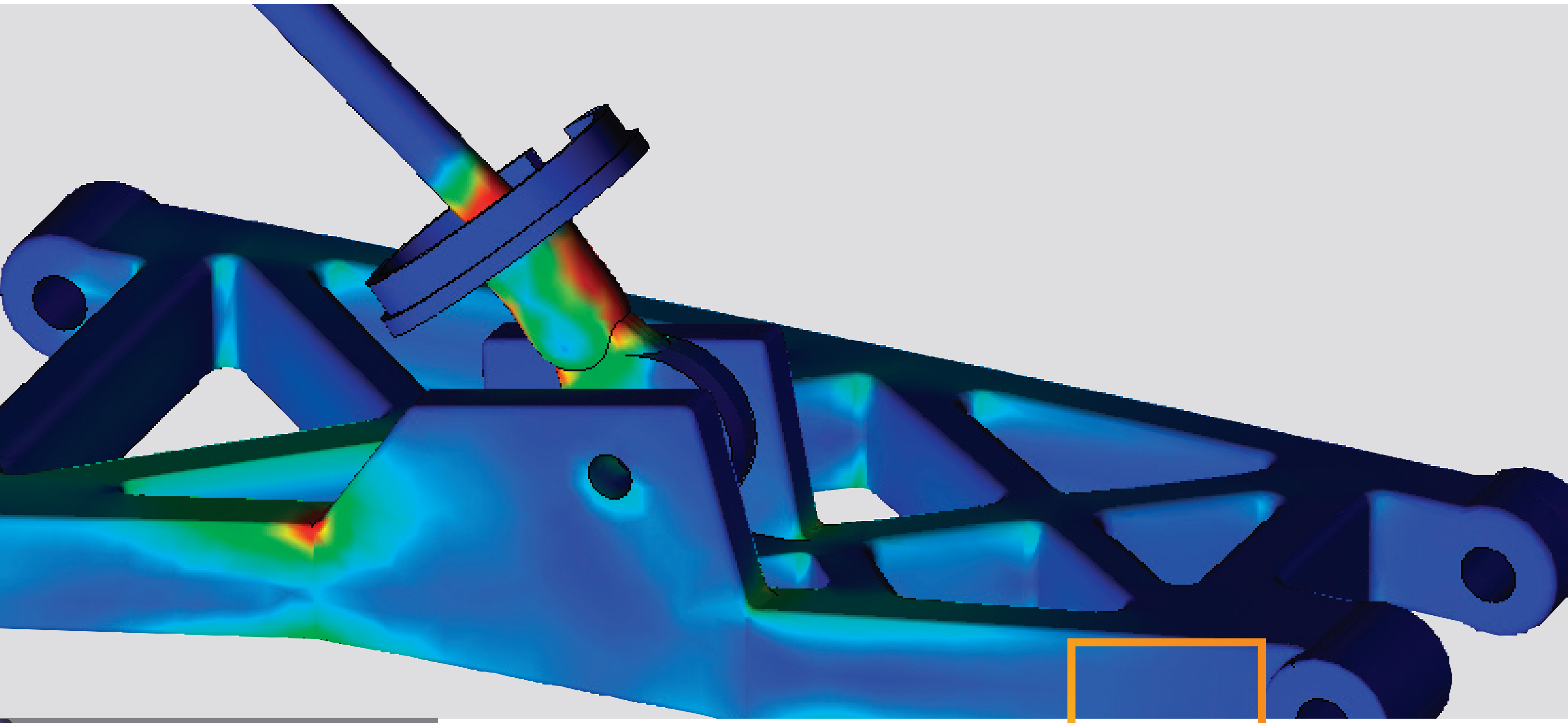
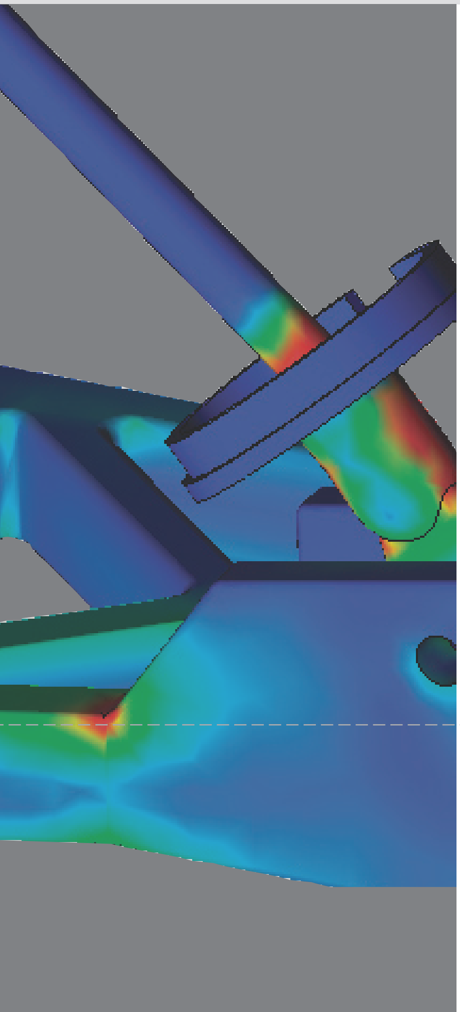
Design to Prevent Fatigue





