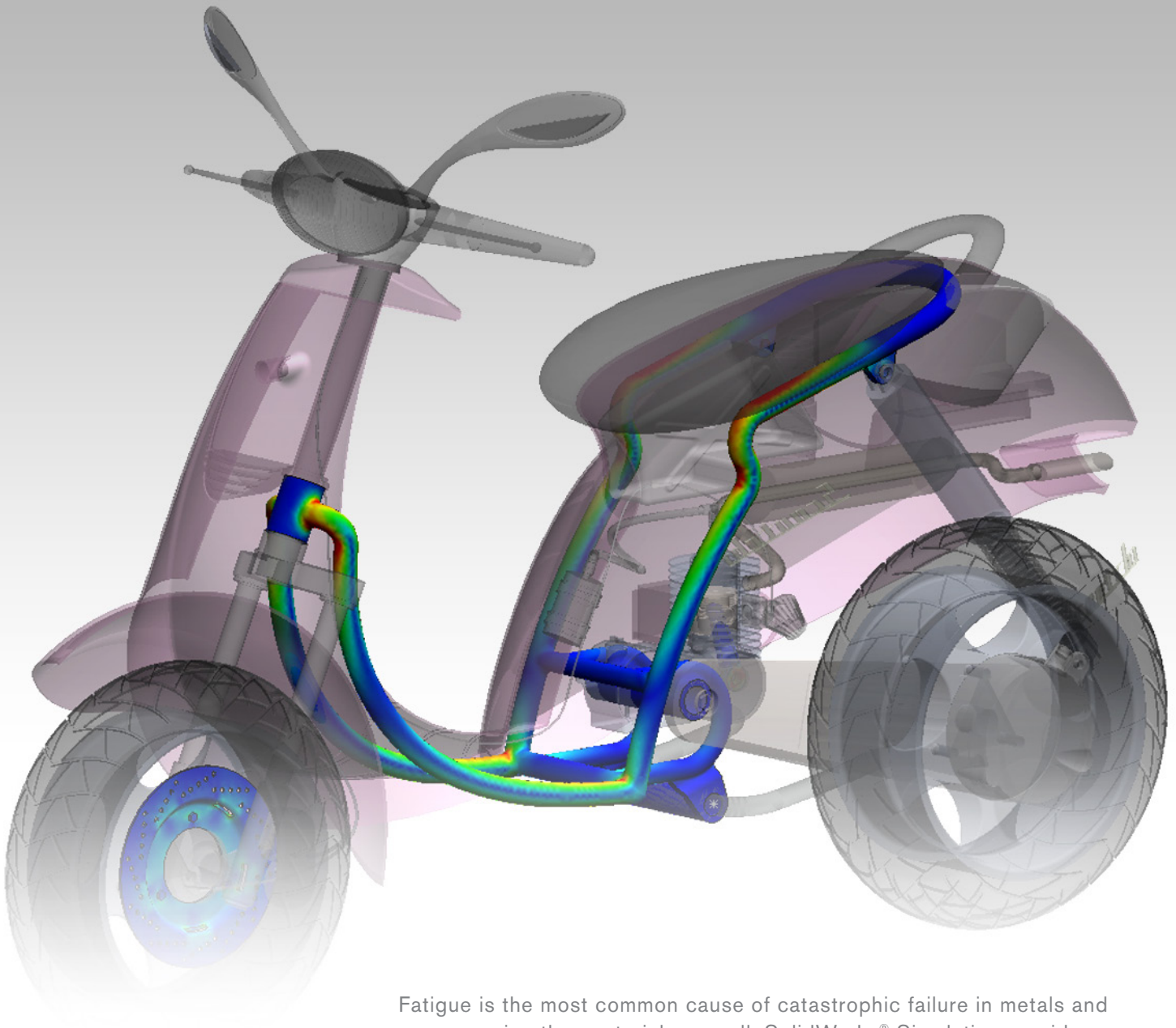


Preventing Mechanical Fatigue



Fatigue is the most common cause of catastrophic failure in metals and can occur in other materials as well. SolidWorks® Simulation provides a fast, reliable, and cost-effective way to predict and resolve fatigue-related problems before they happen.

Introduction

In 1954, two crashes involving the world's first commercial jet 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 apart¹. 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.

The importance of analyzing fatigue continues to grow, as companies strive to be more efficient. Saving material saves money, after all. Reducing the thickness of a water bottle the slightest amount can mean *huge* material savings through mass production. But preventing mechanical fatigue is even more vital.

Fortunately, a tool to address this complex issue – and address it *quickly* – is available. SolidWorks Simulation provides a fast, reliable, and cost-effective way for engineers to predict and resolve problems with fatigue.

