1

Methods for Analyzing Failures

"Hypothesize, Quantify, Verify, Rectify, Utilize"

In engineering and other sciences, decisions have to be made when failures occur. The mechanical engineering field I was in was concerned with machinery systems, pressure vessels, structures, and the various catastrophic failures that occurred. It was important to find the source of the failures quickly and implement a safe and cost-effective repair. This was not the time for guessing or using past experiences on similar failures. Each failure can be quite different. When the cause can't be identified, it can't be rectified. An example of this was when a high-speed coupling failed on a large centrifugal compressor system. A new coupling was installed without determining the cause. It failed again in 2 days. This was a dangerous situation as coupling debris flew everywhere. Luckily, no one was injured.

Many of the failures used in this book aren't of the typical type that have obvious solutions. These failures are classified as being catastrophic, meaning they either produced a dangerous situation, had legal implications, were costly because of lost production or repair costs or all of the above.

Some of the examples were done just out of curiosity about something I had witnessed, read about, or was questioned about. It was a way to sharpen my analytical skills and techniques to see if my analysis agreed with actual observed data.

My primary contribution to a failure investigation team was to develop a mathematical model that could represent the system which failed. In this way, failures could be examined on the computer to see if they made sense with the data recovered from the failed system.

This information was provided to the investigation team so they could concentrate on areas of importance. The model could also be used to see how worthwhile a proposed modification might be.

This approach certainly enhanced my career and greatly reduced the risk of a failure on a re-start-up [1]. The personal stress involved in a start-up was greatly reduced.

Decoding Disasters: An Engineering Approach to Understanding Technical Failures and Natural Catastrophes, First Edition. Anthony Sofronas.

While this approach made me many managerial friends by eliminating repeat failures and allowing safe start-ups at their plant, it also caused problems. Sometimes, management was not agreeable with the expensive downtime necessary for the investigation and repairs recommended and didn't want to implement them. They just wanted to replace parts and start back up. There's always the respected uninformed person who will tell them there's no problem in doing this. My approach was to let them know it was their unit and their decision, but I was obligated to write up the team's safety concerns along with my supporting calculations. With the do-nothing approach and luck, the unit might start-up and run fine. However, the team had used a scientific approach that was documented and defendable. Another catastrophic failure could bring legal action, especially if a fatality were involved. That would not fare well in a court of law. The court would want to know why the recommended modifications weren't implemented. Cost and timing would be a weak defense.

This scientific approach has worked well during a 50-year career and has resulted in no-repeat start-up catastrophes for investigations I was involved with.

Some caution should be noted. This approach is recommended only for senior-level engineers with considerable experience and no history of bad decisions. For new engineers, do the calculations, provide your input but don't confront management directly without support from a chief engineer or someone of a similar status who agrees with your calculations, reasoning, and logic.

1.1 Mathematical Modeling

Mathematical modeling is a scientific technique of producing the workings of a machine, structure, or any phenomena such as explosions in the form of equations. The wonderful part of this type of modeling is that these equations are like a time machine and can be used to predict the past, present, and future state of equipment.

The equations can be simple or complex. For example, the force required to accelerate an automobile to a given speed could be done with the simple equation, $F = m \times a$, where (F) is the force required, (m) the mass of the automobile, and (a) the acceleration. A practical use for this would be to determine the strength of various structural components.

With development of mathematical models to analyze the cause of actual failures in industry, the results were sometimes surprising. They might not have been quite what was expected from observations of historical failures. When this happens, this just means we don't understand something well enough, have the wrong model or data or not enough data.

Most of us may not be scientific geniuses, but we can do our own thought experiments. In my simplistic way I realized I used these creative images in my mind when building mathematical models to solve problems. Figure 1.1.1 is one envisioned when analyzing how far an attached gage on a vessel would fly if a poor weld holding it failed during high-pressure pneumatic testing. This was important because the plant safety officer was only going to restrict a pneumatic pressure test safety distance of 100 ft. The spring represents the pressure energy behind the piece of flying debris and was related to the pressure in the vessel.

