a completion resistor used for quarter bridges, usually either 350 or 120 ohms. It can be set independently per channel. Check your gauge calibration sheet for the correct value.
- Bridge strain gage factor: Usually a value around “2”. Check your gauge calibration sheet for the correct value.
- Offset zeroing: Possible values are Always/Never/Once, default is 'Always'. Channels marked as 'Always' will be have an offset applied to make the signal read zero when performing a Zeroing operation. Zeroing of the channel is done in the Calibration or Measure worksheet and is covered in-depth later in this article. If a channel should not be zeroed, then set to 'Never' (for example, a non-gauge transducer). The mode 'Once' is not often used - Zeroing can only be done in the Acquisition Setup screen by switching from Autorange mode to Zeroing at the bottom of the screen. The 'Once' mode was intended to be used if a gauge had to be initially set to zero white setting up the test, before the measurement campaign started. It prevents the gauge from accidentally be zeroed again in the Measurement worksheet.



Bridge supply		Bridge gage resi..		Bridge strain gag..		Offset zeroing
3	V	350	Ohm	2	/	Always
5	V	350	Ohm	2	/	Always
5	V	350	Ohm	2	/	Never
5	V	350	Ohm	2	/	Always
0	V	350	Ohm	2	/	Always
0	V	350	Ohm	2	/	Always
0	V	350	Ohm	2	/	Always
0	V	350	Ohm	2	/	Always

Picture 5: Simcenter Testlab Channel Setup settings

- Actual Sensitivity: The mV/EU (Engineering Unit) value. This value can be calculated during calibration or can be entered directly from the specification sheet if it is known.
- Simulated Value: If using a strain gauge to measure a value other than strain (for example, could be load/force for strain gauge-based load cell), this is where the expected value can be set for a 100 kOhm shunt resistor in units other than strain.
- Range: To avoid quantization errors the range should be set to 0.1 V for strain gauges. The default for strain gauges is 0.1 V, not 10 V. This is because strain gauge signals are very low voltage levels compared to other transducers.

Virtual Channels

Math channels can be calculated from the strain measurements. Channels can be filtered and integrated. Rosette calculations can be performed live. See the 'Rosette Strain Gauge' Knowledge base article for more information.

Software: Calibration

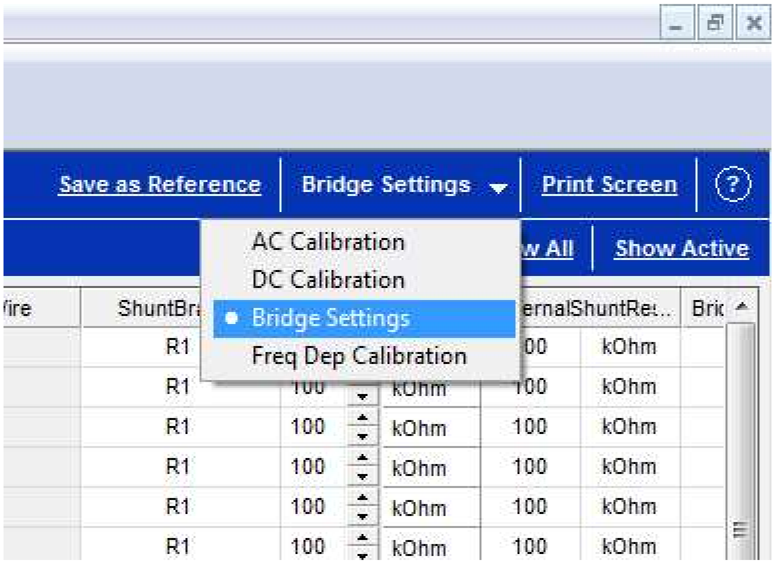
This section can be skipped if the all the needed strain gauge calibration information is already provided. Go to the section titled “Software: Calibration Verification” to validate the supplied information is correct.

Otherwise, proceed with this section to perform a strain gauge calibration directly in Simcenter Testlab.

The sensitivity value of the gauge can be calculated in the Simcenter Testlab software via the “Calibration” worksheet.

Picture 6: Calibration Worksheet

Click on the "Calibration" worksheet. Once the worksheet is opened, click in the upper right corner, and select "Bridge Settings" (default is AC Calibration).

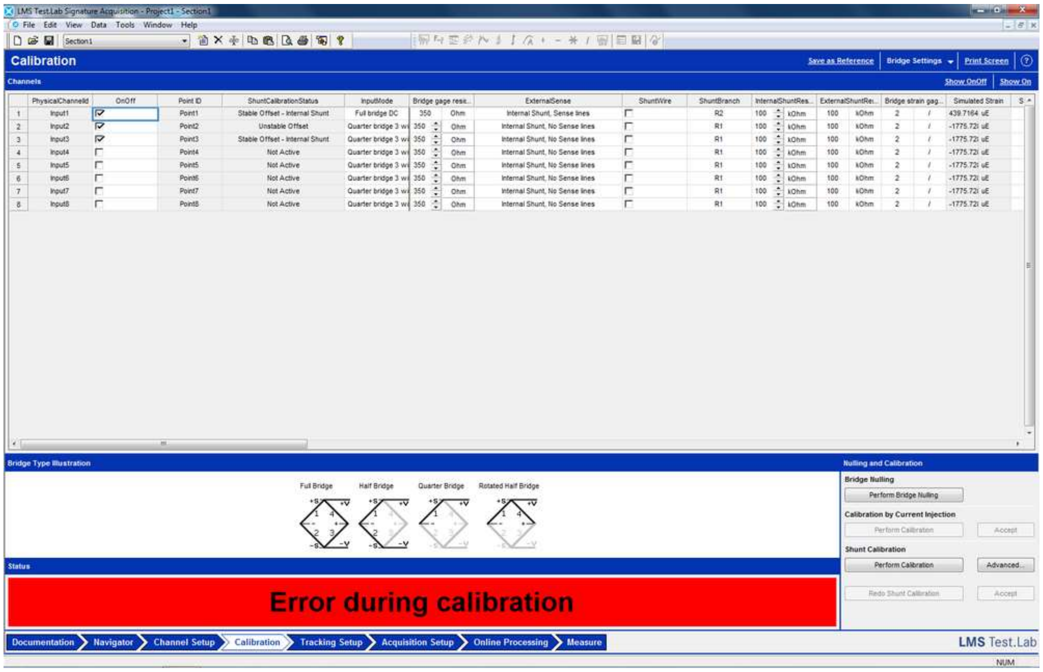


Picture 7: Select "Bridge Settings" in the upper right-hand corner of the Calibration worksheet

After selecting the channels to be calibrated, do the following:

- Press the "Perform Bridge Nulling" button
- Select "Perform Calibration" button
- Press "Accept" when calibration finishes.

The system calibrates the gauge with two data points: a zero and at a shunt value. The "Perform Bridge Nulling" zeros the gauge.



	PhysicalChannelId	OnOff	Point ID	ShuntCalibrationStatus	InputMode	Bridge gage resis..		ExternalSense	ShuntWire	ShuntBranch	InternalShuntRes..		ExternalShuntRe..		Bridge strain gag..		Simulated Strain	S
1	Input1	☑	Point1	Stable Offset - Internal Shunt	Full bridge DC	350	Ohm	Internal Shunt, Sense lines	☐	R2	100	kOhm	100	kOhm	2	/	439.7164 uE	
2	Input2	☑	Point2	Unstable Offset	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
3	Input3	☑	Point3	Stable Offset - Internal Shunt	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
4	Input4	☐	Point4	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
5	Input5	☐	Point5	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
6	Input6	☐	Point6	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
7	Input7	☐	Point7	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
8	Input8	☐	Point8	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	

Error during calibration

Picture 8: If the gauge is improperly wired or not connected, an error occurs during calibration.

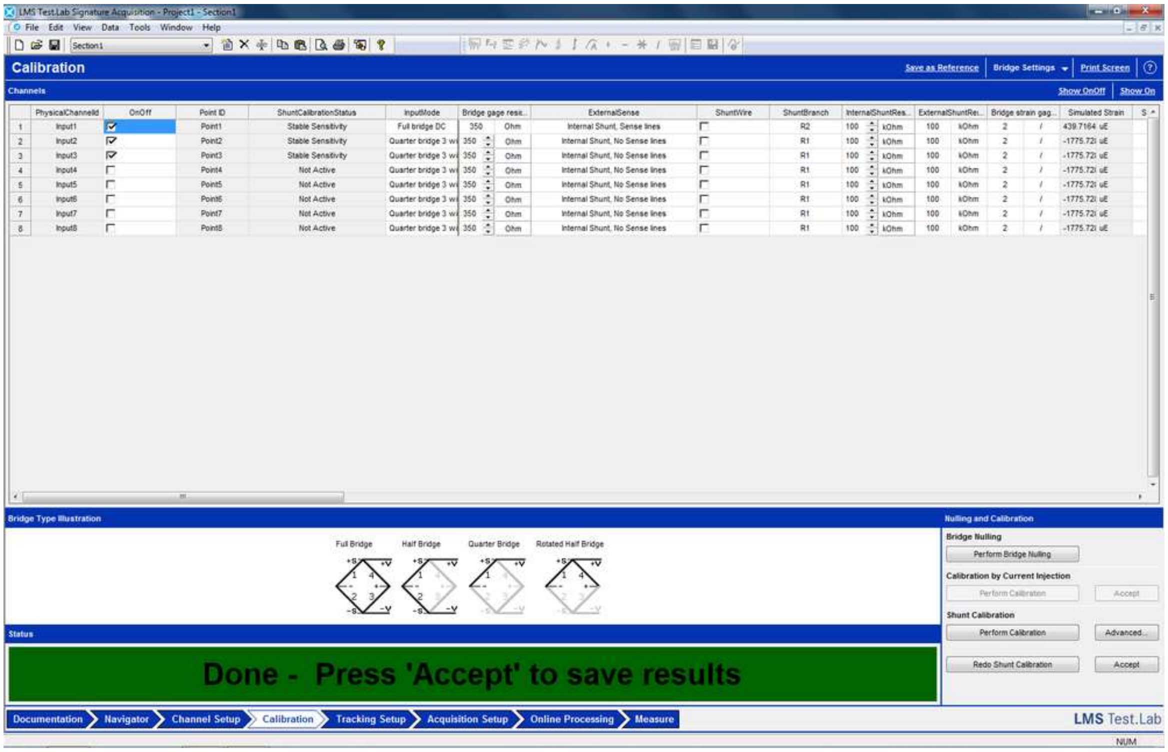
If there are problems with the gauge (for example, excessive drift due to temperature, or an improper wiring installation) usually the nulling or calibration will fail. A big red message “Error during Calibration” will appear at the bottom of the screen.

The cause of failure can be in the ShuntCalibrationStatus field. For example, if the gauge is installed improperly and is electronically drifting, the message “Unstable Offset” may be displayed.

	PhysicalChannelId	OnOff	Point ID	ShuntCalibrationStatus	InputMode	Bridge gage resis..	
1	Input1	☑	Point1	Stable Offset - Internal Shunt	Full bridge DC	350	Ohm
2	Input2	☑	Point2	Unstable Offset	Quarter bridge 3 wi	350	Ohm
3	Input3	☑	Point3	Stable Offset - Internal Shunt	Quarter bridge 3 wi	350	Ohm
4	Input4	☐	Point4	Not Active	Quarter bridge 3 wi	350	Ohm
5	Input5	☐	Point5	Not Active	Quarter bridge 3 wi	350	Ohm
6	Input6	☐	Point6	Not Active	Quarter bridge 3 wi	350	Ohm
7	Input7	☐	Point7	Not Active	Quarter bridge 3 wi	350	Ohm
8	Input8	☐	Point8	Not Active	Quarter bridge 3 wi	350	Ohm

Picture 9: The type of error encountered during calibration is indicated in the ShuntCalibrationStatus field.

After correcting the problem with the gauge or gauge setup, the calibration should proceed without error. In the lower right corner of the Calibration worksheet, the "Advanced..." button has the criteria used to determine if the gauge has a stable signal. The default settings check if the signal has low variation for at least 3 seconds to determine if the gauge is working properly and in a stable manner.



	PhysicalChannelId	OnOff	Point ID	ShuntCalibrationStatus	InputMode	Bridge gage resis...		ExternalSense	ShuntWire	ShuntBranch	InternalShuntRes...		ExternalShuntRe...		Bridge strain gag...		Simulated Strain	S
1	Input1	☑	Point1	Stable Sensitivity	Full bridge DC	350	Ohm	Internal Shunt, Sense lines	☐	R2	100	kOhm	100	kOhm	2	/	439.7164 uE	
2	Input2	☑	Point2	Stable Sensitivity	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
3	Input3	☑	Point3	Stable Sensitivity	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
4	Input4	☐	Point4	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
5	Input5	☐	Point5	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
6	Input6	☐	Point6	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
7	Input7	☐	Point7	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	
8	Input8	☐	Point8	Not Active	Quarter bridge 3 wi	350	Ohm	Internal Shunt, No Sense lines	☐	R1	100	kOhm	100	kOhm	2	/	-1775.72i uE	

Done - Press 'Accept' to save results

Picture 10: The status bar at the bottom of the screen turns green when the calibration is successful.

One should get a big green message at the bottom of the screen saying “Done – Press ‘Accept’ to save the results. After press the “Accept” button in the lower right corner, one can proceed to the “Measure” worksheet.

Software: Calibration Verification

To check that the strain gauges are working properly at any time, a “Shunt Check” can be performed. In a Shunt Check, a known resistance is applied across the gauge and compared to the expected value.

Simcenter SCADAS VB8-II cards contain internal shunt resistors that can be applied to the gauges to perform a shunt check. The default shunt resistor is a 100 kOhm shunt.