What is Fatigue?

Designers consider the most important safety consideration to be the overall strength of the component, assembly, or product. To accommodate for this, you must create a design that will stand up to the probable ultimate load, and add a safety factor for insurance. In operation, however, the design is less likely to experience a constant load. More likely, that the design will experience load variations and even undergo multiple applications of these load variations, which may lead to failure over time.

Fatigue is defined as "failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application." It is the most common cause of failure among metals, and often occurs in other materials as well². Fatigue happens in three stages:

1. crack initiation
2. crack propagation
3. final fracture

This paper focuses on predicting the total fatigue life of a component and on preventing cracks in the first place. Therefore, the last two stages are beyond the scope of this discussion³.

The first stage of fatigue is cracks resulting from plastic stresses in localized areas. Such stresses are usually caused by stress concentration sites on the surface of a component or by a pre-existing defect on or just below the surface.

While it may be difficult or even impossible to model such defects in CAD, the variability in materials is much easier to account for. SolidWorks Simulation not only can predict stress concentration areas, but also can help design engineers predict how long their designs are likely to last before experiencing the onset of fatigue.

A SCUBA tank is one example of a device that is prone to fatigue failure without proper design. Divers do not often go to depths where overloading the metal tank becomes a problem. Yet, a tank will experience many stress cycles throughout its lifetime, most of all when adding pressurized oxygen⁴. In subsequent discussions, this paper refers to the SCUBA tank in Figure 1 below.

¹ Atkinson, R. J.; Winkworth, W. J.; and Norris, G. M. (1960). Behaviour of skin fatigue cracks at the corners of windows in a comet fuselage.

² Callister, W. D. (2007). *Materials science and engineering: An introduction*. John Wiley & Sons.

³ Adams, V. Fatigue analysis in product Design—An Overview of Technologies and Techniques.

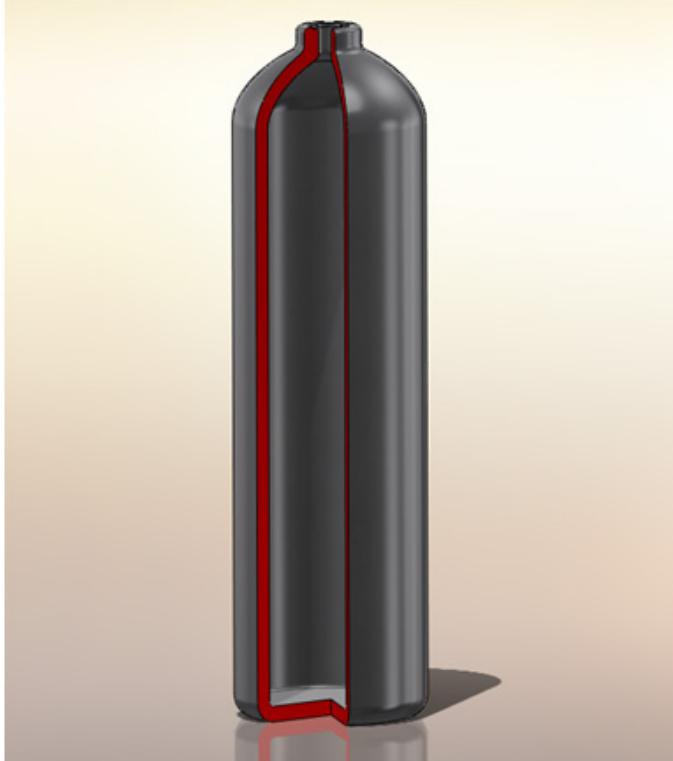


FIGURE 1. THE SCUBA TANK USED FOR A FATIGUE STUDY.

Fatigue 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 1 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. This is due to the crack becoming large enough to form a geometrical stress concentration (Stage II). Stage II cracks create a tensile plastic zone at the tip; after this point, the crack grows perpendicular to the direction of the applied load.

When considering component stress levels for fatigue, initiation, and propagation, the von Mises stress levels may be good for crack initiation prediction, but the maximum principle stress will propagate the crack.

The advancing crack effectively reduces the component's local cross-sectional area so that the component ruptures. When examining failed components, one sees that fatigue fractures have a characteristic appearance that reflects the initiation site and the progressive development of the crack front, culminating in an area of final overload fracture.

⁴ Barsky, S. M.; and Neuman, T. (2003). *Investigating Recreational and Commercial Diving Accidents*. Hammerhead Press.

How to Analyze Fatigue

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 the stress field. The three main ways to calculate fatigue life are: Stress Life (SN), Strain Life (EN), and Linear Elastic Fracture Mechanics (LEFM).