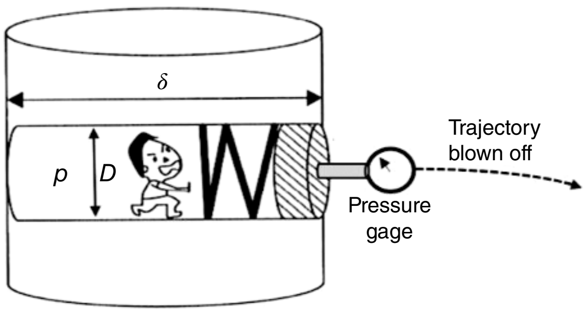

Figure 1.1.1 Modeling a pressure explosion.

Certainly not any monumental discovery and not a highly accurate model, but it did address and solve an industrial safety concern quickly. The analysis indicated that depending on the fragment size, the fragment could travel up to 1,000 ft. The conclusion was to place blast blankets on the critical testing locations. It seems the 100-ft restriction code compliance clearance was only for the pressure shock wave and not for flying fragments.

Richard Feynman (theoretical physicist 1918–1988), known for his brilliant research into quantum mechanics, once stated in a physics classroom, to paraphrase him, “If a mathematical model, even if it is elegant and from a well-known scientist, doesn’t agree with good experimental data, it’s wrong.” I certainly agree with this, but wrong doesn’t mean not useful. In engineering much analysis work that doesn’t come out with the correct magnitude is still useful. For example, with the pneumatic testing model, when verifying the equation with data from a similar incident, the distance was found to be closer to 1,500 ft away, not the 1,000-ft distance predicted. The analysis still was useful for the engineering decision made. Next time used, the calculation method will be modified and will be more accurate.

Reference

1 Sofronas, A., Unique Engineering Methods for Analyzing Failures and Catastrophic Events: A Practical Guide for Engineers, Wiley, 2022.

1.2 Methods for Solving Problems

A valuable trait someone can have is good problem-solving skills. This is because there are all types of problems that have to be solved in everyday life. Some allow others to solve their problems by using those who have more experience in a particular area. Consultants, doctors, or using the advice of others are some that come to mind.

Most of us are capable of being good problem solvers. You might say, "But I'm not a doctor so how can I solve my health problems?" The answer is by doing some research and finding out what others have done who have had a similar problem and finding a good solution for yourself. You can then see your doctor and use their experience and education to address your concerns. You can ask questions based on your limited knowledge.

This section isn't about personal problems but engineering ones. It's about solving problems like those presented in this book. Both complex and fairly straightforward analysis methods are shown to help illustrate the versatility of these methods.

1.2.1 The Scientific Method

Arriving at the scene of a devastating type of failure such as a machine, structure, or explosion can be confusing. Everything is scattered about and no cause is evident. I call it "The Fog Of Confusion" because that's how all the uncertainty feels to me. The following method helps eliminate this uncertainty in engineering.

One of the most used methods for problem-solving in engineering is the scientific method. In its simplest form it consists of the following:

1. Stating the problem you are trying to solve.
2. Developing a hypothesis, meaning what's your best guess on what the problem cause might be.
3. Testing this guess by gathering data, interviewing personal, researching similar failures, performing calculation on analytical models, or running experimental tests. Since you can never really determine if you have found the exact solution, it's valuable to see if your guess was wrong. Many times it is, and you need to state another best guess based on the data and test it in a similar way.

4. Asking your trusted associates to prove the hypothesis wrong you have developed.
5. Implementing a solution to the problem and documenting it.
6. Following up to ensure it solved the problem. Similar problems tend to reappear elsewhere, and this is good data to have.

The method isn't only for scientific problems, and with a little imagination it can be used for solving many of life's problems.