real inspiration

SUMMARY

In 1954, two crashes involving the world's first commercial airliner, the de Havilland *Comet*, brought the words "metal fatigue" to newspaper headlines and into long-lasting public consciousness. The aircraft, also one of the first to have a pressurized cabin, had square windows. Pressurization combined with repeated flight loads caused cracks to form in the corners of the windows, and those cracks widened over time until the cabins fell apart. As well as being a human tragedy in which 68 people died, the *Comet* disasters were a wake-up call to engineers trying to create safe, strong designs.

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Since then, fatigue has been found at the root of failure of many mechanical components such as turbines and other rotating equipment operating under intense, repeated cyclical loads.

The primary tool for both understanding and being able to predict and avoid fatigue has proven to be finite element analysis (FEA).

What is fatigue?

Designers normally consider the most important safety consideration to be the overall strength of the component, assembly, or product. To design for this, engineers want to create a design that will stand up to the probable ultimate load, and add a safety factor to that, for insurance.

In operation, however, the design is very unlikely to experience static loads. Much more frequently, it will experience cyclical variation, and undergo multiple applications of such load variation, which may lead to failure over time.

The definition of fatigue, in fact, is: failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application. The symptoms of fatigue are cracks that result from plastic deformation in localized areas. Such deformation usually results from stress concentration sites on the surface of a component, or a pre-existing, virtually undetectable, defect on or just below the surface. While it may be difficult or even impossible to model such defects in FEA, variability in materials is a constant, and small defects are very likely to exist. FEA can predict stress concentration areas, and can help design engineers predict how long their designs are likely to last before experiencing the onset of fatigue.

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The mechanism of fatigue can be broken down into three interrelated processes:

1. Crack initiation
2. Crack propagation
3. Fracture

FEA stress analysis can predict crack initiation. A number of other technologies, including dynamic nonlinear finite element analysis, can study the strain issues involved in propagation. Because design engineers principally want to prevent fatigue cracks from ever starting, this paper primarily addresses fatigue from that viewpoint. For a discussion of fatigue crack growth, please refer to Appendix A.

Determining the fatigue strength of materials

Two principal factors govern the amount of time it takes for a crack to start and grow sufficiently to cause component failure: the component material and stress field. Methods for determining fatigue testing of materials go back to August Wöhler who, in the 19th century, set up and conducted the first systematic fatigue investigation. Standard laboratory tests apply cyclical loads such as rotating bend, cantilever bend, axial push-pull, and torsion cycles. Scientists and engineers plot the data resulting from such tests to show the relationship of each type of stress to the number of cycles of repetition leading to failure—or S-N curve. Engineers can derive the stress level a material can endure for a specific number of cycles from the S-N curve.