1. SN Method: The Stress Life approach predicts the component's fatigue life based upon a standard material test for failure. It gives results based upon the whole fatigue life and as such does not break down the process into the three stages. The Stress Life Approach is based upon the calculation of varying elastic stresses, which means it cannot be applied to low cycle fatigue (failures with 10,000 load cycles). However, this approach is very accurate for high cycle fatigue, which is the realm of most industrial applications. Considerable material data has been published for materials tested using this method.
2. EN Method: The Strain Life technique can calculate plastic stresses and can be used for both crack prediction and total life calculations. This approach can be used for both low cycle fatigue and for studying fatigue in plastics. However, there is much less available data for materials based on this method.
3. LEFM Method: Linear Elastic Fracture Mechanics is used to calculate crack growth rates. This approach assumes that a crack is already present and predicts crack growth with respect to the stress intensity at the crack tip.

SolidWorks Simulation aims to help people make designs that will not fatigue in the first place. For these cases – where stresses are low (elastic) and may repeat for hundreds of thousands of cycles or more – the Stress Life and the Strain Life approaches are both very accurate. With this specific goal, though, the added accuracy of the EN method in low cycle fatigue is a moot point. SolidWorks Simulation focuses *solely* on the likelihood of high cycle fatigue.

One major advantage of the SN method over the EN approach is data availability. Far more material experiments have been conducted with Stress Life than with Strain Life. For this reason, SolidWorks Simulation relies on the SN approach instead of the EN method.

In fact, the primary input to the SN method – the S-N curve – was the first effective approach to tackling fatigue analysis. This graph was established by August Wöhler who, in the 19th century, set up and conducted the first systematic fatigue investigation. Standard laboratory tests applied cyclical loads, such as rotating bends, cantilever bends, axial push-pulls, and torsion. The data compared the number of load cycles to failure (N) to the stresses induced (S): hence the name “S-N curve.” Today, scientists and engineers produce S-N curves to show the relationship of each type of stress to the number of cycles of repetition leading to failure. From these curves, engineers can derive the stress level a material can endure for a specific number of cycles. A mock S-N curve for carbon steel is shown in Figure 2 below.