To apply the shunt resistor, go to the Measure worksheet:

- Press “F3 Ranges” tab
- Press the “F12 Shunt” tab
- Press “Start”. Everything should come back Green.
- Press “Stop” when finished.

	Physical Channel ID	DOF	New Value	Reference
1	Input1	Point1	439.6878 uE	439.7164 uE
2	Input2	Point2	-1776.76 uE	-1775.72 uE
3	Input3	Point3	-1776.14 uE	-1775.72 uE

Measuring : with shunt

Picture 11: Success shunt check will have a green status on all channels

If one of the gauges is not working properly, or the structure undergoing test was damaged significantly, the shunt check on that channel may fail.

	Physical Channel ID	DOF	New Value	Reference
1	Input1	Point1	439.8973 uE	439.7164 uE
2	Input2	Point2	-1775.19 uE	-1775.72 uE
3	Input3	Point3	-40847.2 uE	-1775.72 uE

Measuring : with shunt

Picture 12: Channel value will be red if there is a problem during shunt

The channel will be colored red indicating a problem with the gauge setup, the gauge itself, or excessive damage to the part undergoing test.

Zeroing

To Zero the gauges before measuring, go to the Measure worksheet:

- Press “F3 Ranges” tab
- Press the “F11 Zero” tab
- Press “Start Zero”. Everything should come back Green.
- Press “Stop Zero” and “Set Offsets” when finished.

Zeroing offsets

	Char...	DOF	Compens...	New Cor...	Heac...	New Hea...	Unit
1	Input1	Point1	203.53657	0	16459.	0	uE
2	Input2	Point2	-707.82183	0	39213.	0	uE
3	Input3	Point3	-1000.9175	0	38883.	0	uE

Picture 13: Zeroing menu

It is possible to set which channels are zeroed, and which channels are NOT to be zeroed. Use the “Offset Zeroing” field in “Channel Setup” worksheet and select Always, Once or Never as desired.

Measure

Go to the “Measure” worksheet (or press F8 if already in the worksheet) to acquire strain gauge data by pressing the Arm button and then the Start button (with Arrow symbol).

Measuring Time...

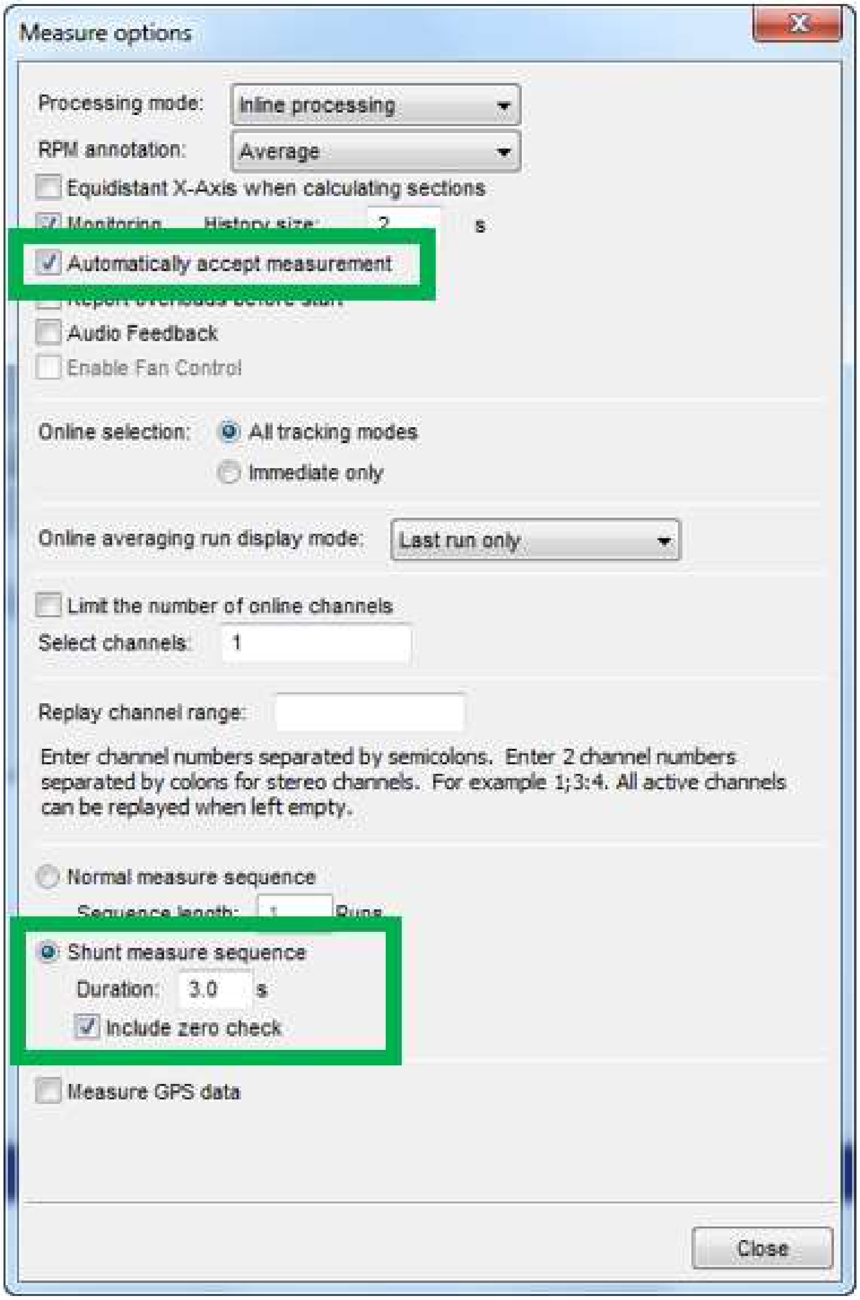
NO OVERLOAD

Sufficient disk space left

Picture 14: Measurement in progress

A useful feature is the “Shunt Measure Sequence”. This will automatically acquire separate 3 second measurements of zero values and shunt value before and after each measurement.

Under the “More...” button on the middle right side of the “Measure” worksheet, turn on the “Automatically Accept Measurement” and “Shunt measure sequence”. Then press the “Close” button.



Processing mode: Inline processing

RPM annotation: Average

☐ Equidistant X-Axis when calculating sections

☑ Monitoring History size: 2 s

☑ Automatically accept measurement

☐ Report overloads before start

☐ Audio Feedback

☐ Enable Fan Control

Online selection: ● All tracking modes ○ Immediate only

Online averaging run display mode: Last run only

☐ Limit the number of online channels

Select channels: 1

Replay channel range:

Enter channel numbers separated by semicolons. Enter 2 channel numbers separated by colons for stereo channels. For example 1;3:4. All active channels can be replayed when left empty.

○ Normal measure sequence

Sequence length: 1 Runs

● Shunt measure sequence

Duration: 3.0 s

☑ Include zero check

☐ Measure GPS data

Picture 15: Options under "More..." button for setting up Shunt measurement sequence

Now when measuring, a blue status “Zeroing” and “Shunting” will appear immediately before and after each measurement. Each time this occurs, a separate three second recording is made.


Zeroing...

NO OVERLOAD

Sufficient disk space left

Shunting...

NO OVERLOAD

Sufficient disk space left

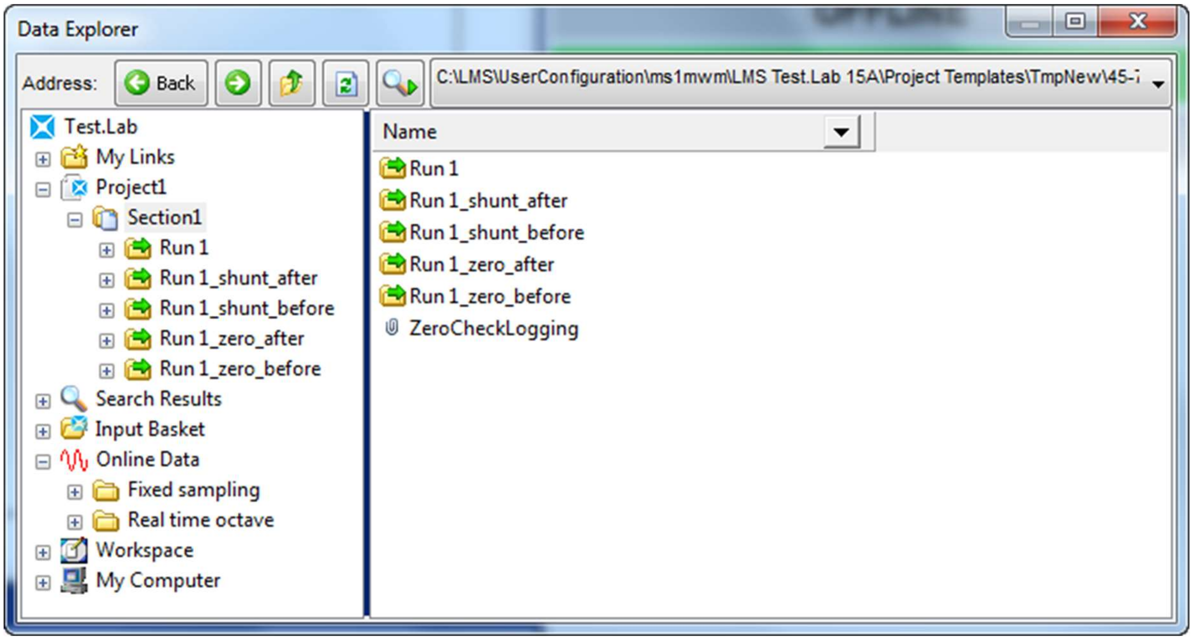
Measuring Time...

NO OVERLOAD

Sufficient disk space left

Picture 16: Shunt measurement sequence automatically takes zero and shunt measurements (default 3 seconds each) before and after acquisition. Status is indicated by blue message.

These separate recordings can be referenced to discover when and if a part yielded in the middle of a measurement campaign. This can be done by comparing before and after shunt and zero values.



Picture 17: Time histories of before and after measurements are stored automatically and separately

Rosette Strain Gauges

A single strain gauge can only measure strain in one direction. In real life applications, this is often inadequate due to the complex nature of most structures and their loads.

Strains and stresses may come in various directions and thus a gauge capable of measuring several different directions simultaneously is necessary.

The Challenges with Single Strain Gauges

In *Figure 1*, would the single, uniaxial gauge capture the strain field correctly?

Only the strain gauge on the left properly measures the strain field. A single uniaxial strain gauge only measures the strain field correctly in one direction. To measure more complicated strain fields, a rosette strain gauge may be required.

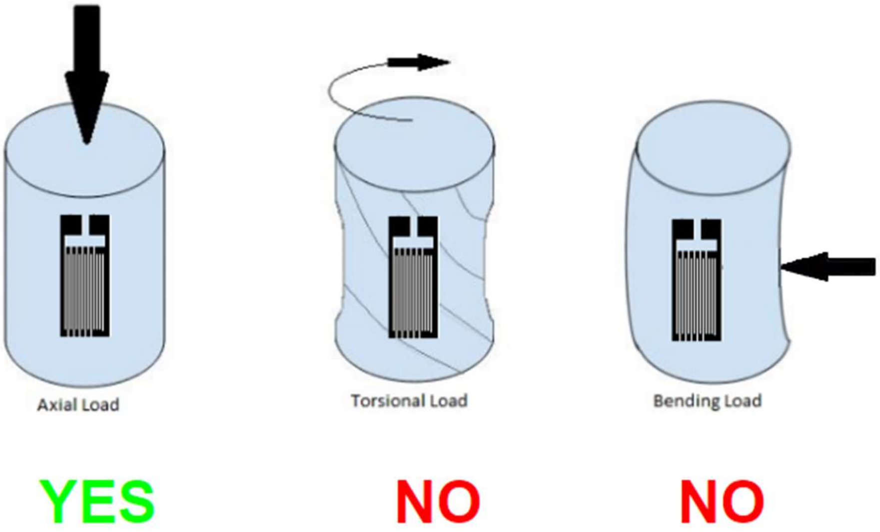


Figure 1: Three different force loads on a metal cylinder. Only for the axial load case on the left does the uniaxial strain gauge measure properly. For the torsional and bending loads on the right, the uniaxial strain gauge is insufficient.

Most real systems/products have complicated geometries and multi-directional loads that cannot be measured by an individual strain gauge.

Instead of thinking of the strain in a single, uniaxial direction, a planar approach can be used to think of strain in a XY axis system as shown in *Figure 2*.

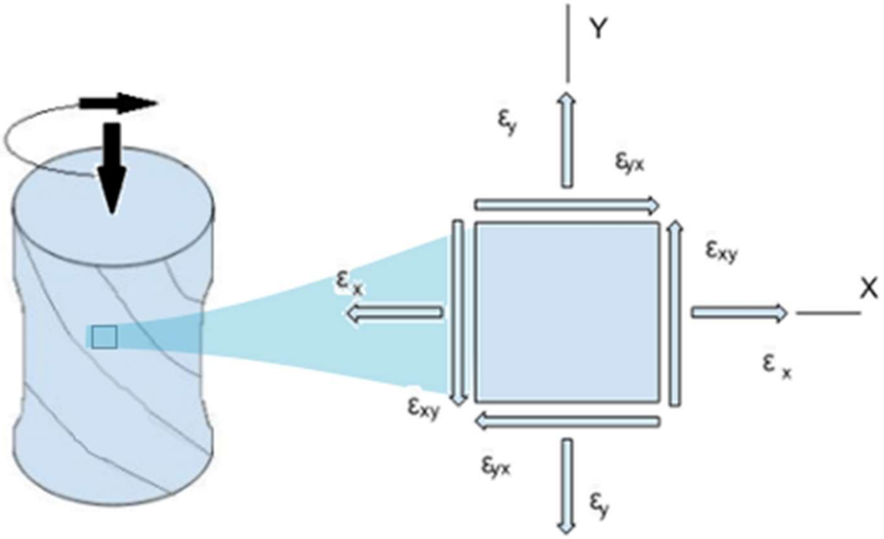


Figure 2: For complicated strain fields, a planar approach can be used.