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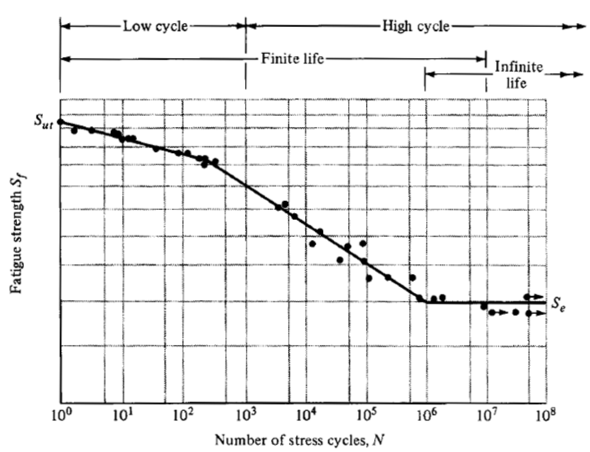
The curve splits into low and high cycle fatigue. Generally, low cycle fatigue occurs at fewer than 10,000 cycles. The shape of the curve depends on the type of material tested. Some materials, such as low-carbon steels, show a flattening off at a particular stress level—referred to as the endurance or fatigue limit. Materials that contain no iron show no endurance limit. In principle, components designed so that the applied stresses do not exceed the known endurance limit shouldn't fail in service. However, endurance limit calculations don't account for localized stress concentrations that may lead to initiation of cracks, despite the stress level appearing to be below the normal "safe" limit.



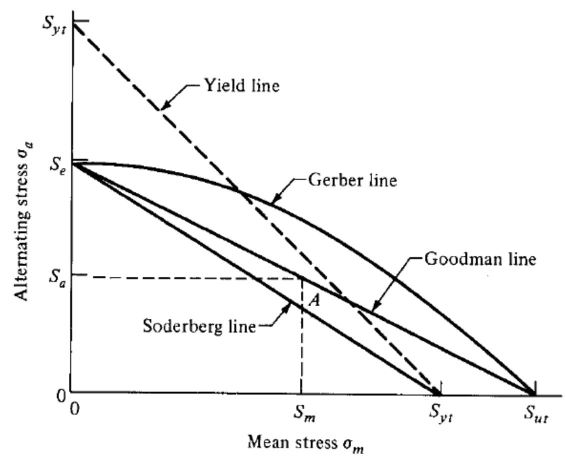
SAMPLE S-N (STRESS VS. CYCLES) CURVE

Fatigue load history, as determined by testing with rotating bend tests, provides information about mean and alternating stress. The rate of crack propagation in tests has been shown to be related to the stress ratio of the load cycle, and the load's mean stress. Cracks only propagate under tensile loads. For that reason, if the load cycle induces compressive stress in the area of the crack, it will not produce more damage. However, if the mean stress shows that the complete stress cycle is tensile, the whole cycle will cause damage.

Many service load histories will have a non-zero mean stress. Three mean stress correction methods have been developed to eliminate the burden of having to carry out fatigue tests at different mean stresses:

Companies want and need to reduce weight and material use, and yet still to avoid failures due to fatigue, which even if not fatal, can be very expensive. All of these factors have served to make performing fatigue engineering studies much more important earlier in the design process.

Goodman method	- generally suitable for brittle materials
Gerber method	- generally suitable for ductile materials
Soderberg method	- generally the most conservative



MEAN CORRECTION METHODS

All three of these methods apply only when all associated S-N curves are based on fully reversed loading. Moreover, these corrections only become significant if the applied fatigue load cycles have large mean stresses compared to the stress range. The diagram above shows the relationship between the alternating stress, material stress limits, and the loading mean stress, and is called a Goodman diagram.

Experimental data has shown that the failure criterion falls between the Goodman and Gerber curves. Thus, a pragmatic approach would calculate the failure based upon both and use the most conservative answer.

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Methods for calculating fatigue life

Physical testing is clearly impractical for every design. In most applications, fatigue-safe life design requires prediction of component fatigue life that accounts for predicted service loads and materials.

Computer-aided engineering (CAE) programs use three major methods to determine the total fatigue life. These are:

- **Stress life (SN)**

This is based on stress levels only, and uses the Wöhler method only. Although unsuitable for components with areas of plasticity, and providing poor accuracy for low cycle fatigue, it is the easiest to implement, has ample supporting data, and offers a good representation of high cycle fatigue.

- **Strain life (EN)**

This approach provides more detailed analysis of plastic deformation at localized regions, and is good for low cycle fatigue applications. However, some uncertainties in the results exist.

- **Linear Elastic Fracture Mechanics (LEFM)**

This method assumes that a crack is already present and detected, and predicts crack growth with respect to stress intensity. This can be practical when applied to large structures in conjunction with computer codes and periodic inspection.

Because of its ease of implementation and the large amounts of material data available, the most commonly used method is SN.