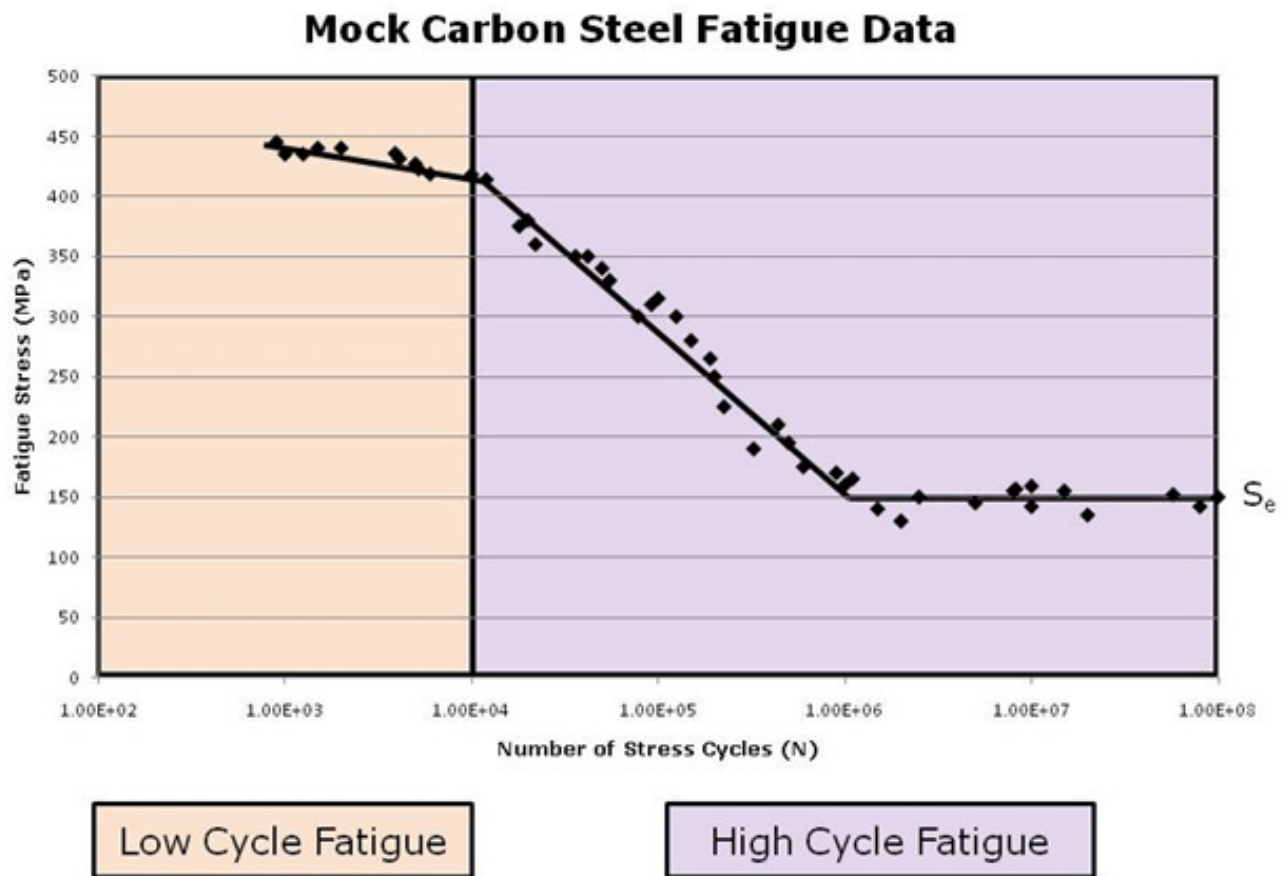


FIGURE 2. A SAMPLE S-N CURVE.

Any S-N curve can be broken down into a few important parameters and regions. First, is there an endurance limit? In other words, is there some stress level that will never cause the material to fail, regardless of the number of cycles? For steel, the answer is yes; but for many other materials, the answer is no. We see an endurance limit in Figure 2, which appears as a horizontal line starting at about 10^6 cycles, and is denoted S_e .

Another key feature is the distinction between high cycle and low cycle fatigue. High cycle fatigue begins when the gently sloping line toward the left of the graph suddenly dives. This, of course, is easier to define in some materials than in others, but 10,000 is generally regarded as a typical transition value. Designers and engineers have to prioritize between high cycle and low cycle fatigue for their subsequent analyses.

The S-N curve provides valuable information about a material's ability to endure various stresses. However, it fails to account for different load scenarios, as shown in Figure 3 below.

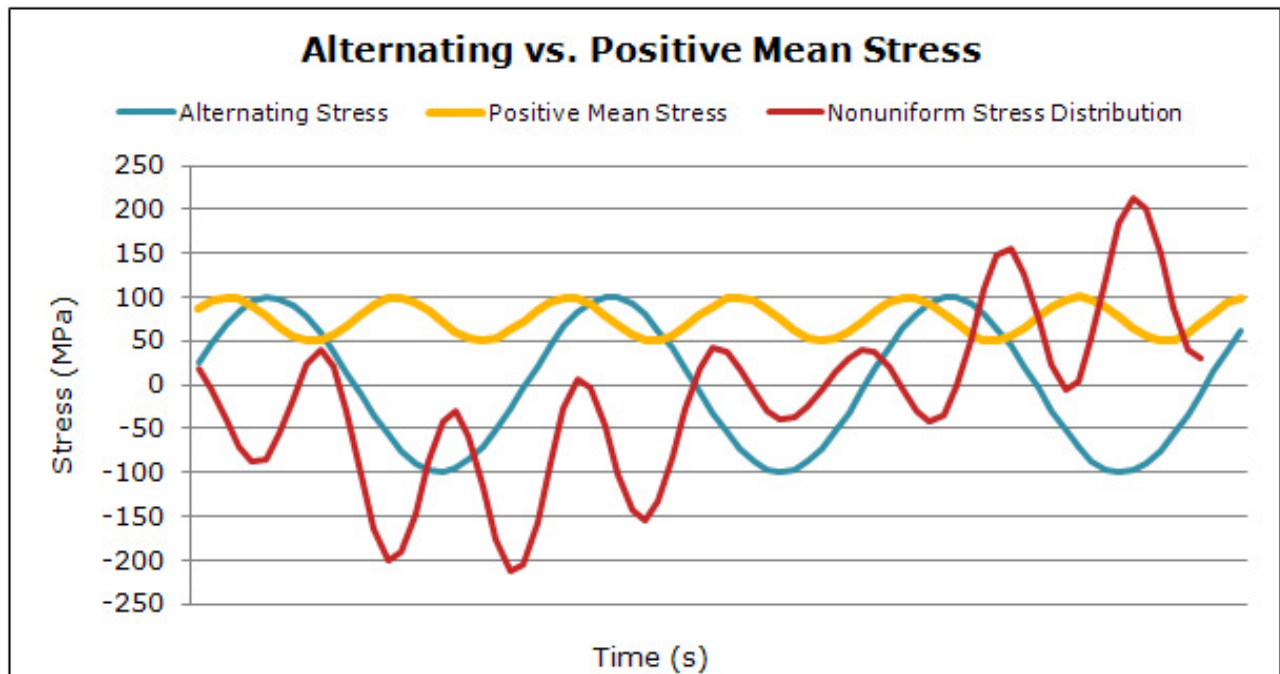


FIGURE 3. ALTERNATING, POSITIVE MEAN, AND NONUNIFORM STRESS DISTRIBUTIONS.