In a plane, strain can manifest itself in three ways:

- Normal strain in X direction (εx)
- Normal strain in Y direction (εy)
- Shear strain in XY (εxy)

Strain Tensor vs. Principal Strain

There are two methods to define strain in a plane: strain tensor or principal strain. Both methods define the *same* planar strain state at a point on a test piece, but with a *different* "perspective":

Method 1: Strain Tensor - The first method considers three strain components: two normal components (εx,εy) and a shear component called γxyor εxy. The strains are considered in the xy coordinate system as shown in *Figure 2* (left side).

Method 2: Principal Strain - Two principal strains and an angle are used. The gauge is "virtually" rotated so that the shear strain is zero, leaving the two largest principal strain components in the plane. The angle of the principal strain indicates how it is rotated relative to the XY axis as shown in *Figure 3* (right side).

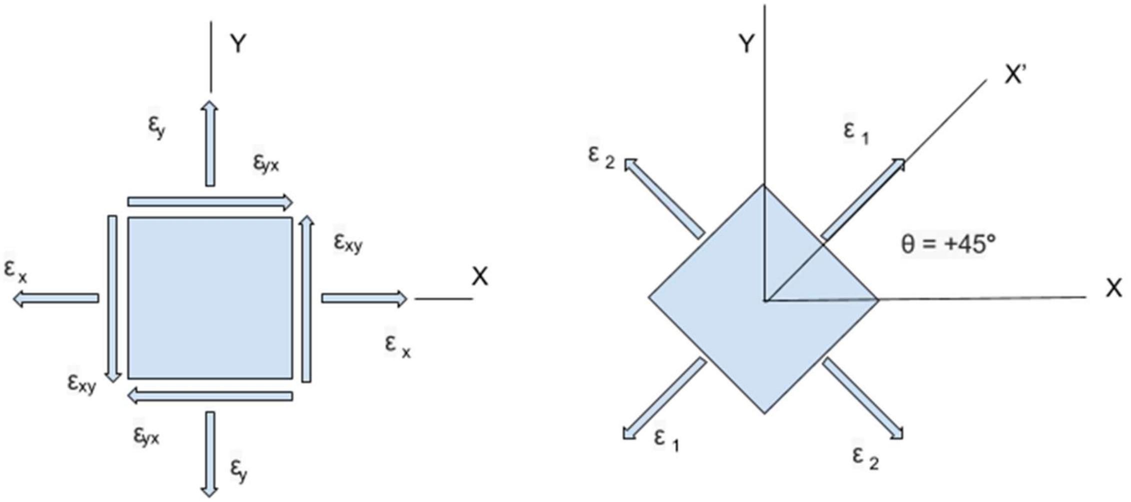


Figure 3: Left is Strain Tensor, Right is Principal Strain

Correctly identifying the principal (i.e., largest) strain is very important. The fatigue life of the part is determined by the largest strain. If a smaller component strain was used in a fatigue life calculation, it would be underestimated, and the part would fail sooner than predicted.

The two principal strains and angle are related to the strain tensor by a series of equations known as the "strain-transformation."

The "strain-transformation" can be easily visualized with the aid of Mohr's circle (*Figure 4*). Mohr's circle plots the normal strain (x axis) with respect to the shear strain (y axis) and provides a model by which both the principal strain and the maximum shear can be determined.

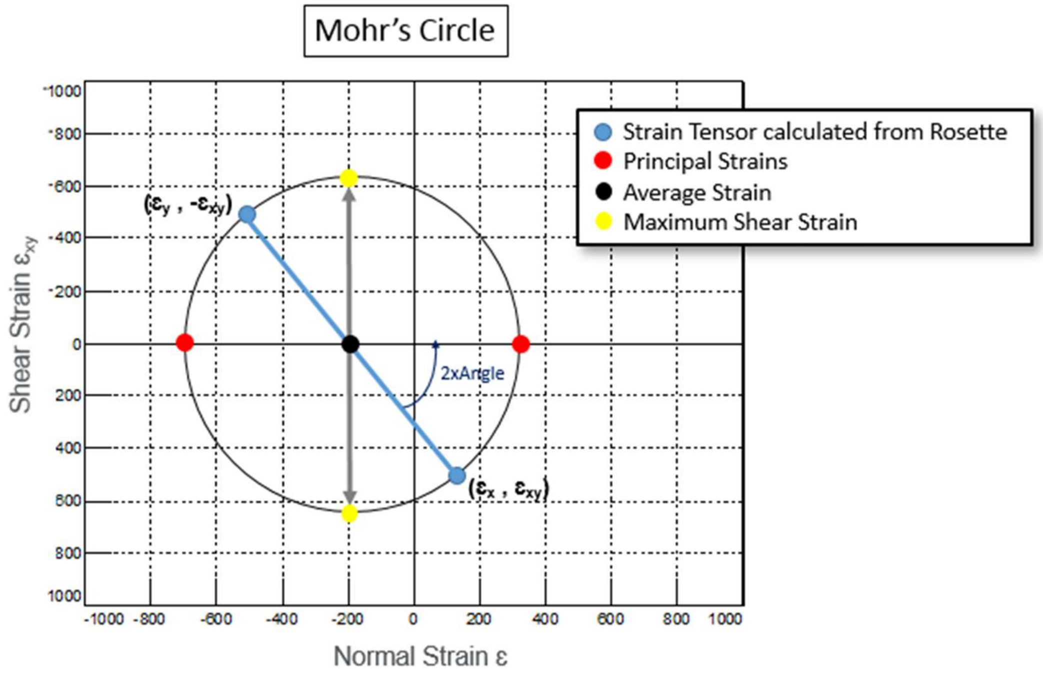


Figure 4: Mohr's circle

The Mohr’s circle has the following properties:

- A strain tensor consisting of two normal (εx, εy) strains and a shear strain (εxy) are calculated from the measured rosette strain gauge arms ε1, ε2, and ε3 as shown in *Figure 6* or *Figure 7*.
- The average strain is calculated as (εx+ εy)/2 and plotted on the X axis where the shear strain is zero.
- Using the calculated normal and shear strains, two points (εx, εxy) and (εy, -εxy) are plotted on the graph.
- A circle is fit thru the two points (εx, εxy) and (εy, -εxy) with the average strain as the center of the circle.
- The two principal strains are the minimum and maximum values where the Mohr’s circle intersects the x axis at zero shear strain.
- The angles of the Mohr's circle are twice the angles of the rosette gauge. Depending on the convention used, the angle will either be between 0 and 180 degrees, or between -90 and +90 degrees.
- Note that Mohr’s circle is constructed with positive shear strain plotted downward. This is done so that the positive rotational direction of the angle in Mohr’s circle is the same (CCW) as for the rosette.

Commonly, the normal strain and the shear strain output of a CAE simulation is based on the strain tensor method. The strain output of a test using a rosette gauge is based on the principal strain method. To compare the output of a CAE simulation to a test, the “strain-transformation” must be used.

Rosette Strain Gauge Calculations

A rosette strain gauge can be used to capture multi-directional strain fields and determine the principal (i.e., largest) strains at any given location on a test piece at any point in time.

Strain gauge rosettes combine *three co-located strain gauges* at specific fixed angles to measure the normal strains along the surface of a test part as shown in *Figure 5*.

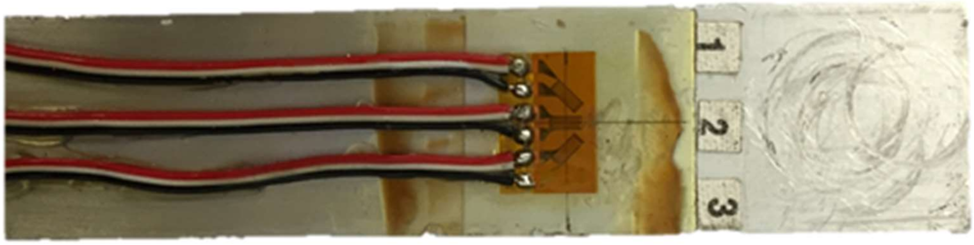


Figure 5: Rosette Strain Gauge consists of three co-located strain gauges.

In theory, each strain gauge should measure the strain at the same position on the part. This is done by placing the gauges in a tight grouping near the rosette center. Rosette gauges even come in "stacked" configurations if strain needs to be measured on the exact same point due to large strain gradients.

The three strain gauge measurements, Young’s modulus of the material, and Poisson’s Ratio are used to calculate the following nine different values from a rosette strain gauge:

- principal strain 1 (SN1): the strain in the direction of the principal stress 1
- principal strain 2 (SN2): the strain in the direction of the principal stress 2
- shear strain (SNSH)
- angle (AG): the angle from strain 1 to the principal axis
- principal stress 1 (SS1): the maximum principal stress
- principal stress 2 (SS2): the minimum principal stress
- shear stress (SNSH)
- equivalent stress (ES): the equivalent stress according to von Mises
- biaxiality ratio (BR): the ratio of the two principal stresses

Three actual measurements give nine calculated outputs! That's a three to one return!

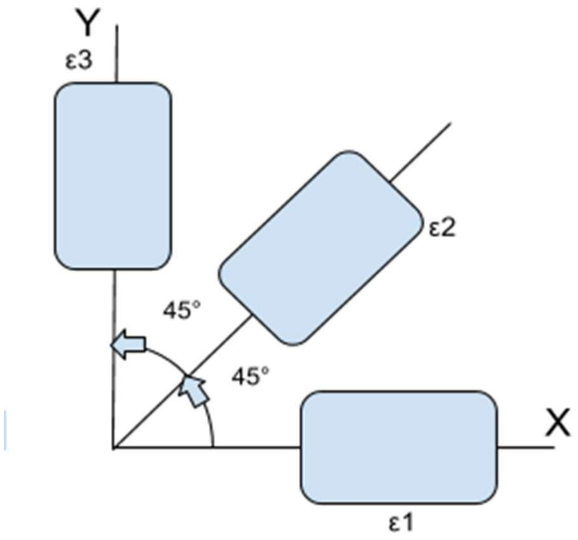
Delta and Rectangular Rosettes

Rosette strain gauges have two common configurations: rectangular or delta. These configurations simplify much of the math involved in the rosette calculations.

Rectangular Rosettes

Rectangular Rosettes separate gauges by 45° placing a strain gauge on both the X and Y coordinate axes as seen in *Figure 6*.

Due to the placement of the gauges, the math for a rectangular gauge is simpler than a delta gauge. With today's computers, this is not an important criterion to consider when selecting rosette gauges.



$$\{\varepsilon_x = \varepsilon_1\}$$

$$\{\varepsilon_y = \varepsilon_3\}$$

$$\{\varepsilon_{xy} = \varepsilon_2 - (\varepsilon_1 + \varepsilon_3)/2\}$$

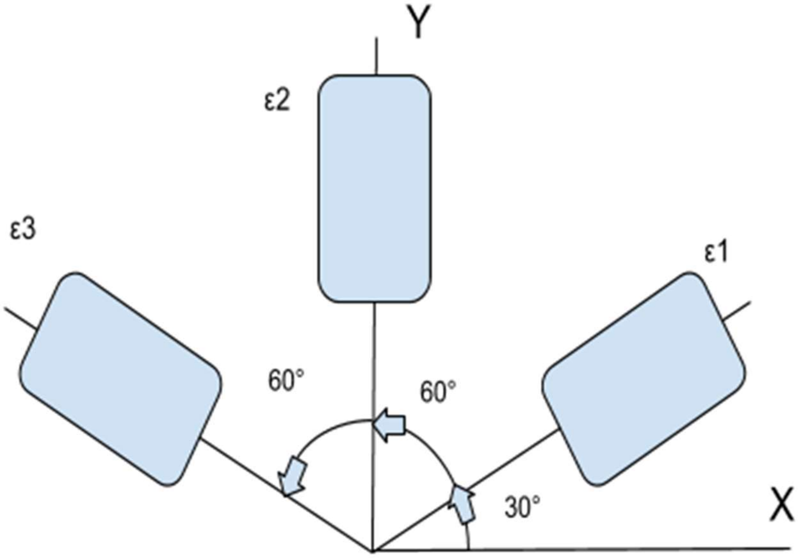
Figure 6: Rectangular Rosette diagram

The following formulas are used to calculate the nine outputs of a rectangular rosette gauge:

$$SN1,\ SN2 = 1/2\ (\varepsilon_1 + \varepsilon_3) \pm 1/\sqrt{2}\ \mathrm{sqrt}((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2)$$
$$SH = 2\varepsilon_2 - \varepsilon_1 - \varepsilon_3$$
$$AG = ½\ \tan^{-1}[\ (2\varepsilon_2 - \varepsilon_1 - \varepsilon_3)/(\varepsilon_1 - \varepsilon_3)]$$
$$SS1 = E/(1-\nu^2)\ (SN1 + \nu\ SN2)$$
$$SS1 = E/(1-\nu^2)\ (SN2 + \nu\ SN1)$$
$$SH = ½\ (SS1 - SS2) * \sin\ (2*AG)$$
$$ES = [(SS1)^2 - (SS1\ x\ SS2) + (SS2)^2]^{1/2}$$
$$BR = |SS2|\ /\ |SS1|$$