Fatigue life calculation for designers using SN method

Constant and variable amplitude loading may be considered in calculating fatigue life. The following offers a brief description of the differing results.

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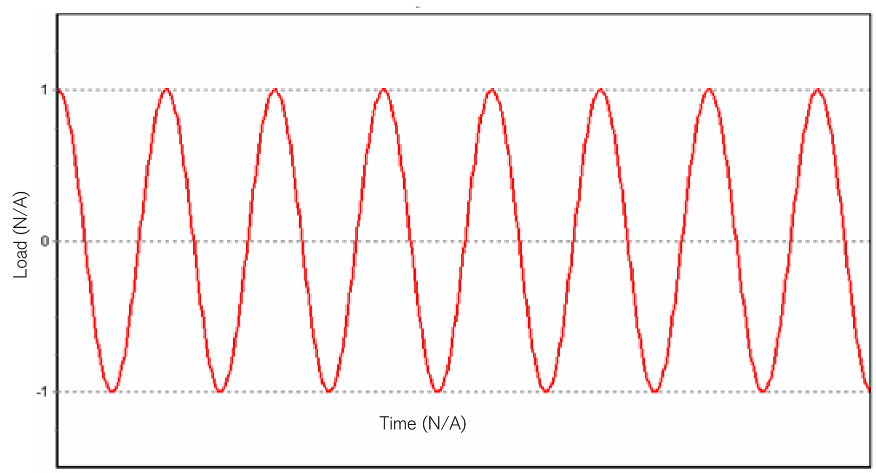
Constant amplitude loading:

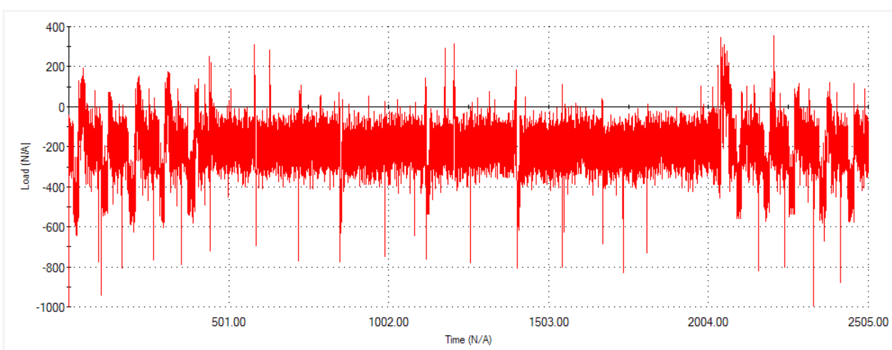


CONSTANT AMPLITUDE LOADING

This method considers a component subjected to a constant amplitude, constant mean stress load cycle. By using an SN curve, designers can calculate the number of such cycles leading to component failure quickly.

However, in cases where the component is subjected to more than one load, Miner's Rule provides a way to calculate the damage of each load case and combine all of them to obtain a total damage value. The result, or "Damage Factor," is expressed as a fraction of the failure. Component failure occurs when D = 1.0, so, if D = 0.35 then 35 percent of the component's life has been consumed. This theory also assumes that the damage caused by a stress cycle is independent of where it occurs in the load history, and that the rate of damage accumulation is independent of the stress level.

Variable amplitude load:



VARIABLE AMPLITUDE LOADING

Most components undergo a varying load history in real life conditions, in terms of both amplitude and mean stress. Therefore, a far more general and realistic approach considers variable amplitude loading, in which the stresses, although repetitive over time, have varying amplitude, making it possible to split them into load “blocks.” To solve this type of loading, engineers use a technique called “rainflow counting.” Appendix B, which discusses how to study FEA fatigue results, offers more information on rainflow counting.

FEA provides excellent tools for studying fatigue with the SN approach, because the input consists of a linear elastic stress field, and FEA enables consideration of the possible interactions of multiple load cases. If set to calculate the worst case load environment, a typical approach, the system can provide a number of different fatigue computation results, including life plots, damage plots, and factor of safety plots. In addition, FEA can provide plots of the ratio of the smaller alternating principal stress divided by the larger alternating principal stress, called a biaxiality indicator plot, as well as a Rainflow Matrix chart. The latter is a 3D histogram in which the X and Y axes represent the alternating and mean stresses, and the Z axis represents the number of cycles counted for each bin.