The blue curve in Figure 3 is classified as an alternating load scenario. The stresses cycle evenly between positive and negative values centered about zero stress. The S-N curve is developed assuming this type of loading sequence.

However, the other cases are also common. Many devices operate entirely in tension like the yellow curve. Others are nonuniform like the red curve – far from the alternating case. In these complicated loading scenarios, a crucial parameter is the mean stress. Studies have shown that a nonzero mean stress significantly affects fatigue life. After all, crack propagation only occurs under tensile loads. So, a device should crack more quickly if its entire cycle is in tension instead of having some compression. In short, the higher the mean stress, the more damage the device will usually experience. Fortunately, three popular methods of mean stress adjustment have been developed, as shown in Figure 4 below.

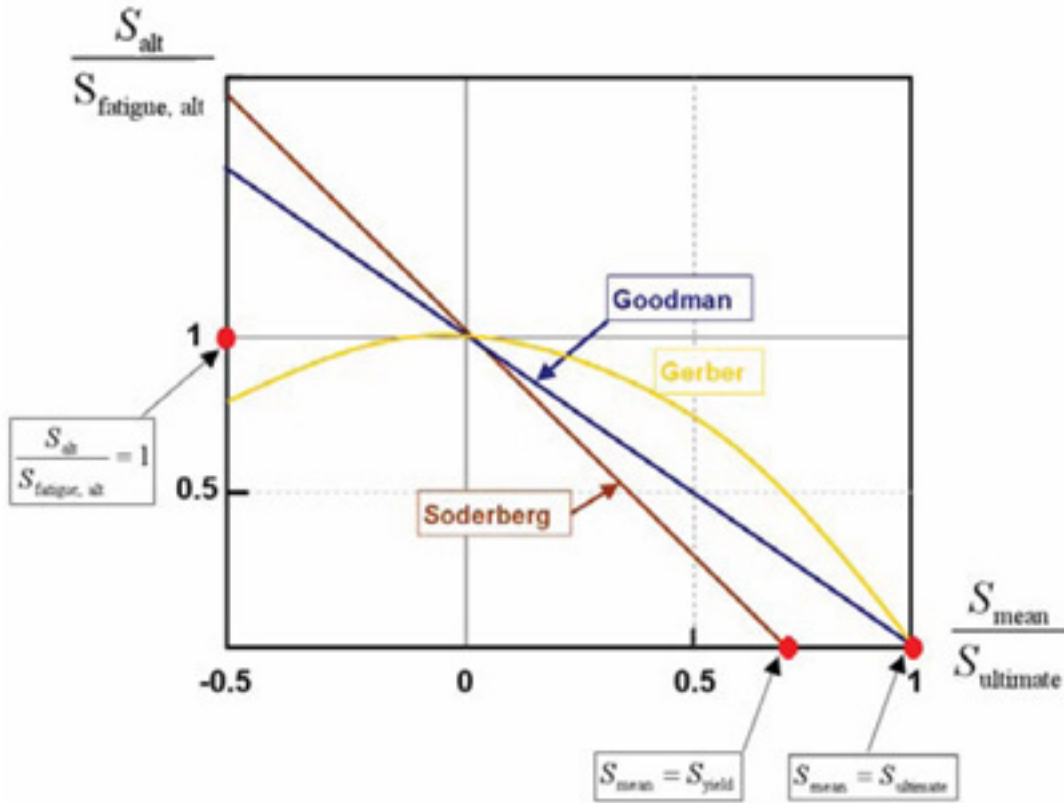


FIGURE 4. THE GERBER, GOODMAN, AND SODERBERG LINES FORM THE BASES OF CLASSIC MEAN CORRECTION TECHNIQUES.

The Gerber, Goodman, and Soderberg methods denote the predicted failure behavior according to the mean correction lines shown with the same names in Figure 4. The Gerber method uses a quadratic, non-conservative approach related to the endurance limit (S_e) and ultimate tensile strength (S_{ut}), which is generally applicable to ductile materials. The Goodman approach relies on a conservative, linear relationship between the same parameters. The Soderberg line is the most conservative of all relationships as it links S_e to the tensile yield strength (S_{yt}). The intersection of the alternating and mean stresses (S_a and S_m , respectively) can provide some sense of the likelihood of failure according to the different standard lines.