Delta Rosette Gauges

Delta gauges have a wider coverage versus rectangular gauges. The strain gauges are separated by 60°, and the middle strain gauge is aligned with the y-axis as shown in *Figure 7*.



$$\{\varepsilon_x = 2/3(\varepsilon_1 - 1/2\varepsilon_2 + \varepsilon_3)\}$$
$$\{\varepsilon_y = \varepsilon_2\}$$
$$\left\{\varepsilon_{xy} = 1/\sqrt{3}(\varepsilon_1 - \varepsilon_3)\right\}$$

Figure 7: Delta Rosette diagram

The following formulas are used to calculate the nine outputs of a delta rosette gauge:

$$SN1,\ SN2 = 1/3\ (\varepsilon_1 + \varepsilon_2 + \varepsilon_3) \pm \sqrt{2}/3\ \mathrm{sqrt}((\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2)$$
$$SH\ = 2/\sqrt{3}\ *(\ \varepsilon_2 - \varepsilon_3)$$
$$AG = ½\ \tan^{-1}[\sqrt{3}\ (\varepsilon_2 - \varepsilon_3)/(2\ \varepsilon_1 - \varepsilon_2 - \varepsilon_3)]$$
$$SS1 = E/(1-\nu^2)\ (SN1 + \nu\ SN2)$$
$$SS1 = E/(1-\nu^2)\ (SN2 + \nu\ SN1)$$
$$SH = ½\ (SS1 - SS2) * \sin\ (2*AG)$$
$$ES = [(SS1)^2 - (SS1\ x\ SS2) + (SS2]^2]^{1/2}$$
$$BR = |SS2|\ /\ |SS1|$$

Biaxiality Ratio

When doing the calculations for a rosette gauge, a biaxiality ratio can also be calculated. The biaxiality ratio is the ratio of the two principal stresses (SS1 and SS2) as seen in *Equation 1* (assuming

|SS1| > |SS2|). The principal stress with the largest absolute value is always put in the denominator so that the biaxiality values are always between -1 and 1.

$$\text{Biaxiality Ratio} = \frac{SS2}{SS1}$$

Equation 1: Biaxiality Ratio is the ratio of Principal Stresses

The biaxiality ratio can be any value between -1 and 1:

- 0 : If the biaxiality ratio is 0, the stress/strain field is uniaxial tension or compression
- -1 : If the biaxiality ratio is -1, the stress/strain field is pure shear stress or strain
- 1 : If the biaxiality ratio is 1, the stress/strain is equal in all directions

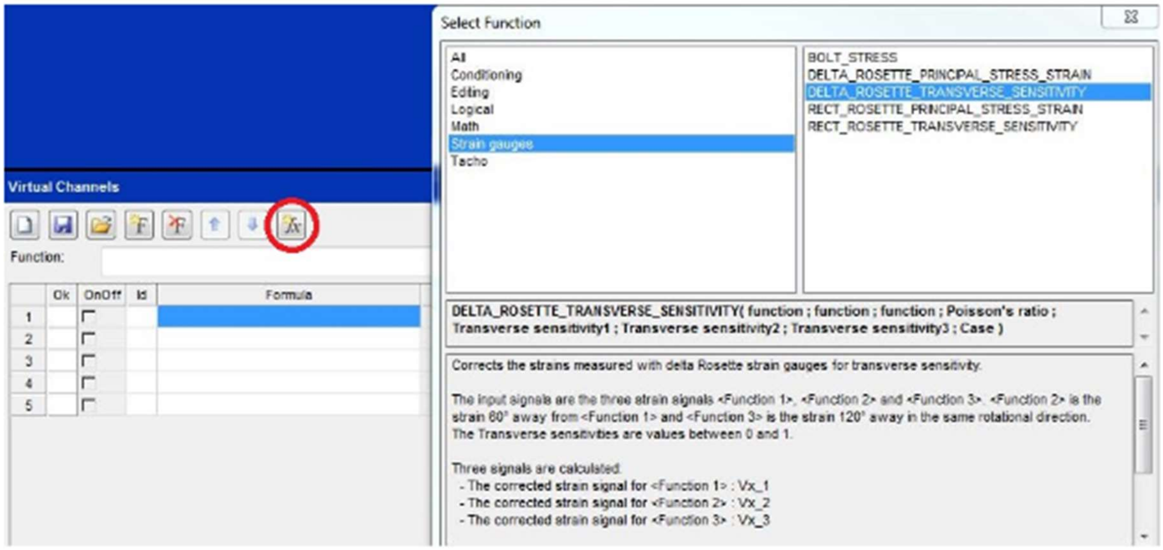
The biaxiality ratio is one of the parameters calculated using the ROSETTE virtual channel calculations in Simcenter Testlab.

Rosette Gauges in Simcenter Testlab

Rosette strain gauges can be setup via "Virtual Channels" in Simcenter Testlab. In Signature acquisition, change "Channel setup" to "Virtual Channels" using the pulldown in the upper right of the "Channel Setup" worksheet as shown in *Figure 8*.

Figure 8: Virtual Channels in Simcenter Testla Channel Setup worksheet.

After selecting "Virtual Channels" a formula area appears at the bottom of the Channel Setup worksheet as shown in *Figure 9*.



DELTA_ROSETTE_TRANSVERSE_SENSITIVITY(function ; function ; function ; Poisson's ratio ; Transverse sensitivity1 ; Transverse sensitivity2 ; Transverse sensitivity3 ; Case)

Corrects the strains measured with delta Rosette strain gauges for transverse sensitivity.

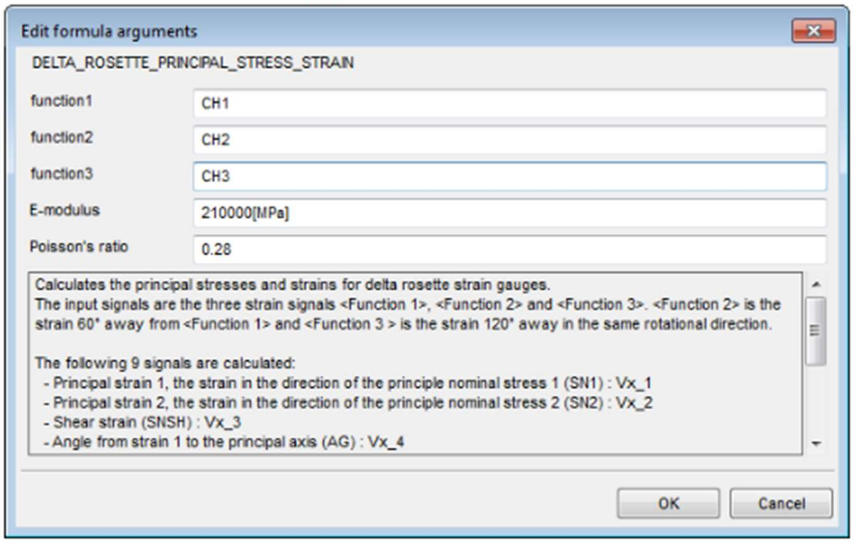
The input signals are the three strain signals <Function 1>, <Function 2> and <Function 3>. <Function 2> is the strain 60° away from <Function 1> and <Function 3> is the strain 120° away in the same rotational direction. The Transverse sensitivities are values between 0 and 1.

Three signals are calculated:
- The corrected strain signal for <Function 1> : Vx_1
- The corrected strain signal for <Function 2> : Vx_2
- The corrected strain signal for <Function 3> : Vx_3

Figure 9: Function Selection in Virtual Channels via the "f(x)" button

Click on the “insert function” button with the “f(x)” symbol and select “Strain gauges” group of functions. Then, select the type of strain gauge that is being used in the test: delta or rectangular.

In the “Edit formula arguments” menu, enter the three channels of the Rosette strain gauge, Young’s Modulus and Poisson’s ratio (*Figure 10*).



DELTA_ROSETTE_PRINCIPAL_STRESS_STRAIN

function1	CH1
function2	CH2
function3	CH3
E-modulus	210000[MPa]
Poisson's ratio	0.28

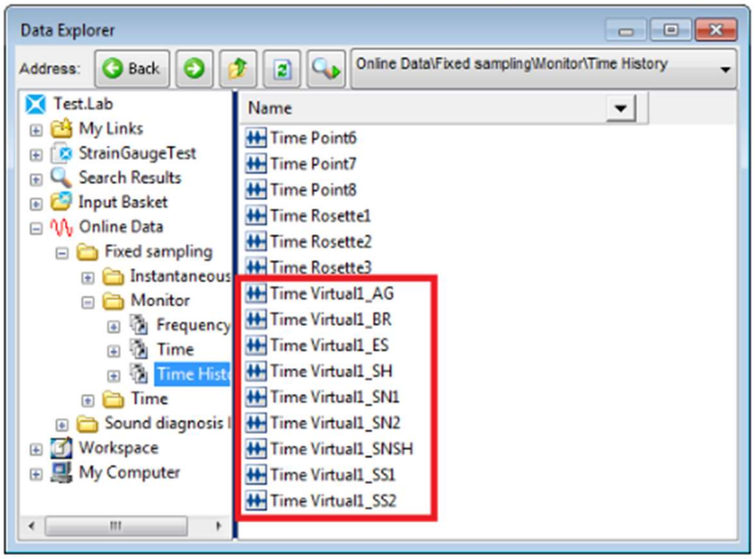
Calculates the principal stresses and strains for delta rosette strain gauges.
The input signals are the three strain signals <Function 1>, <Function 2> and <Function 3>. <Function 2> is the strain 60° away from <Function 1> and <Function 3 > is the strain 120° away in the same rotational direction.

The following 9 signals are calculated:
- Principal strain 1, the strain in the direction of the principle nominal stress 1 (SN1) : Vx_1
- Principal strain 2, the strain in the direction of the principle nominal stress 2 (SN2) : Vx_2
- Shear strain (SNSH) : Vx_3
- Angle from strain 1 to the principal axis (AG) : Vx_4

Figure 9: “Edit formula arguments” menu for Rosette gauge

Note: Young’s modulus is 210000 MPa for a typical steel.

Press the ‘OK’ button on the ‘Edit formula arguments’ menu when finished. Nine new rosette time calculation channels will be created in the resulting time history file as seen in *Figure 11*.



Address: Online Data\Fixed sampling\Monitor\Time History

Time Point6
Time Point7
Time Point8
Time Rosette1
Time Rosette2
Time Rosette3
Time Virtual1_AG
Time Virtual1_BR
Time Virtual1_ES
Time Virtual1_SH
Time Virtual1_SN1
Time Virtual1_SN2
Time Virtual1_SNSH
Time Virtual1_SS1
Time Virtual1_SS2

Figure 11: Rosette Time Calculation channels in Time File

Rosette strain gauge calculations can also be performed offline using the Simcenter Testlab Time Signal Calculator.

Calculating damage in Simcenter Tecware ProcessBuilder

With Simcenter Testlab Revision 16 or higher, the Simcenter Tecware (formerly called LMS TecWare) can be run using Simcenter Testlab tokens.

Simcenter Tecware ProcessBuilder is a *graphical* environment where multiple methods can be combined together to create a data processing routine. Methods that can be combined include:

- Filtering
- Integration/Differentiation
- Spike removal
- Drift removal
- Resampling
- Fatigue and damage calculations
- Logic operations

Building a Processing Routine

To calculate damage from a load time history in Simcenter Tecware Processbuilder, the following steps are required:

1. *Select Time Histories: Identify files for analysis*
2. *Process Creation: Select methods to calculate fatigue damage*
3. *View results: View rainflow matrices, save damage results in Excel*

Select Time Histories

Time history file selection can be done via the menu File-Data Import, or just by drag-and-drop of time data files from the Windows Explorer to the ProcessBuilder.

First select some time data to process, by choosing the 'Data Import' icon in the upper left as shown in *Figure 1*. An 'Import' dialog box will open.

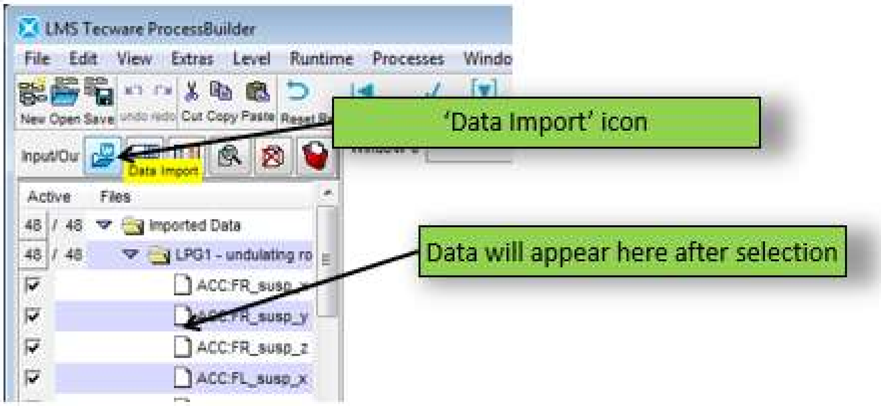
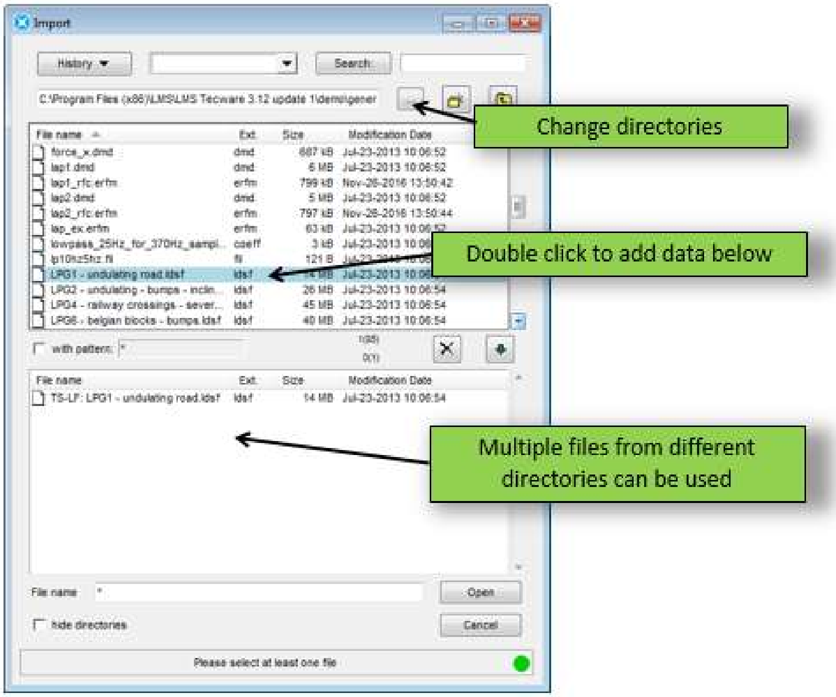


Figure 1: 'Data Import' icon for selecting time histories to process

In the 'Import' dialog box, several different file types can be selected, including Simcenter LDSF, RPC, ASCII, etc. Navigate to a directory containing data and double click on it to select it for processing as shown in *Figure 2*.