1.3 The Crack Growth Equation

In Section 2.5 an equation will be used to determine the cycles to grow a defect. While this type of equation had been developed for stainless steel (Eq. 1.3), it wasn't available for titanium Ti 6Al-4V. An equation will be developed here for ductile materials only, meaning those that have a well-defined yield point. These are approximate type solutions used for determining if a problem may exist. They are not design equations.

How materials such as titanium and carbon fiber composites perform and their limitation is important to understand.

This is usually an area where a specialist such as a metallurgist, an engineer who studies materials, would be requested. Mechanical engineers and others need to understand the basic use of materials to help in analyzing designs and failures.

An important area of research in metals is crack growth, which means how much a crack will grow during each stress cycle. Consider Figure 1.3.1.

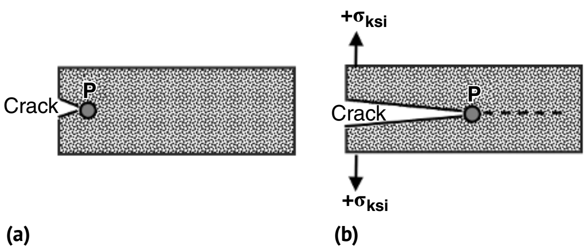

Figure 1.3.1 Crack growth.

A small crack has developed in a material. Due to cyclic stress (σ_{ksi}), which cycles between zero and some tensile stress, the crack will grow, as it is opened, during each cycle. Shown is (P), which is the small plastic zone at the tip of the crack.

P.C. Paris (engineer, 1930–2017) developed the equation $da/dN = C \times \Delta K^m$, where ($da/dN$) is the fatigue crack growth per stress cycle and (ΔK) is called the stress intensity factor and relates to the stress at the tip of the crack and its size in a small plastic zone. The terms (C) and (m) are experimentally determined to fit this power law.

The term $(\Delta K) = \Delta\sigma_{\mathbf{ksi}} \times (\pi \times a)^{1/2}$ and the constants can be determined for $\frac{da}{dN} = C \times \Delta K^{\mathbf{m}}$. This relationship is for a crack length (a) in a large plate [1, p. 193].

Using the data in Ref. [1, p. 296] and performing some curve fitting on titanium results in:

$$\frac{da}{dN} = \left(3 \times 10^{-11}\right) \times [\Delta K]^{3.94}$$

Inserting the constants and performing some mathematical gymnastics results in the number of cycles to grow a crack.

$$\frac{da}{dN} = \left(28.3 \times 10^{-11}\right) \times \left[\Delta\sigma_{\mathbf{ksi}}{}^{3.94} \times a^{1.96}\right]$$

$$\int dN = \frac{\int da}{\left(28.3 \times 10^{-11}\right) \times \left[\Delta\sigma_{\mathbf{ksi}}{}^{3.94} \times a^{1.96}\right]}$$

$$N = \frac{3.5 \times 10^{9}}{\Delta\sigma_{\mathbf{ksi}}{}^{3.94}} \int \frac{da}{\left(a^{1.96}\right)}$$

In the following expression, $(\Delta\sigma_{\mathbf{ksi}})$ is the initial nominal stress trying to open the crack in ksi and $(a_{\mathbf{o}})$ is the initial crack length and $(a_{\mathbf{f}})$ the final length in inches. The final length is based on the length necessary for the yield strength to be reached. This means stress calculations are needed.

For various crack types in a large plate, solving this crack growth equation results in: $\Delta\sigma_{\mathbf{ksi}}{}^{3.94}$

$$N = \left[\frac{3.56 \times 10^{9}}{\Delta\sigma_{\mathbf{ksi}}{}^{3.94}}\right] \times \left(\frac{1}{a_{\mathbf{o}}{}^{0.96}} - \frac{1}{a_{\mathbf{f}}{}^{0.96}}\right) \text{ cycles}$$

This shows it will take these many cycles to grow the initial crack size $(a_{\mathbf{o}})$ to the final crack size $(a_{\mathbf{f}})$ in titanium.