All three 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. Testing has shown that fatigue failure generally occurs somewhere in the region between the Goodman line and the Gerber line. Thus, to give some leeway in a design, it is most practical to use the more conservative of the two as the upper boundary.

Following a static analysis study, fatigue is often studied through two classic forms of analysis called Miner's rule and "rainflow counting." Miner's rule assumes that if an object can endure N cycles of S stress levels, then each cycle removes a fraction of the object's fatigue life that equals $1/N$. For example, if a steel bar fails after being subjected to 90,000 cycles at 200 MPa, each cycle took $1/90,000$ of its life. (This rule also allows multiple loads to be taken into account through a weighted average, which only requires slight modifications.) Miner's rule has two major limitations: it cannot take into account; the probability of fatigue initiation and it does not consider the *order* of stresses reached in any way. However, its results are generally consistent with testing, so the Miner's rule has become a standard form of analysis.

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.” Rainflow counting enters the picture in order to find the stresses and the *frequency* that those stresses occur on a part for Miner’s rule calculations. An example of rainflow counting is shown in Figure 5 below.

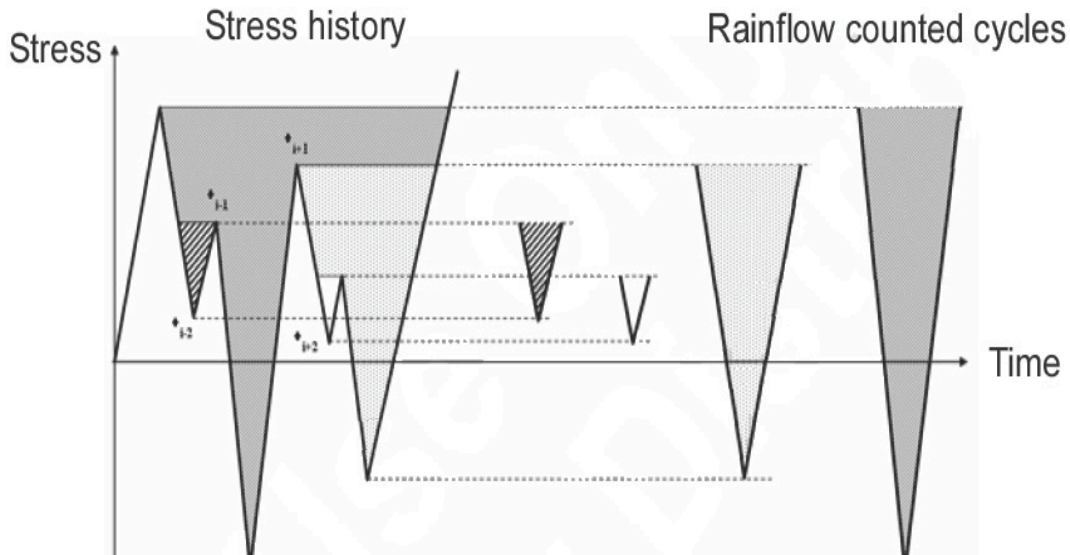


FIGURE 5. AN EXAMPLE OF RAINFLOW COUNTING. SOFTWARE STARTS WITH A FILLED REGION (LEFT) AND “DRAINS” THE GRAPH IN PIECES, LEAVING ONE SECTION BEHIND AFTER THE FIRST ITERATION (RIGHT).

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.” 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” are then determined. From the results, Miner’s rule can be applied, and the fatigue life can be calculated.

Imagine that this is a segment of an S-N curve that shows a combination of tensile stresses, with the zero line located at the bottom of the graph, as shown in Figure 5 above. Starting at the highest point on the left, the graph is “drained.” Imagine the jagged line as a roof turned sideways, and drain to the right – you should see it fall off as shown. The region on the right in Figure 5 remains after the first iteration. For this section, the range and mean are taken into account for Miner’s rule. The effects of each region can be combined via superimposition⁵.

Naturally, most objects do not always experience the same loads. The typical SCUBA tank, for example, may be loaded with different pressures at different times for different durations. Rainflow counting is a graphical way to average these mean stresses during a product’s life, and Miner’s rule can combine the effects of these stresses.

SolidWorks Simulation provides excellent tools for studying fatigue with the SN approach, because the input consists of a linear elastic stress field, and analysis allows you to consider 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, damage, and factor-of-safety plots. In addition, simulation 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.

⁴ Potter, J. M.; and Watanabe, R. T. (1989). *Development of fatigue loading spectra*. ASTM International.