C:\Program Files (x86)\LMS\LMS Tecware 3.12 update 1\demo\gener

File name	Ext.	Size	Modification Date
force_x.dmd	dmd	687 kB	Jul-23-2013 10:06:52
lap1.dmd	dmd	6 MB	Jul-23-2013 10:06:52
lap1_rfc.erfm	erfm	799 kB	Nov-28-2016 13:50:42
lap2.dmd	dmd	5 MB	Jul-23-2013 10:06:52
lap2_rfc.erfm	erfm	797 kB	Nov-28-2016 13:50:44
lap_ex.erfm	erfm	63 kB	Jul-23-2013 10:06:52
lowpass_25Hz_for_370Hz_sampl...	coeff	3 kB	Jul-23-2013 10:06
lp10hz5hz.fil	fil	121 B	Jul-23-2013 10:06
LPG1 - undulating road.ldsf	ldsf	14 MB	Jul-23-2013 10:06
LPG2 - undulating - bumps - inclin...	ldsf	26 MB	Jul-23-2013 10:06:54
LPG4 - railway crossings - sever...	ldsf	45 MB	Jul-23-2013 10:06:54
LPG6 - belgian blocks - bumps.ldsf	ldsf	40 MB	Jul-23-2013 10:06:54

File name	Ext.	Size	Modification Date
TS-LF: LPG1 - undulating road.ldsf	ldsf	14 MB	Jul-23-2013 10:06:54

Please select at least one file

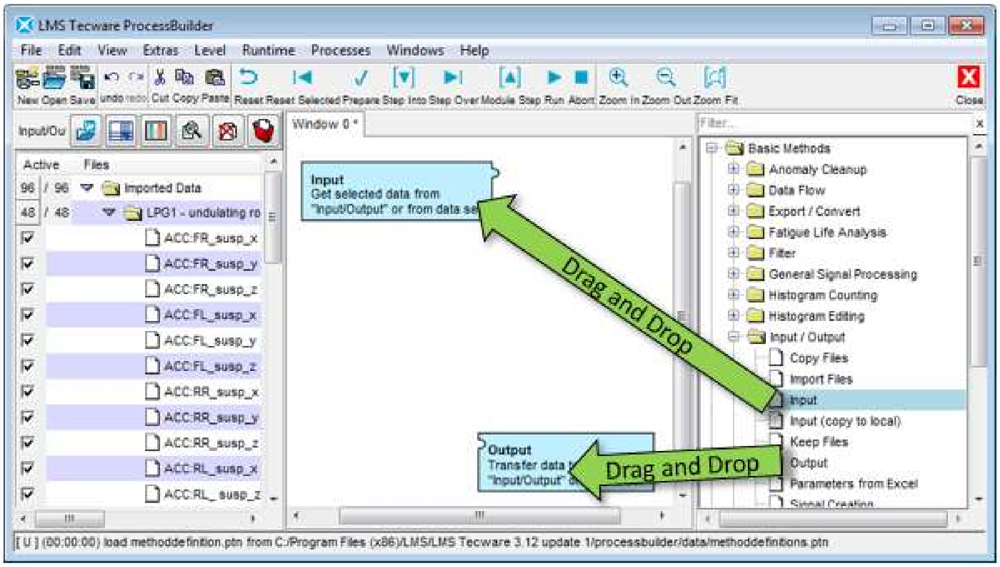
Figure 2: 'Import' dialog for selecting load time histories

Press 'Open' when finished. There are checkboxes for selecting entire files or individual channels to be processed. By default, all added data is to be processed.

Process Creation

Next a processing routine consisting of different methods is built.

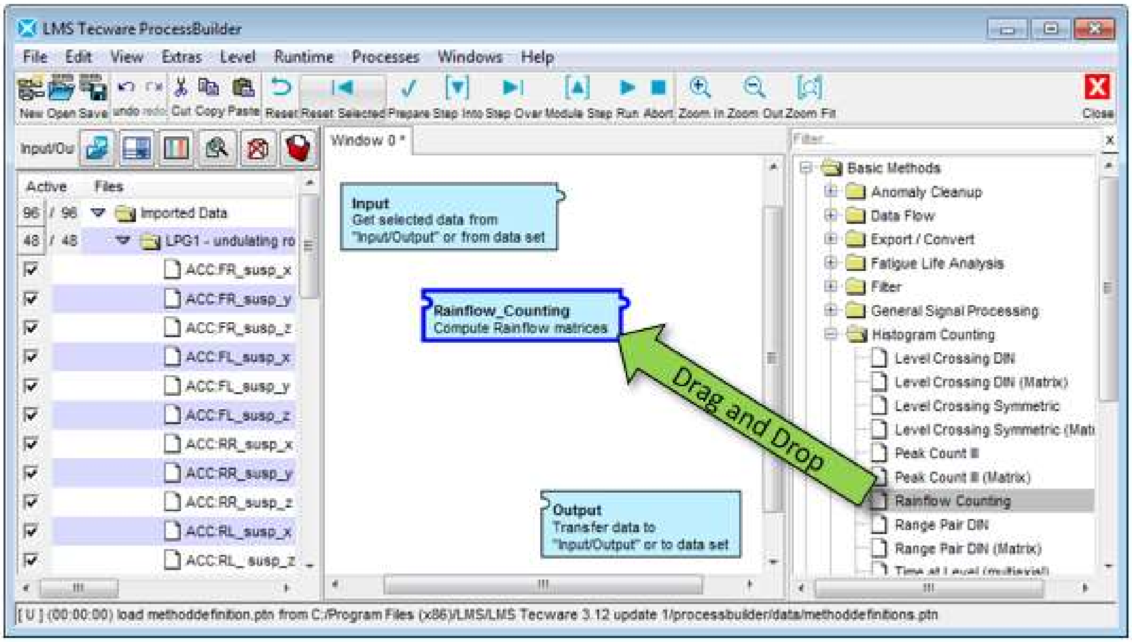
Drag and drop from the 'Input/Output' methods (right side of screen) one 'Input' method and one 'Output' method as shown in *Figure 3*. These will be at the beginning and end of the process.



[U] (00:00:00) load methoddefinition.ptn from C:/Program Files (x86)/LMS/LMS Tecware 3.12 update 1/processbuilder/data/methoddefinitions.ptn

Figure 3: Drag and drop an 'Input' method and 'Output' method

Then from the ‘Histogram Counting’ methods, drag and drop the ‘Rainflow Counting’ icon in the middle screen (*Figure 4*).

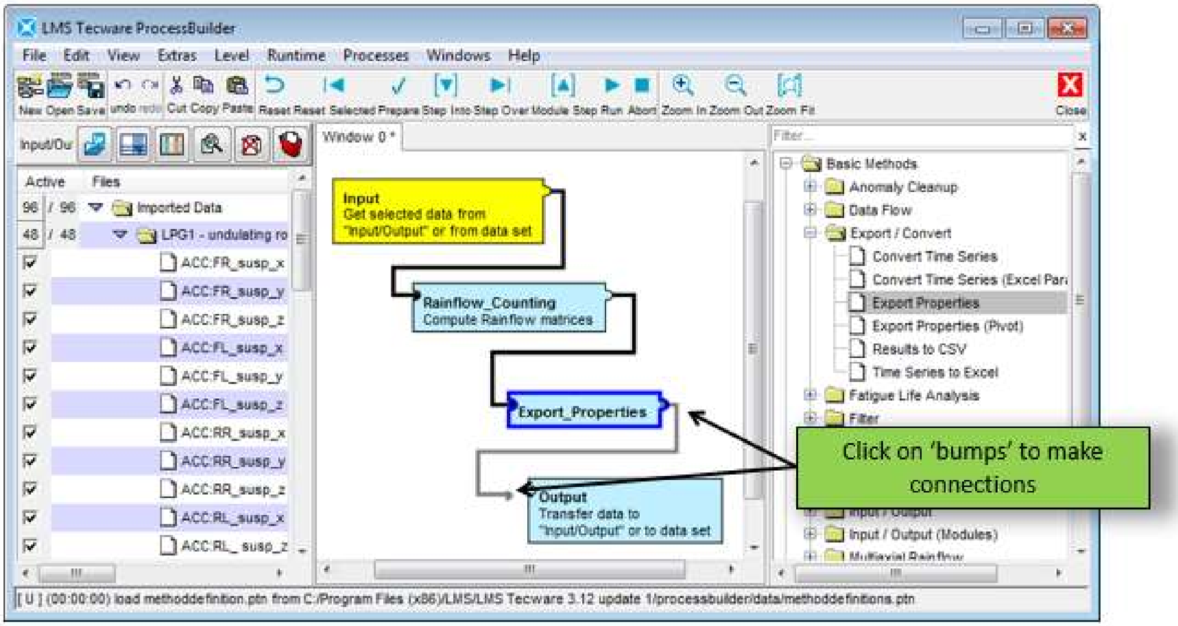


Drag and Drop

[U] (00:00:00) load methoddefinition.ptn from C:/Program Files (x86)/LMS/LMS Tecware 3.12 update 1/processbuilder/data/methoddefinitions.ptn

Figure 4: Drag and drop the ‘Rainflow Counting’ method

From the group ‘Export/Convert’ drag and drop the ‘Export Properties’ method into the process as shown in *Figure 5*. ‘Export Properties’ allows data results to be exported into Excel easily.



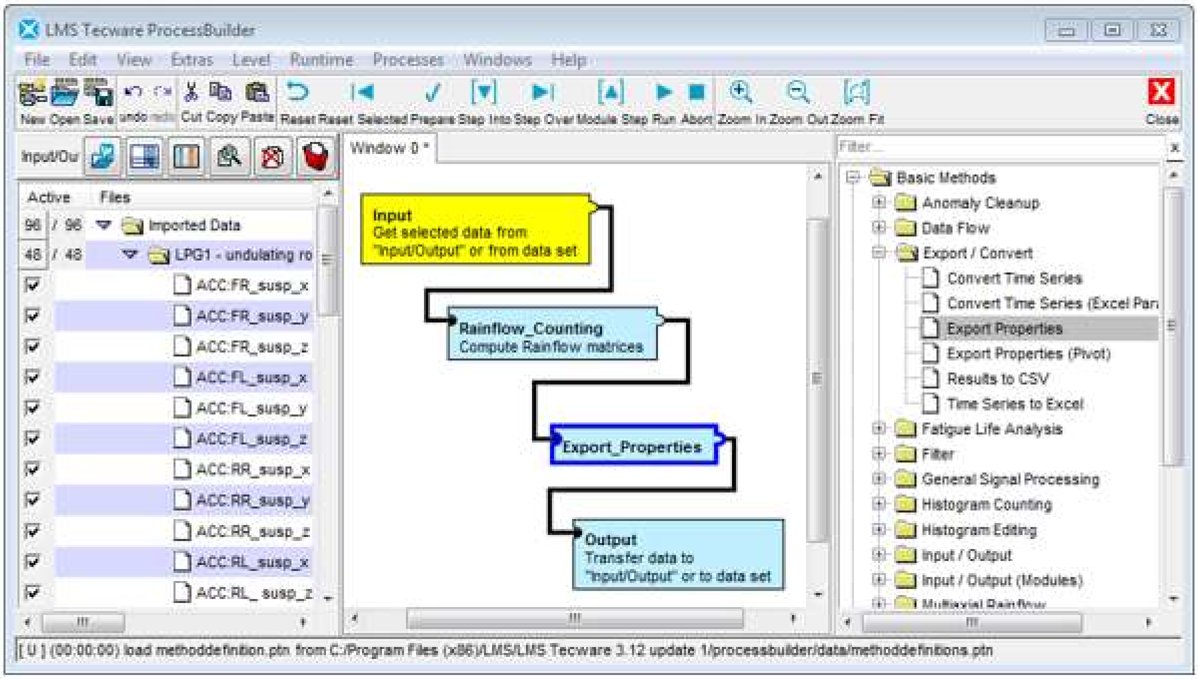
Click on ‘bumps’ to make connections

[U] (00:00:00) load methoddefinition.ptn from C:/Program Files (x86)/LMS/LMS Tecware 3.12 update 1/processbuilder/data/methoddefinitions.ptn

Figure 6: Making connections between methods

Note: Dropping a method on an existing method in the middle area automatically connects the two methods.