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Conclusion

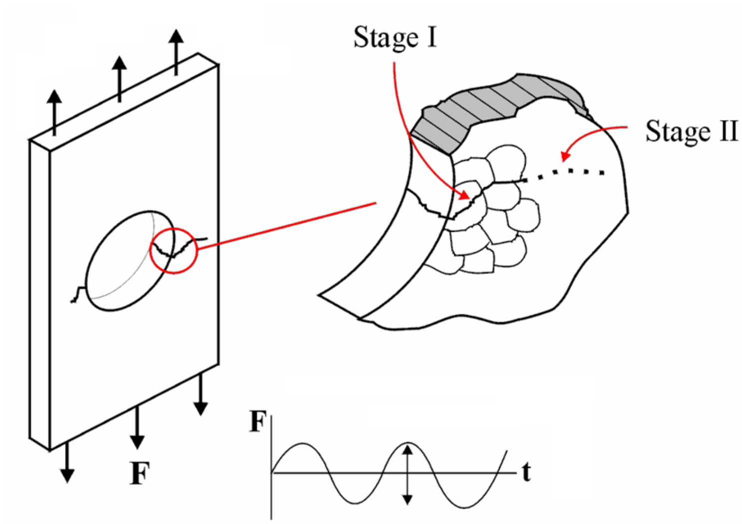
The tools and approaches discussed in this review can help designers improve component safety while reducing overengineered, heavy, and costly designs. By making use of today’s technology to avoid fatigue, catastrophes can often be averted. And on a day-to-day basis, fatigue-safe design reduces service failures and gives designers greater opportunities to design new products instead of fixing old problems.

Appendix A – Crack Growth

Two physical mechanisms drive the process of fatigue crack growth. Under a cycling load, slip planes in the microstructure of the material grain move back and forth, causing micro extrusions and intrusions on the surface of the component. These are far too small to see—measuring between one and 10 microns in height—but can be considered to be embryonic cracks (Stage I).

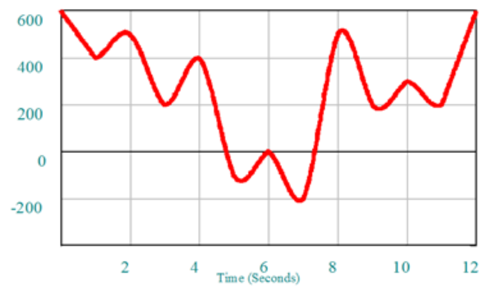
When the Stage I crack reaches the grain boundary, the mechanism transfers to the adjacent grain. Stage I cracks grow in the direction of the maximum shear, 45 degrees to the direction of loading.

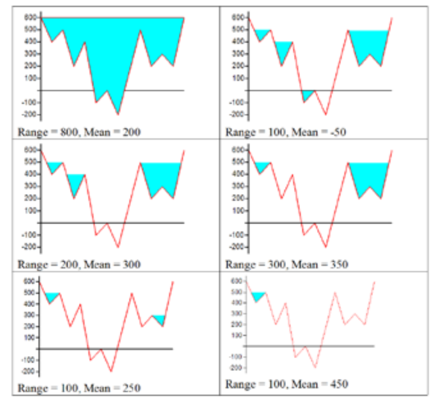
At approximately three grains in size, the crack behavior changes, because the crack has become large enough to form a geometrical stress concentration (Stage II). Stage II cracks create a tensile plastic zone at the tip, and after this point, the crack grows perpendicular to the direction of the applied load.



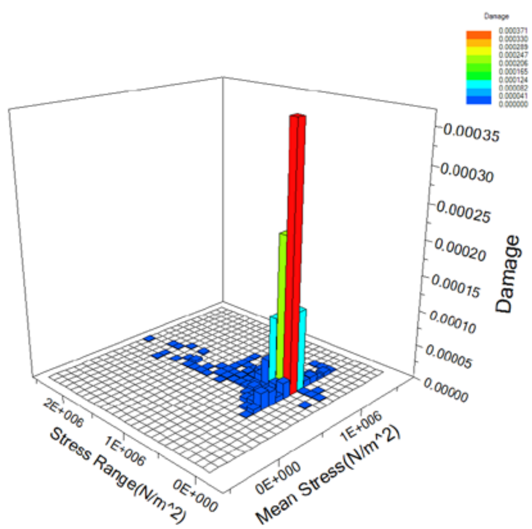
Appendix B - Rainflow Counting

Taking a graphic depiction of the varying amplitude loads and extracting the peaks and valleys of the load history, it becomes possible to determine the stress range and its associated mean stress. The graph shows a load history that's "filled with rain" initially.