Simple Loading Scenarios

Multiple factors are used to determine the safety of the SCUBA tank, the factor of safety at the operating pressure, the burst pressure and, the tank's life expectancy. The root of a fatigue analysis is a static study to calculate the elastic stress field due to an internal pressure. The first check a designer will make is to ensure that the stress factor (σ/σ_{max}) is greater than the required minimum. If the design passes the strength test, then the fatigue check plot will indicate the regions of the material in danger of fatigue failure.

The results of the operation pressure simulation are shown below. We can see that the factor of safety reports a minimum value of 1.5, which in many cases would be too low. This indicates that none of the material of the tank is above yield. In the fatigue check plot, we have specified a minimum fatigue factor of safety of 4. The red regions in Figure 6 below indicate the areas for which the stresses fall outside of the safety zone in Figure 4. The value of this plot is that it gives the analyst a place to start with more in-depth fatigue analysis. Rather than conducting an exhaustive study of the entire tank, focusing on these potential hot spots may be a more productive use of time and resources.

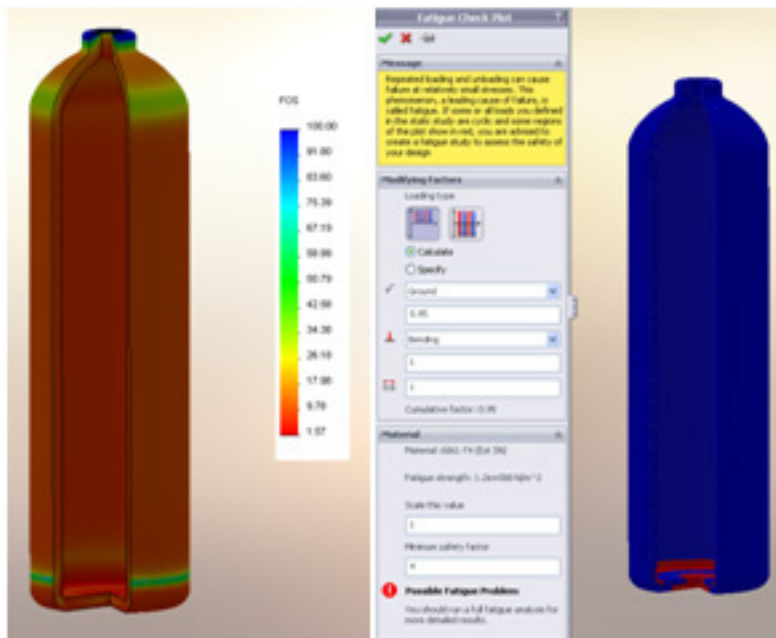


FIGURE 6. RESULTS OF THE SCUBA TANK PRESSURE SIMULATION. MATERIAL FACTOR OF SAFETY (LEFT) AND FATIGUE CHECK PLOTS (RIGHT).

The pressure test simulation indicates the need for a full fatigue analysis. A full fatigue analysis will provide not only a fatigue factor-of-safety plot, but also a damage and a total life plot. The damage plot shows how much of the fatigue life of the material has given up due to the applied load cycles. Once the damage percentage is greater than 100, we can assume that this portion of the material has a crack through it. The total life plot shows how many load cycles have to be applied to fully fatigue any portion of the material. In this case we can see that the SCUBA tank can be filled a maximum of 149,000 times before fatigue would be an issue. This value must be seen as an upper boundary, and the fatigue factor of safety would reduce this to well below 100,000.