In the end, the process should look like *Figure 7*.



[U] (00:00:00) load methoddefinition.ptn from C:/Program Files (x86)/LMS/LMS Tecware 3.12 update 1/processbuilder/data/methoddefinitions.ptn

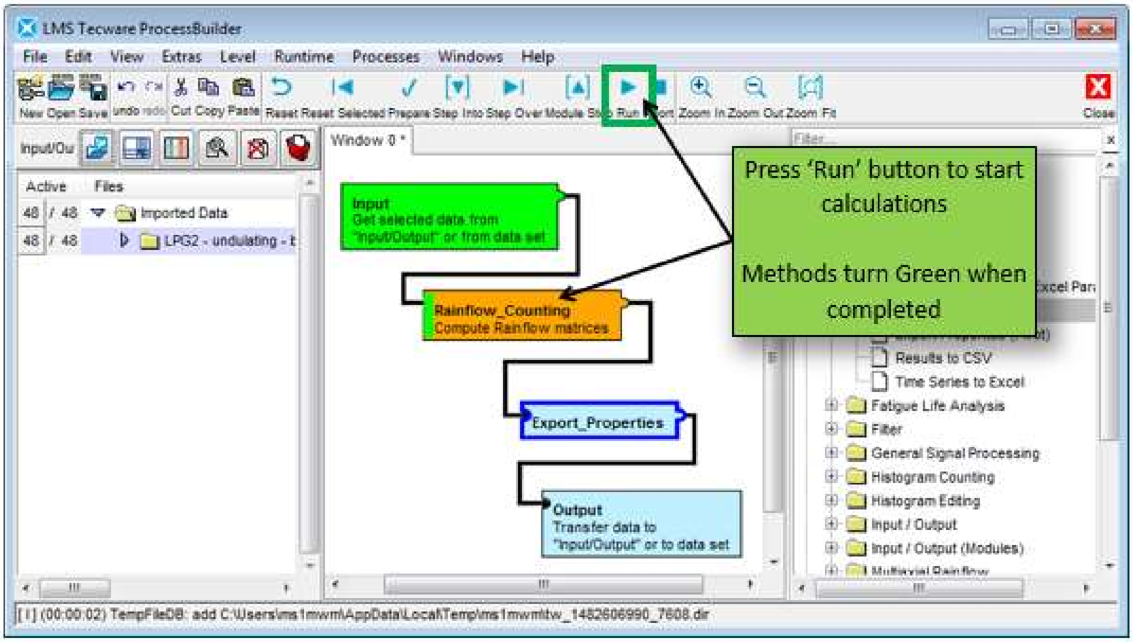
Figure 7: Appearance of final process

Double-clicking an individual method will open the parameters. For Rainflow Counting, adjustments can be made to the number of bins, the limits, hysteresis gate, and whether groups of channels should share the same limits.

To compare different loads based on their damaging behavior, the damage can be calculated based on a SN-Curve. The SN-Curve can come from a number of different sources:

- Known SN-Curve parameters
- A default SN Curve with a slope of 5. No endurance limit and no maximum tensile strength is used.
- A material database, for example the FKM libraries from VDMA (Verband Deutscher Maschinen- und Anlagenbau e.V.)

Now press the "Run" button to run the methods as shown in *Figure 8*. Methods will turn green as they are completed.



Press ‘Run’ button to start calculations

Methods turn Green when completed

[I] (00:00:02) TempFileDB: add C:\Users\ms1mwm\AppData\Local\Temp\ms1mwmtw_1482606990_7608.dir

Figure 8: Running methods in ProcessBuilder turn green as they complete

Viewing Results: Excel

The Excel file with the damage values is available using a right-click on the ‘Export Properties’ method and select ‘Show Excel’ as shown in *Figure 9*.

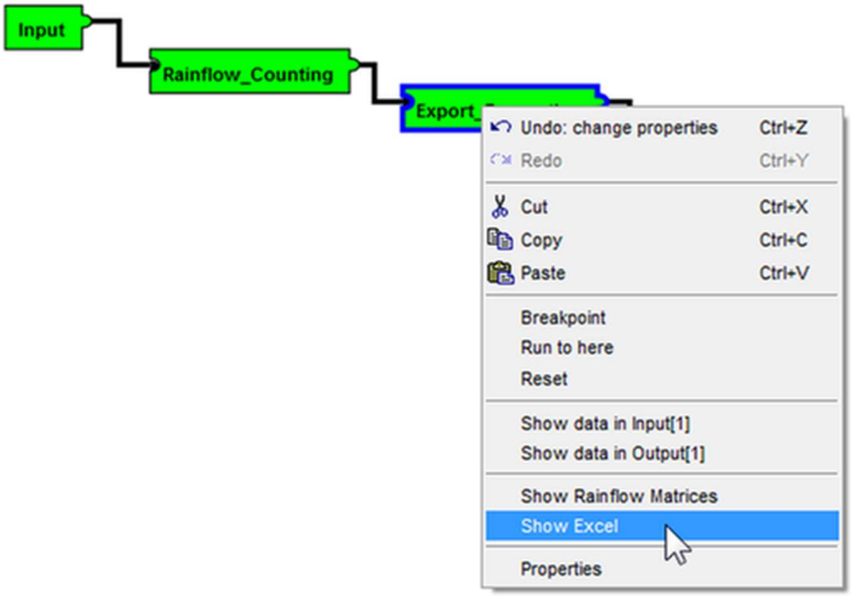
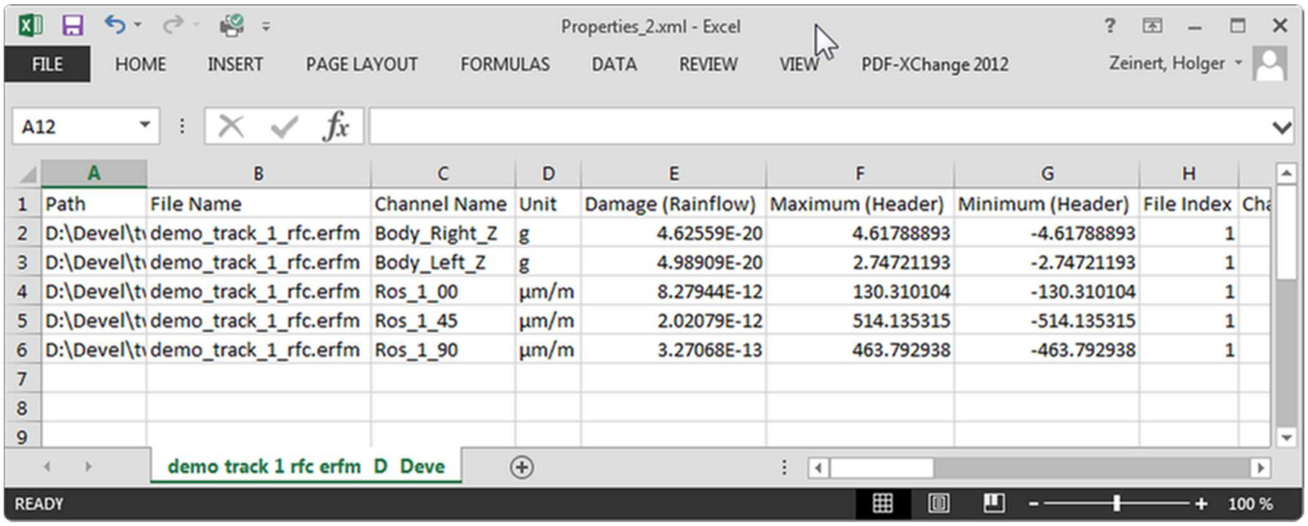


Figure 9: Right click on ‘Export Parameters’ and select ‘Show Excel’

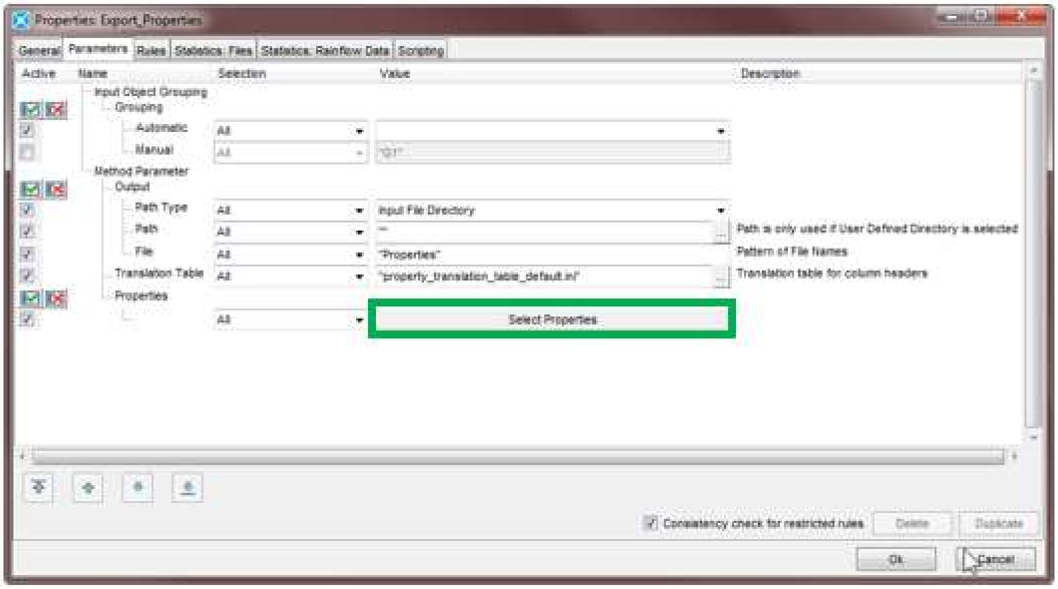
The Excel file contains one line per channel and a default set of attributes like path, file name, channel name, unit, statistics and damage as shown in *Figure 10*. If multiple files were processed, they appear on different Excel worksheets.



	A	B	C	D	E	F	G	H	Cha
1	Path	File Name	Channel Name	Unit	Damage (Rainflow)	Maximum (Header)	Minimum (Header)	File Index	Cha
2	D:\Devel\t	demo_track_1_rfc.erfm	Body_Right_Z	g	4.62559E-20	4.61788893	-4.61788893	1	
3	D:\Devel\t	demo_track_1_rfc.erfm	Body_Left_Z	g	4.98909E-20	2.74721193	-2.74721193	1	
4	D:\Devel\t	demo_track_1_rfc.erfm	Ros_1_00	µm/m	8.27944E-12	130.310104	-130.310104	1	
5	D:\Devel\t	demo_track_1_rfc.erfm	Ros_1_45	µm/m	2.02079E-12	514.135315	-514.135315	1	
6	D:\Devel\t	demo_track_1_rfc.erfm	Ros_1_90	µm/m	3.27068E-13	463.792938	-463.792938	1	
7									
8									
9									

Figure 10: Excel file with damage

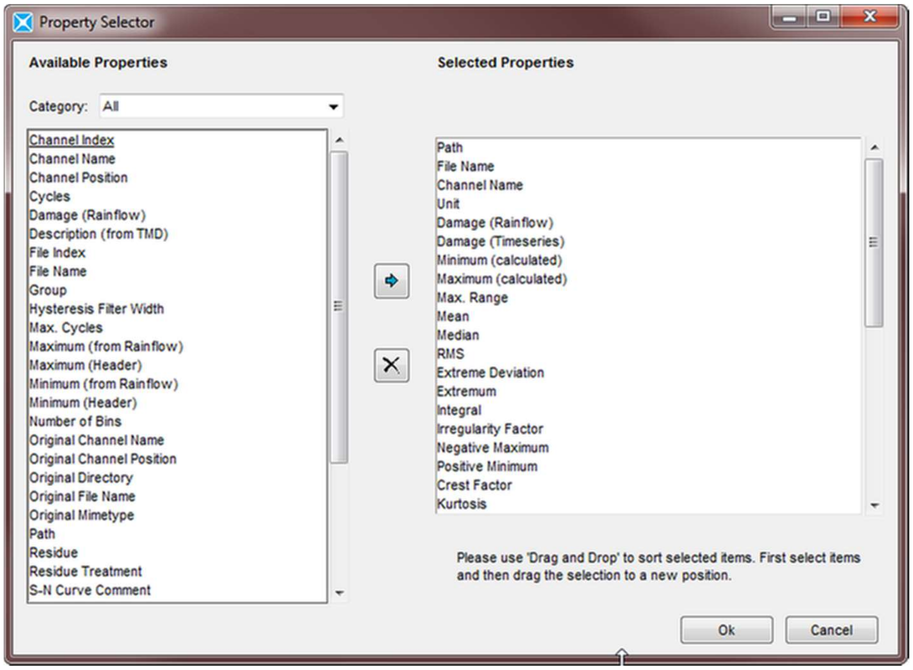
To change the selection of attributes, double-click on the ‘Export Properties’ method and press the button ‘Select Properties’ as in *Figure 11*.



Active	Name	Selection	Value	Description
	Input Object Grouping			
	Grouping			
☑	Automatic	All		
☐	Manual	All	"G1"	
	Method Parameter			
	Output			
☑	Path Type	All	Input File Directory	
☑	Path	All	""	Path is only used if User Defined Directory is selected
☑	File	All	"Properties"	Pattern of File Names
☑	Translation Table	All	"property_translation_table_default.ini"	Translation table for column headers
	Properties			
☑		All	Select Properties	

Figure 11: Choose ‘Select Properties’

Either remove ‘Selected Properties’ on the right or add more attributes from the ‘Available Properties’ area on the left. If the ‘Available Properties’ on the left is empty, a run must be processed, so that the available attributes are filled in as shown in *Figure 12*.