Now for ductile materials this final crack length $(a_{\mathbf{f}})$ is the length of the crack in inches needed to reach the yield stress of the part (i.e. in ksi). Usually, a value of $(a_{\mathbf{f}}) = L/2$ is used for most structures such as gear teeth and blade dovetails.

This means the remaining material can't support the loads and bends in yield.

In the analysis the nominal stress $(\Delta\sigma_{\mathbf{ksi}})$ is based on the stress intensity factor in a flat plate. Different types of cracks, meaning the type at the start, can be used [2, p. 332].

The following values can be used:
For titanium:

$$N = \left[\frac{3.56 \times 10^9}{\Delta\sigma_{ksi}^{3.94}}\right] \times \left(\frac{1}{a_o^{0.96}} - \frac{1}{a_f^{0.96}}\right) \text{ cycles} \tag{1.1}$$

For stainless steel:

$$N = \left(\frac{8.3 \times 10^8}{\Delta\sigma_{ksi}^{3.25}}\right) \times \left(\frac{1}{a_o^{0.635}} - \frac{1}{a_f^{0.635}}\right) \text{ cycles} \tag{1.2}$$

For carbon fibers with a small hole as a defect:

$$N = \frac{8 \times 10^8}{\Delta\sigma_{ksi}^{5.9}} \text{ cycles} \tag{1.3}$$

References

1 Barsom, J.M., Rolfe, S., Fracture and Fatigue Control in Structures, 2nd Edition, Prentice-Hall, 1977.
2 Sofronas, A., Analytical Troubleshooting of Process Machinery and Pressure Vessels: Including Real-World Case Studies, Wiley, 2006.

1.4 Failure of Carbon Fibers in Compressive Fatigue

I had little experience with carbon fiber composites. All of my work was with metals and welds and the fatigue failures that occurred in these materials. Crack growth was due to cyclic tensile stresses, not compressive stresses. Not much carbon fiber was used in the petrochemical industry during my career. Research was the only way I could understand what was happening with these types of materials.

Metals tend to eventually fail under fatigue from a crack. Carbon fiber composites do not undergo failure and tend to degrade under fatigue throughout the entire volume of the structure.

When designing composite parts, one cannot simply compare properties of carbon fiber and steel. Steel has properties that are the same at all points in the part (i.e. isotropic). These properties are also the same along all axes. By comparison, in a carbon fiber part, the strength resides along the axis of the fibers, and thus fiber properties and orientation greatly impact mechanical properties. This is shown in

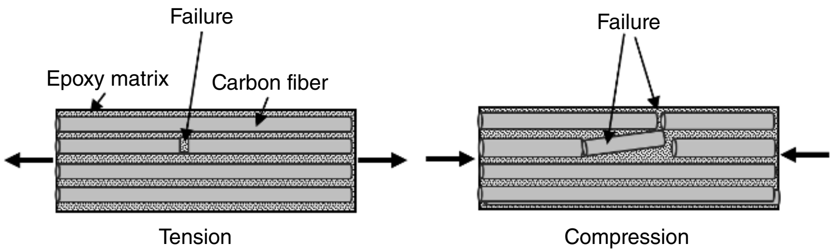

Figure 1.4.1 Carbon fiber composite failure.

Figure 1.4.1 for a given fiber orientation. Notice also that if there was compression on the vertical axis another failure mode would develop. Also see how one strand breakage can affect others.

Carbon fiber-reinforced composites have several highly desirable traits. One of the most important traits is a high strength-to-weight ratio. This means the same part can do the same job as steel but be much lighter.

There are also trade-offs. First, solid carbon fibers will not undergo plastic deformation (i.e. yielding). Under load, the carbon fiber bends but will not remain in a permanently deformed state once the load is removed. Instead, once the ultimate strength of the material exceeds, the carbon fiber will fail suddenly and catastrophically. Unlike metals, where localized yielding near a crack or hole (i.e. void) causes a redistribution of the stresses, the carbon fiber will almost invariably fail locally by forming a crack, that is, delamination.