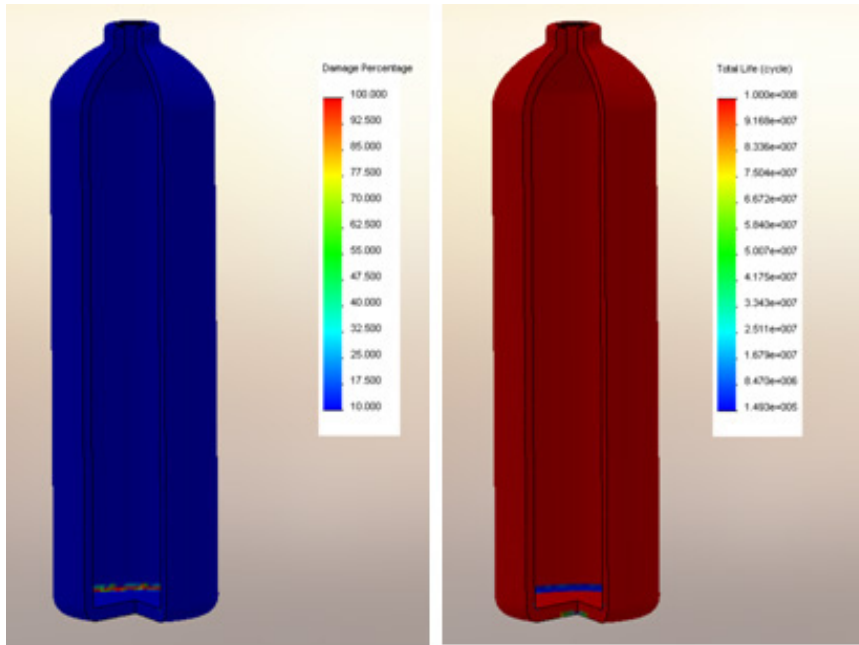


FIGURE 7. RESULTS OF THE SCUBA TANK PRESSURE SIMULATION. DAMAGE PERCENTAGE (LEFT) AND TOTAL LIFE PLOTS (RIGHT).

Advanced Loading Scenarios

Unfortunately, many real-life scenarios involve more complicated forces than those experienced by the SCUBA tank case study. A combination of different types of loads is important when analyzing the fatigue of many devices in operation. For example, loads can be classified as “dead loads” and “live loads.” A dead load is constant: if a defunct train is simply sitting on the tracks, that train’s weight exerts a dead load on the tracks. In contrast, a live load – like that exerted by a train passing over some length of track – changes with time.

SolidWorks Simulation provides the tools necessary to examine simultaneous loading, but sequential loading is still a “black box” to some degree. Two case studies – a funicular train and a wind turbine – demonstrate the roles of fatigue analysis in unique situations.

Funicular Train

You want to determine the likelihood of fatigue in the frame of a funicular. The car repeatedly follows a course where the loads on the frame from the wind, the turns in the track, and the passengers are known. This showcases study a set of loads that *can* be analyzed with SolidWorks Simulation.



FIGURE 8. A FUNICULAR ON A TRACK. THE COMBINED LOADS ACTING ON THE FRAME CAN BE COMBINED FOR FATIGUE ANALYSIS.

These loads occur simultaneously in real life. Passengers are standing within the funicular car's frame while the wind blows and the car turns along the rail. But the loads can be discretized: each force can be treated as a separate "event" within the simulation software. The loads at each node can then be summed, and that summation can be repeated over time. By knowing the stresses on the funicular's frame and the number of cycles at which each stress level occurs, the software uses Miner's rule to estimate the structure's life. SolidWorks Simulation works very effectively with these combined, simultaneous loading scenarios—and can save valuable time compared with hand calculations or mechanical testing.

Wind Turbine

Imagine a designer who would like to analyze the likelihood of fatigue for his wind turbine design. He has recorded ten-minute samples of the loads experienced by the structure in startup, stopping, and standard operating mode. He wants to see if the structure can withstand 10,000 starts and stops over 20 years of working conditions. This scenario is one that *cannot* be analyzed through SolidWorks Simulation.

The first issue is the time span. No matter how many minutes or even hours of stresses he recorded, it would be difficult to generalize those results over *years* of operation, assuming constant wind is sufficient for a funicular, for which the wind is a minor factor. But that is one of the major stresses on a wind turbine. Random changes in wind patterns are crucial, and constant amplitude is not an adequate approximation. The wind blows at hurricane strength one day and stays idle the next – and in no orderly pattern.

With respect to the software, this is a fundamentally different case that cannot be analyzed effectively. SolidWorks Simulation defines “events” that can be instantaneously combined, as described with the funicular. But different events that are ordered *sequentially* cannot be grouped together. Again, one of the limitations of Miner’s rule is that it neglects the effect of the order of events on a structure: Miner’s rule can only work with repeated cycles at random.

The best possible estimate to date is to use analysis and study these events in parallel. The column of stresses at each node over time can then be placed into a large spreadsheet. Then, he would have to manually combine these stresses and attempt to sum them with Miner’s rule. But this process is fairly time consuming and error prone, so a fatigue study like this still remains effectively unsolvable.

Conclusion

Striking a balance between saving materials and preserving design life is becoming more important every day. The motivation to study fatigue in mechanical design goes hand in hand with this growing need. SolidWorks Simulation provides many different tools for you to account for fatigue, but saving time is the most significant contribution. You can do many of these calculations by hand, but the likelihood of computational error and the intense time commitment are significant drawbacks compared with SolidWorks Simulation. And while experimental testing is the only way to acquire completely accurate data, the costs and time associated with these tests can be tremendous. The analysis tools that SolidWorks Simulation provides can help your team go a long way toward designing better products.

Additional ideas and help are available on the SolidWorks website at www.solidworks.com. The SolidWorks eNewsletter, press releases, and information on seminars, trade shows, and User Groups are available at www.solidworks.com/pages/news/newsandevents.html.



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