Property Selector

Available Properties

Category: All

Channel Index
Channel Name
Channel Position
Cycles
Damage (Rainflow)
Description (from TMD)
File Index
File Name
Group
Hysteresis Filter Width
Max. Cycles
Maximum (from Rainflow)
Maximum (Header)
Minimum (from Rainflow)
Minimum (Header)
Number of Bins
Original Channel Name
Original Channel Position
Original Directory
Original File Name
Original Mimetype
Path
Residue
Residue Treatment
S-N Curve Comment

Selected Properties

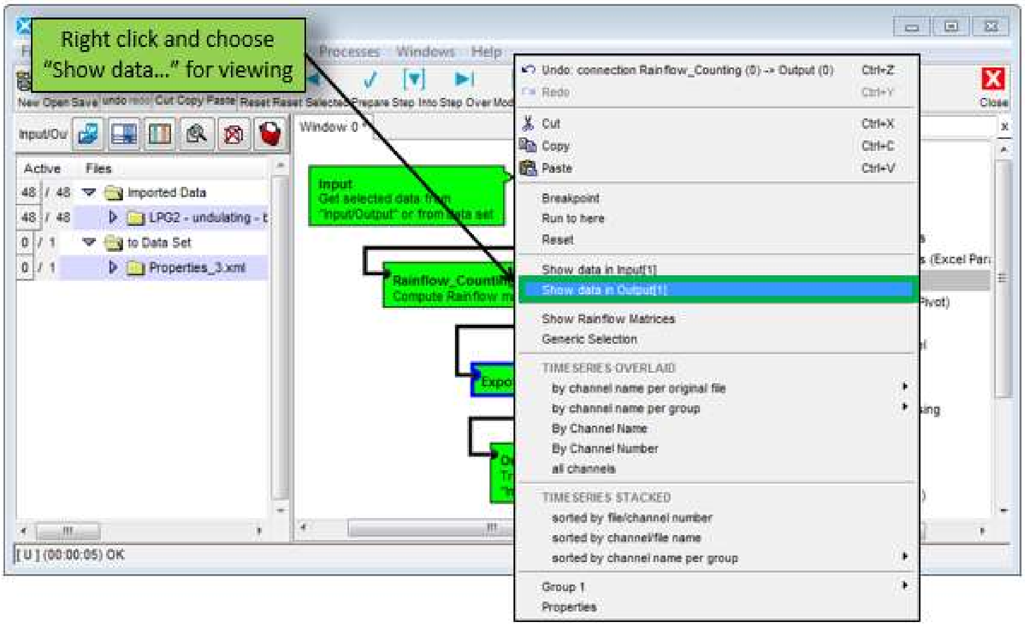
Path
File Name
Channel Name
Unit
Damage (Rainflow)
Damage (Timeseries)
Minimum (calculated)
Maximum (calculated)
Max. Range
Mean
Median
RMS
Extreme Deviation
Extremum
Integral
Irregularity Factor
Negative Maximum
Positive Minimum
Crest Factor
Kurtosis

Please use 'Drag and Drop' to sort selected items. First select items and then drag the selection to a new position.

Figure 12: Properties can be selected for display in the Excel output

Viewing Results: Rainflow Matrices and Data Graphs

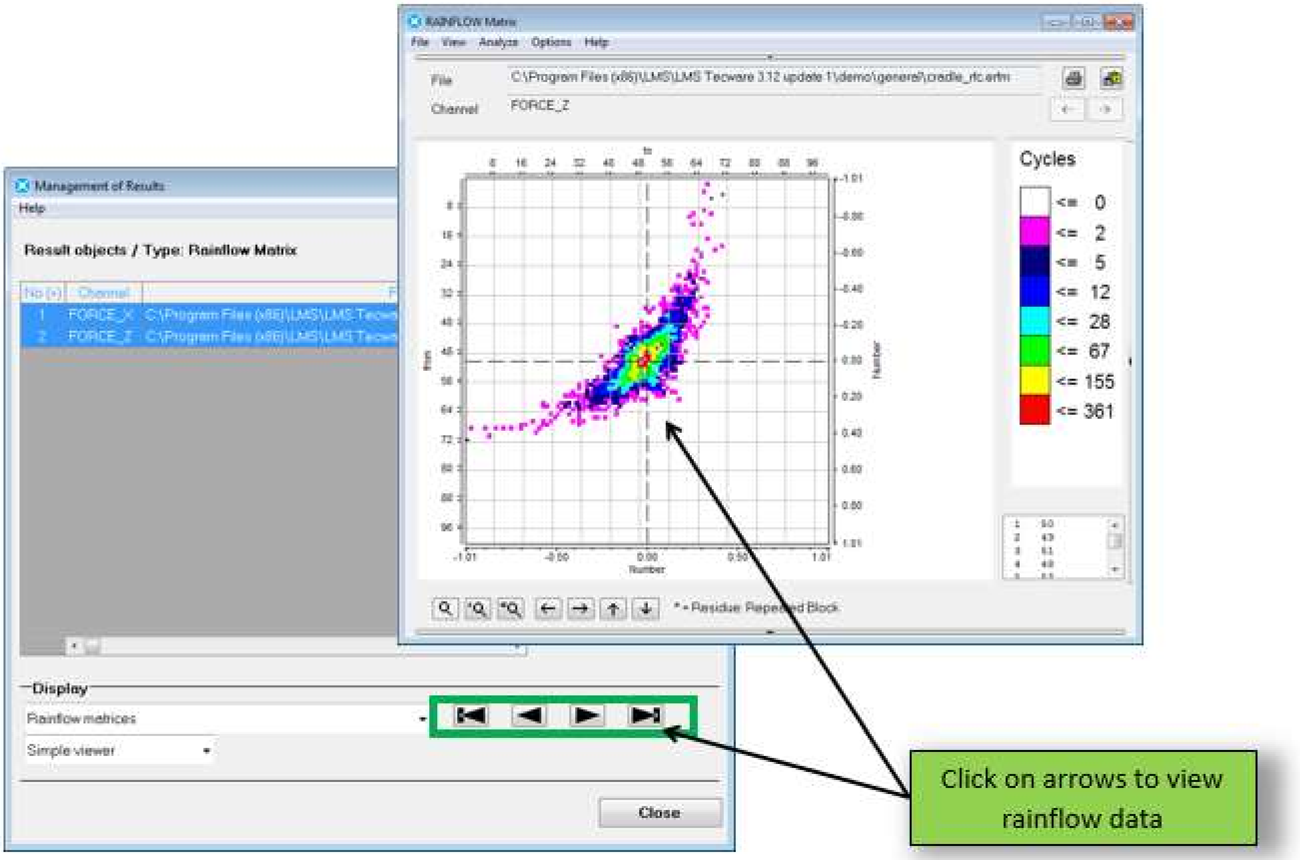
To view the input data time histories or the resulting rainflow matrices, right click on the 'Rainflow Counting' method, and select "Show data in input" or "Show data in output" as appropriate (*Figure 13*). For the Rainflow Counting method, input data is the time history, while the output data is the rainflow matrix.



Right click and choose "Show data..." for viewing

Figure 13: Showing input and output data on method

After selecting ‘Show data in output’ a ‘Management of Results’ dialog box is opened (*Figure 14*). Here one can view the Rainflow matrices and use the arrow buttons to scroll thru the different channels.



File: C:\Program Files (x86)\LMS\LMS Tecware 3.12 update 1\demo\general\cradle_rfc.erfm

Channel: FORCE_Z

Result objects / Type: Rainflow Matrix

No (+)	Channel	
1	FORCE_X	C:\Program Files (x86)\LMS\LMS Tecwa
2	FORCE_Z	C:\Program Files (x86)\LMS\LMS Tecwa

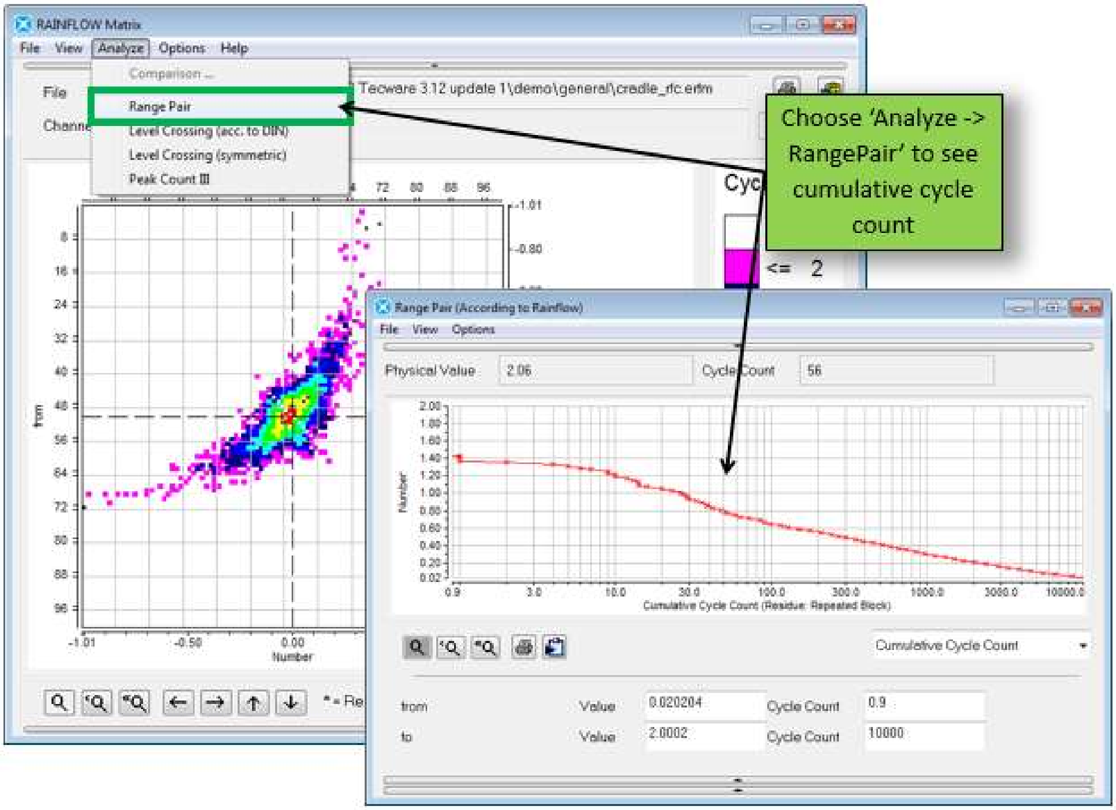
Display: Rainflow matrices

Simple viewer

Click on arrows to view rainflow data

Figure 14: ‘Management of Results’ and viewing of data

From the Rainflow matrix display, it is possible to view the cycle counts and accumulated damage. To do so, choose ‘Analyze -> Range Pair’ from the menu (*Figure 15*). An accumulated cycle display is shown, showing the amplitude of the cycles versus the number of cycles.
To see the residue, select ‘Options -> Graphic Residue’ in the Rainflow display menu.



File Tecware 3.12 update 1\demo\general\cradle_rfc.erfm

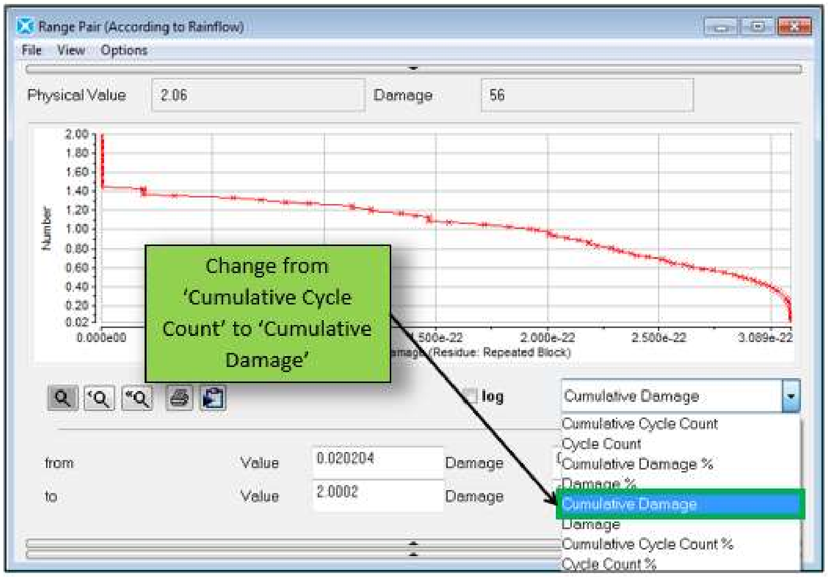
Choose 'Analyze -> RangePair' to see cumulative cycle count

Physical Value 2.06 Cycle Count 56

from Value 0.020204 Cycle Count 0.9
to Value 2.0002 Cycle Count 10000

Figure 15: Choose 'Analyze -> RangePair' to see Cumulative Cycle Count

In the RangePair display, one can then switch to accumulated damage using the toggle bar in the lower left (*Figure 16*). Remember, when the accumulated damage is equal to or greater than one, failure occurs.



Physical Value 2.06 Damage 56

Change from 'Cumulative Cycle Count' to 'Cumulative Damage'

from Value 0.020204 Damage
to Value 2.0002 Damage

Figure 16: Viewing 'Cumulative Damage' instead of 'Cumulative Cycle Count"

More Methods

There are several other methods for fatigue life calculation in Simcenter Tecware ProcessBuilder. There are methods for Stress Life and Strain Life calculations.

These other fatigue methods can be run via Simcenter Testlab tokens with Testlab Revision 16 revision or higher.