Cracks in steel are typically easy to see, but cracks or voids in the carbon fiber due to the manufacturing process or fatigue cycling can be internal to the part. When the carbon fiber fails, it fails spectacularly. While steel and titanium might buckle and bend, the carbon fiber can shatter into pieces.

1.5 Failure of Carbon Fiber, Titanium, and Steel in Compressive Fatigue

Most of the metal compressive stress failures I've experienced have been buckling-type failures. Compressive stresses under a ball or roller bearing (i.e. Hertzian Contact Stresses) are not considered here. Carbon fiber doesn't experience true buckling because buckling requires the material to yield when it became unstable. The yielding is usually a local yielding due to a crease-type buckling. This is shown in Figure 1.5.1 with the hydraulic press test of stainless steel [1]. Titanium acts in a similar manner.

In Chapter 4, the implosion of the carbon fiber submersible Titan will be compared with the successful stainless steel deep sea submersible Trieste.

Let's evaluate the stresses in the Trieste's spherical shell and the depth it could achieve made out of stainless steel or carbon fiber. To do this, the failure stress in compression of these two materials needs to be determined.

Fortunately, for this simple analysis, some easy-to-understand data is available. Tests using a hydraulic press show a stainless steel tube, which is similar to titanium, can take five times the axial compressive loads of a wound carbon fiber tube. The stainless steel yields at failure, and the carbon fiber chips and flakes until a pile of pieces and strands remained. This is shown as a sketch in Figure 1.5.1, and the actual test photos are in Ref. [1].

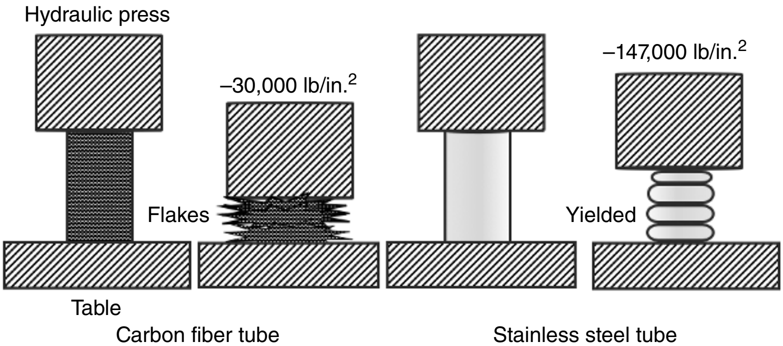

Figure 1.5.1 Failure hydraulic test of tubes.

Table 1.5.1 Sphere failure data.

Material	Failure stress (lb/in.^{2})	Failure stress depth (ft)
Stainless steel tube	−147,000	72,000
Titanium tube	−85,000	42,000
Carbon fiber tube	−30,000	15,000

Table 1.5.1 shows that Trieste had a safety factor of over 2× at the depth it was operating, not considering windows, seals, or stress concentrations. It went 6 miles deep (32,000 ft). Had this spherical submersible been made of the carbon

fiber, its failure depth would have been 15,000 ft and subject to degradation due to cycling on each dive. This again does not consider windows, seals, or stress concentrations.

Reference

1 YouTube, Strength Test Shows How Carbon Fiber Compares to Steel, Other Materials, Motor1.com, 2023.

1.6 Cycles to Failure for Carbon Fiber Laminate and Stainless Steel

It's interesting to understand the fatigue life of a deep sea vessel made of carbon fiber laminate (CFL) and that of steel. The structure of these types of cylindrical vessels with end plates has longitudinal and hoop stresses that are in compression with external pressure. When cracks are present in steel or defects or delamination is present in CFL, these tend to close during each dive. They do not open and grow cracks as would normally occur with cyclic internal pressure.

However, it has been noted that CFL does fail catastrophically when compression forces are high enough. Cracking sounds are said to have been heard during dives of Titan [1]. Tests have shown that under high compressive forces, such as illustrated in Figure 1.6.1, fibers tend to buckle. In buckling they bend and break in tensile stress. This was the case in compression tests where the failure was actually a bending tensile stress-type ultimate failure.