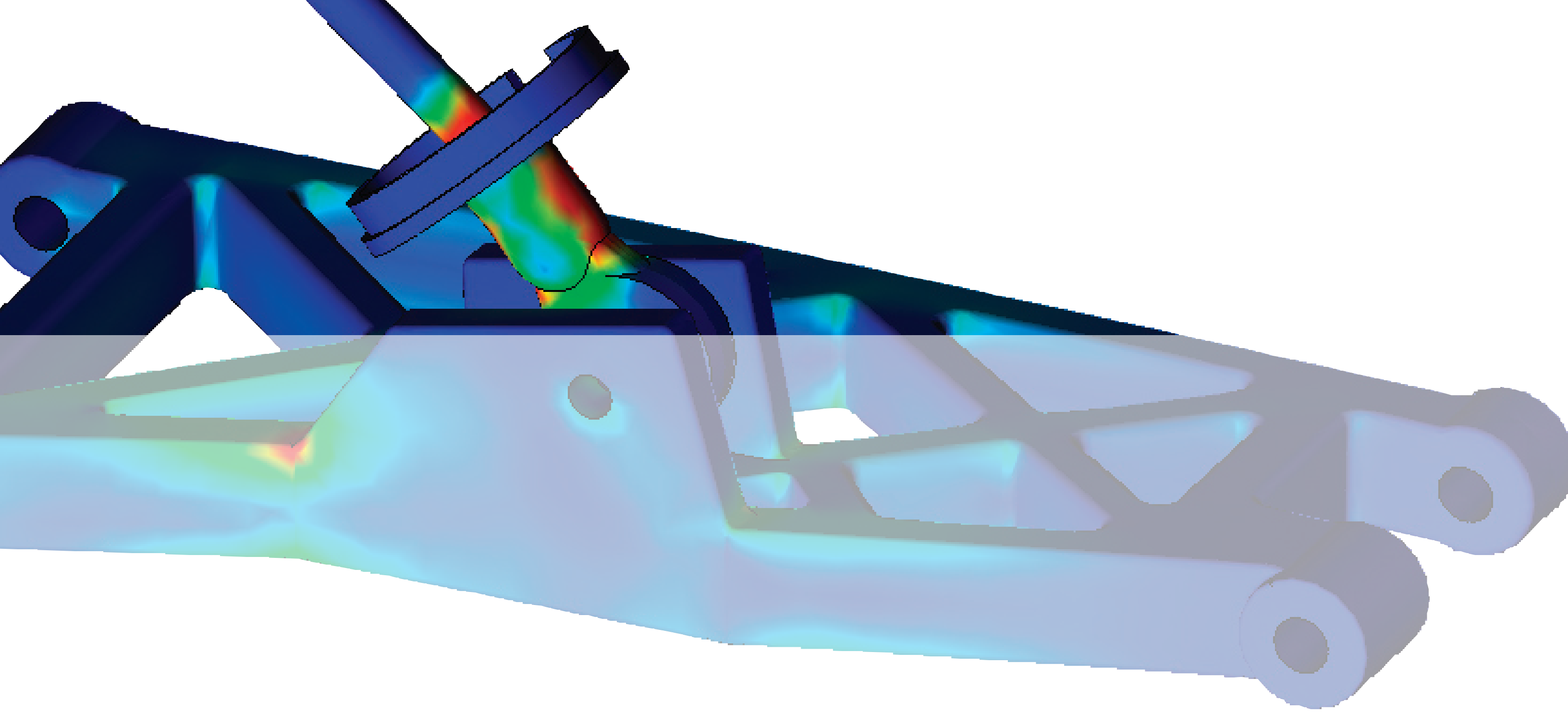




The stress range and its associated mean stress are determined from the load history shown in the graph. The load history is "filled with rain" in the graphed load history. After the stress range and mean have been determined, the "rain" is drained from the lowest point. The range and mean for each remaining portion of trapped "rain" is then determined. From the results, Miner's Rule can be applied, and the fatigue life calculated.



Rainflow damage matrix



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