Strain Gauges: Selecting an Excitation Voltage

Strain gauges are "ratiometric" transducers – their signal output is proportional to the supply voltage used to power them. Strain gauges work with a wide variety of voltage supplies. Typical supply voltages range from one volt to ten volts.

But what is the "best" voltage excitation level to use?

When selecting an appropriate voltage supply level, there are two opposing considerations:

- Higher Voltage – A *higher* voltage excitation improves the signal to noise ratio of the gauge.
- Lower Voltage – A *lower* voltage excitation reduces thermally induced errors in a strain gauge measurement.

So, while a high voltage improves a strain gauge measurement from a signal to noise point of view, it can create thermally induced errors. A proper balance is needed to ensure a quality measurement.

In this article, the signal levels and thermal errors are discussed further, as well as strategies for selecting the proper voltage.

Signal Levels

The higher the voltage supplied to the gauge, the higher the signal returned by the gauge during measurement for a given load.

This helps avoid issues like electro-magnetic interference. Strain gauge signals are typically in the microvolt range and can be easily overwhelmed by electrical noise in their wires. For example, strain gauge wires (*Figure 1*) placed near power lines can easily pick up electrically induced signals.

Figure 1: The long cables of a strain measurement system with low level voltage signals are susceptible to electrical interference from nearby power sources.

By using a higher supply voltage, the strain signals in the wires are stronger, and any electro-magnetic noise will have less of an effect on the signal. Higher supply voltages help even when using differential rather than single ended gauges.

Generally speaking, a higher voltage is desirable if no additional issues, like thermal drift or bridge burnout, would be introduced.

Thermal Errors

Thermal drift is an error in the strain measurement. It caused by self-generated heat in the strain gauge or measurement system. This heat causes an apparent change in strain that is not actually due to the deformation of the test object.

The higher the voltage supplied to a gauge, the more heat generated by the current running through the wires. This is similar to how the heating elements inside a toaster work. Ideally, the heat should be dissipated more quickly than it builds up to avoid thermal issues.

Heat can cause an erroneous strain gauge reading, by:

- Causing the strain gauge to expand and contract relative to the test object.
- Changing the resistance of the gauge due to the heat. A gauge normally measures strain using the change in resistance due to the deformation of the test object.
- Changing the gauge factor sensitivity for both AC and DC strains.

There are three main gauge properties that determine the thermal behavior of a strain gauge:

- Gage Resistance – The lower the gauge resistance, the more current/power ($P=V^2/R$) drawn for a given excitation. For example, a 120 Ohm gauge will have worse thermal performance than a 350 Ohm gauge, because it draws more power for a given voltage.

- Thermal Conductivity – The higher the thermal conductivity (λ) of the structure the gauge is mounted upon, the better heat dissipation. For example, a plastic structure dissipates heat more slowly than a steel structure.
- Power Density – The power density is the gauge power divided by the area (A) of gauge (the area is the looping wires of a gauge shown in *Figure 2*). The higher the power density of a strain gauge, the worse the thermal performance.

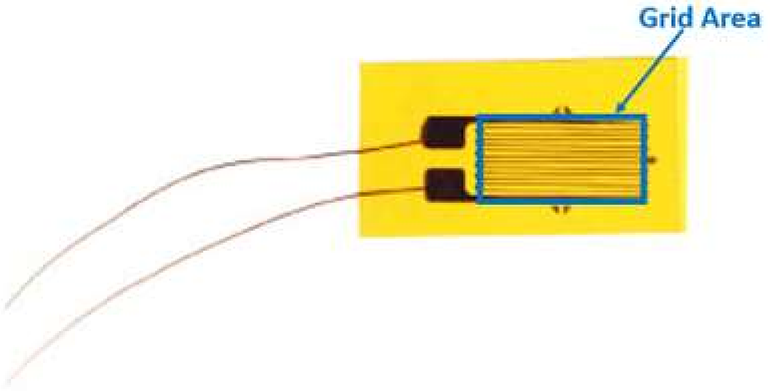


Figure 2: The area (sometimes called the "grid") of the gauge highlighted above.

These properties can be used to determine the maximum supply voltage whose heat would be dissipated when applied to the gauge. If the supply voltage is significantly higher than can be dissipated, there is a danger that the gauge will overheat and burn up.

Maximum Supply Voltage Calculation

Using the "RATY" equation (we made this name up), the maximum supply voltage can be determined from *Equation 1*.

$$\boxed{V_{max} = \sqrt{R \cdot A \cdot T \cdot \lambda}}$$

Equation 1: Maximum supply voltage for lowest thermal error.

Terms:

- Vmax = Maximum supply voltage permissible for minimal thermal error.
- R = Gauge resistance, typically 120 ohm, 350 ohm, or 1000 ohm.
- A = Area of gauge grid, where resistance wires are looped back and forth. See *Figure 2*.
- T = Temperature gradient, change in temperature per unit distance, of the area around strain gauge. Example of a typical value is 0.75°C/mm or 0.75°K/mm (remember 1 degree Celsius = 1 degree Kelvin, but offset by 273.15 degrees).
- λ = Thermal conductivity of part being tested, expressed in units of W/m*K. Steels have high thermal conductivity (50 W/m*K) while plastics have low thermal conductivity (0.05 W/m*K).

Using these terms, some example calculations for different gauge configurations are shown in *Figure 3*.

Gauge Resistance	Gauge Grid Area	Mounting Surface Thermal Conductivity	Temperature Gradient	Supply Voltage
350 ohm	4 mm x 6 mm 24 mm^2	Steel 0.05 W/mm*K	0.75 K/mm	17.7 Volts
120 ohm	4 mm x 6 mm 24 mm^2	Steel 0.05 W/mm*K	0.75 K/mm	10.3 Volts
120 ohm	3 mm x 3 mm 9 mm^2	Steel 0.05 W/mm*K	0.75 K/mm	6.3 Volts
350 ohm	4 mm x 6 mm 24 mm^2	Plastic 0.00005 W/mm*K	0.75 K/mm	0.56 Volts
120 ohm	4 mm x 6 mm 24 mm^2	Plastic 0.00005 W/mm*K	0.75 K/mm	0.32 Volts
120 ohm	3 mm x 3 mm 9 mm^2	Plastic 0.00005 W/mm*K	0.75 K/mm	0.20 Volts

Figure 3: Example maximum permissible voltage for varying gauge configurations.

Strain gauge manufacturers (Vishay, Omega, etc.) typically provide excellent guides that include these values, as well as similar equations for determining the maximum supply voltage. Note that imperfections in the gauge, mistakes in installation, and other factors can make this equation invalid.

Gauge Design Considerations

Based on the terms in *Equation 1*, the following can be considered when selecting a gauge and installing it:

- Gauge Area – Use a gauge with a higher grid area to reduce thermal effects on the strain data. A larger grid area dissipates heat faster (*Figure 4*).

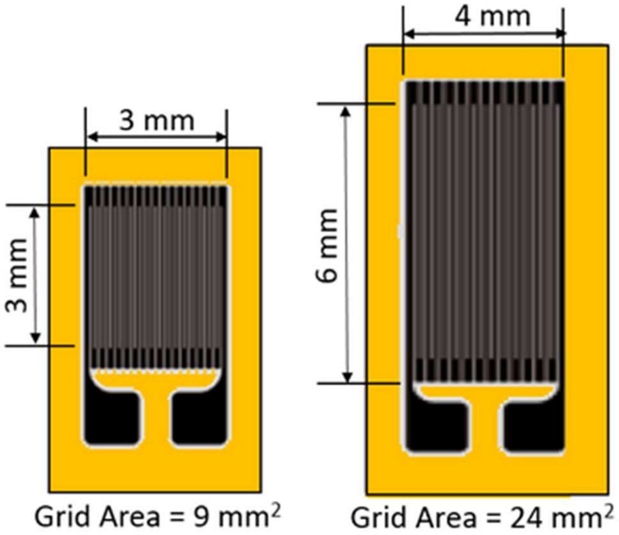


Figure 4: A larger grid area dissipates heat faster.

- Gauge Resistance – Use higher resistance gauges (like 350 Ohm rather than 120 Ohm) to reduce thermal effects on the strain data. Usually 350 Ohm gauges are physically larger than 120 Ohm.
- Rosette Gauges – Stacked rosette strain gauges, which take up less area by stacking three gauges on top of each other, create more heat than traditional rosette gauges (*Figure 5*). Do not use a stacked rosette gauge if it is not needed.

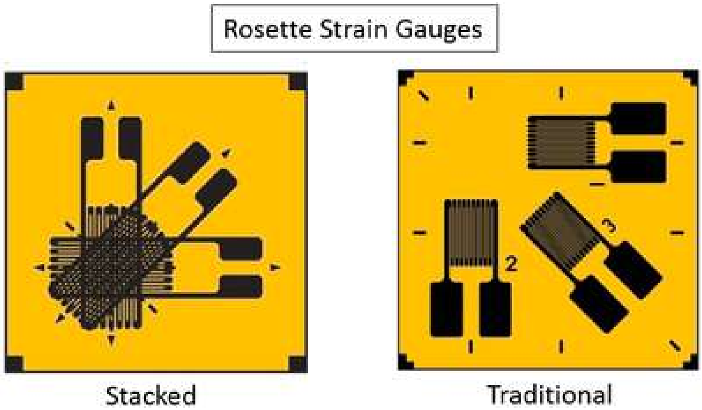


Figure 5: Traditional versus stacked rosette strain gauge configurations.

- Test Structure – Ideally, gauges would be mounted on test objects in areas with high thermal conductivity, like metals rather than plastics. For example, if mounting gauges on plastics, use the lowest possible voltage excitation, for example one volt or less.

Stabilization

If the environmental temperature is not constantly changing, the main thermal effects are seen immediately after the voltage excitation is applied. If the gauge and measurement system can be allowed to stabilize for a long period of time, the thermal effects on the strain measurement are minimized (*Figure 6*).

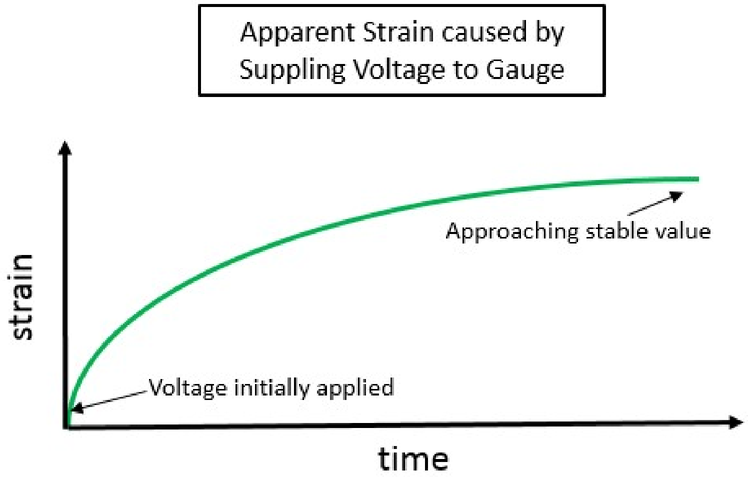


Figure 6: After applying a voltage to the gauge, the thermally induced strain will stabilize, assuming the temperature of the test environment is not changing.

The less thermal load, the quicker the gauge will stabilize - so it is always best to select gauges with better thermal properties (higher resistance, greater grid area, etc.) when possible.

After the voltage is supplied to the gauge, apparent strain (strain not due to deformation of the test object) is created. The apparent strain will stabilize after some time. After it is stabilized, the gauge can be zeroed, and measurements taken with minimal thermal errors.

This stabilization phenomenon can also be used to determine the proper supply voltage without using the equation. Slowly increase the supply voltage and monitor the apparent strain. If the strain is unstable, then the voltage is too high. The voltage supply can then be reduced until the apparent strain is stable. This way, any imperfections in the actual gauge, which are not reflected in Equation 1, are considered.

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Simcenter Testlab Time Signal Calculator

- Simcenter Testlab: Time Signal Calculator Tips

- Simcenter Testlab: Calculating Statistics from Time Histories
- Simcenter Testlab: Appending Time Histories
- Simcenter Testlab: Create a new recording from a segment cut
- Simcenter Testlab: Applying an arbitrary filter shape to a time history
- Simcenter Testlab: Integrating a Time History and Avoiding Offsets
- Analyzing PWM Signals with Time Signal Calculator
- Introduction to Filters: FIR vs IIR
- Applying a Custom Filter Shape: FILTER_FRF command
- Filter an Order and Listen to It
- Generate Custom Signals in Time Signal Calculator
- Removing Spikes from RPM Signals
- Harmonic Removal
- Rosette Strain Gauges

Simcenter Testlab Processing Tips

- Simcenter Testlab Throughput Processing Tips
- RPM Extraction in Simcenter Testlab
- Run Comparison in Simcenter Testlab
- Order Sections: Setting Parameters
- Time Signal Calculator Tips
- Simcenter Testlab: Calculating Statistics from Time Histories
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- Simcenter Testlab: Create a new recording from a segment cut
- Simcenter Testlab Sound Diagnosis
- Can I view data in Google Earth?
- Analyzing PWM Signals in Simcenter Testlab

Simcenter Tecware

- Running Simcenter Tecware with Simcenter Testlab tokens
- Simcenter Tecware: Open Time Files fast!
- Simcenter Tecware: Overlay multiple signals in X and Y display
- Simcenter Tecware: Access to different file formats
- Simcenter Tecware: Spike Filter
- Simcenter Tecware: Removing Multiple Segments
- Simcenter Tecware: Calculate Infinite Life with the Goodman Diagram
- Calculating damage with Simcenter Tecware Processbuilder
- Butterworth filter "regular" and "zero phase"