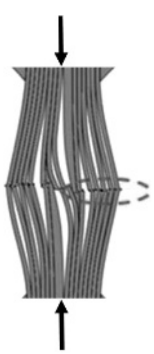

Figure 1.6.1 Compression buckling of carbon fibers.

With this knowledge and for comparative purposes, let's compare the cycles to grow a crack. This would mean there were some localized tensile stress in the shell to cause the fibers to fail during each dive.

Fatigue test data for carbon fibers [2] under tensile cycling will be used after adjusting the equations in the report to the form used in this book.

The following data assumes tensile cycling, which will be calculated in Section 4.3.

$\Delta\sigma = 30$ ksi

The cycles to failure for a CFL plate in cyclic tension with a defect 45°–45° wrap [2]:

$$N = \frac{8 \times 10^{8}}{\Delta\sigma_{\mathbf{ksi}}{}^{\mathbf{5.9}}} \text{ cycles}$$

This calculates to

N = less than 100 cycles to failure.

The cycles to failure for a steel plate in cyclic tension with a side crack:

$$N = \left(\frac{\left(8.3 \times 10^{8}\right)}{\left(\sigma_{\mathbf{ksi}}{}^{\mathbf{3.25}}\right)}\right) \times \left(\frac{1}{a_{\mathbf{oin}}{}^{\mathbf{0.625}}} - \frac{1}{a_{\mathbf{fin}}{}^{\mathbf{0.625}}}\right)$$

$N = 2.4 \times 10^{7}$ cycles to grow a crack to failure.

1.6.1 Summary

The Titan didn't fail from an ultimate compressive strength failure since it went to the depth it failed about 20 times. For this reason, along with the cracking sound mentioned, a fatigue failure is suspected.

This section shows the effect an unknown defect in the shell of a vessel going to depth and resurfacing can have as it opens and closes.

Steel can withstand many more fatigue cycles than CFL with the same thickness and nominal cyclic tensile stress. This could be the result of the homogeneity of metals compared to the nonhomogeneous bonding techniques used in the CFL layups.

While this information can't predict the actual failure of the Titan, it does show that a failure after approximately 20 dives is suspicious. The high compressive stresses could bend and fail carbon fibers in the layers in tension with each dive to depth. This could have been the cause of a fatigue failure.

References

1 Gross, J., Submersible Expert Raised Safety Concern After 2019 Trip on Titan, The New York Times, Internet, June 23, 2023.
2 Shastry, S.G., Chandrashekara, C.V., Computational Fatigue Life Analysis of Carbon Fiber Laminate, Internet, IOP Conference Series, 2018.
3 Sofronas, A., Analytical Troubleshooting of Process Machinery and Pressure Vessels: Including Real-World Case Studies, Wiley, 2006.

1.7 Ockham's Razor

When different theories are being proposed in the scientific community, you will usually hear the term Ockham's Razor. It's a term used in problem-solving that basically says the simplest explanation is usually the best or don't use more assumptions than needed. It's something I do often and don't even realize it. In other words, keep theories and hypotheses as simple as you can while still accounting for all of the observed facts. The method was used by William of Ockham (Franciscan friar, theologian, 1287–1347), thus the name. The Razor part is thought to mean trim out the unnecessary parts.

An example might be if you are requiring an immediate method to calculate the stress in a structure. It's a very simple structure, and you could use basic strength of material calculations and get a reasonable answer in 1 hour. Someone suggests that a consulting company has a complex computer method for providing an exact solution. Ockham's Razor would say to use the simplest calculation method. This would offer an engineering solution that could provide an answer quickly. It is also easy to use, understand, and explain. It doesn't mean that it's exactly correct, only that it's the simplest method that makes sense with the data at hand. This is done in engineering work when results are required quickly.

Throughout this book many of the thought experiments and statements made seem to follow the Ockham's Razor Principle, meaning the simplest one was used because it has made sense with the data available.