1

Engineering Suggestions Based on Experience

A Failure Cause That Hasn't Been Identified Can't Be Rectified

1.1 What Should We Learn from This Book?

This is a very important question we should ask ourselves before using our valuable time. After all, there are many other sources of information available to us. So what makes this book so special? Simply that many of these solutions are those of the author and have never been available to the public before. They have been used to solve actual problems in industry.

Analyzing failures is a gratifying part of a technical person's career, some engineers will say the most interesting and rewarding. This is because it can take you into many areas, all quite different. Various areas of your technical background can be used in solving a problem. During my mechanical engineering career I've worked on all types of failures, learning and documenting something important from each one. Much of my knowledge was based on being curious.

Actual examples and experiences are always valuable, especially when they can show how to simplify and solve difficult problems. While there are many sources of information, it is the personal experiences that make this book unique.

One wonderful thing about analyzing something with mathematics is that once you have a viable model you have developed a time machine of sorts. You can analyze what a piece of equipment has done in the past and what it will do in the future. For example, with fracture mechanics you can determine when a crack formed and how long it will take to propagate to a failed condition. A small crack in a gear tooth and a small crack in a coupling are actual examples. You don't have to know the initial crack size, you can just say it's 1/64 in. long and see what the cyclic stress does to elongate it to a failure length.

Unique Methods for Analyzing Failures and Catastrophic Events: A Practical Guide for Engineers,
First Edition. Anthony Sofronas.

In this book, many different areas are investigated. The purpose is to show how one area in engineering can affect another. Heat transfer, dynamics, and kinematics are used to describe the human body as in Chapter 8. Strength of materials, dynamics, and fluid flow are used to explain various Earth-related phenomena as in Chapter 9.

Copying what nature or other creatures do and trying to mimic them, such as flying, is called the science of biomimetics. The first example that comes to mind is Leonardo da Vinci. He watched and sketched the flight of birds. He never built a flying machine but he realized the science involved. Section 4.5 shows the analytical flight of aircraft and bumblebees. “Walking on Water” is another observation made of a Basilisk lizard and researchers have tried to duplicate this technique. It is shown in Section 10.13 and explains why this is so difficult for an unpowered human to achieve.

The analysis methods used are not meant to be highly accurate, but accurate enough, believable, and understandable enough to solve a problem quickly.

The versatility one can have in the field of science and engineering is immense. Most practicing engineers and scientists know this but for those trying to decide on an area to go into, the following discussion may be useful.

I’ve been a practicing mechanical engineer for over 50 years and during this time, in addition to getting married, sending my wife and children through college and traveling with them around the world, I’ve been:

- Manager of advanced engineering
- Worldwide problem solver
- Contributing editor to a technical magazine with 110 articles
- Researcher who developed a new drill and sampling device for a Martian lander
- Wrote four technical books
- Worked on machinery, pressure vessel, and structural problems of all types
- Taught in a university
- Owned a consulting firm after retirement
- Presented technical seminars to industry worldwide
- Manufactured and sold a motorized tow and vibration indicator for aircraft

My love of mechanical things also allowed me to become a pilot of my own aircraft so I could fly to consulting jobs if I so desired. I also had time to restore my favorite things such as old cars and Jeeps.

I graduated from a 2-year technical college because I loved working on machinery. The design part was extremely interesting to me so I went on for my mechanical engineering degree. I’m sure I could have had a very successful career with this 2-year degree; however, the engineering degree offered many additional opportunities. My only concern was that hands-on engineering might not be possible and I’d be confined to working from behind my desk. This never occurred and 50% of the time was out of the office. Usually, the out of the office was spent at other sites both worldwide and in the United States analyzing failures or reviewing designs with manufacturers. Attending seminars, consulting with field personnel, and visiting outside machine shops and metallurgy laboratories are some of the other activities. There were many trips out of the country and I was able to work on many of the continents. Obtaining an engineering degree requires hard work, but then anything worthwhile often does.

The analytical solutions used in this book are not meant to be highly accurate as many assumptions are made. They are intended to provide data to solve actual problems when little data is available. In this way, they have helped a busy engineer make critical decisions on in-plant problems with minimal risk. It is hoped it will allow the reader to do the same.

1.1.1 Summary

Engineering is extremely versatile and flexible. Advanced degrees can greatly widen one's career opportunities [1]. This book should help the readers by allowing them to mathematically analyze the causes of a failure, and allowing them to provide the most likely cause. This will greatly reduce the personal risk when they are required to provide a solution.

Reference

1 Sofronas, A. (2016). *Survival Techniques for the Practicing Engineer*. Wiley.

1.2 We All Contribute to Each Other's Success

At the start of my career with the help of an excellent mentor, I became quite good at analyzing equipment and structures using analytical techniques. There was a point where I thought that anyone in mechanical engineering who didn't perform detailed calculations wasn't doing real engineering work.

Of course, this was my youthful arrogant thinking and when I realized how absurd it was I repented and was ashamed. I noticed that those I worked with had unique talents that I didn't have. Not having recognized that and my career would have been much less productive. As I have told people "Some of my best works were achieved with the efforts of others."

A way to help explain this is with a few examples.

Example 1.1 A newly installed vibrating conveyor was experiencing extensive cracking and had been noticed by the unit's machinist. Arlon shared with me that he thought the spring hangers were misaligned and measurements confirmed this. We used the measurements to build an analytical model that predicted high stresses and cracking of welds due to the misalignment [1]. Only after reviewing the measurements and calculations did the manufacturer agree to perform the repairs and tighten the tolerances at their cost. Recognizing his knowledge of the equipment, the machinist was asked to supervise the job which benefited his career. All would be much more difficult without his expertise.

Example 1.2 A large gas-engine compressor experienced a crankcase explosion at a remote compressor house site in Louisiana. I was called to determine the cause. A technician who had 20-year experience repairing these large compressors was brought along to help. Crawling around inside the engine he showed me tricks of the trade. He tapped critical bolts with a hammer to see if they were loose. In this way, he located several loose and broken bolts. It seems a cylinder was loose and it rubbed the piston skirt which caused a hot spot to develop. This ignited the oil vapors in the crankcase. Don's practical knowledge of the compressor, being more extensive than mine, had located the cause.

Example 1.3 I worked for a company that was repowering ships with a 3,000-horsepower diesel engine they manufactured. My assignment was to travel the Mississippi river on this seagoing tug to monitor the operation since I would be performing the torsional analysis of the new system. Management wanted to know if this was a good application for our engine. Half-way through the journey, one of the propellers hit a log and broke off a couple of blades. The captain continued on to deliver the barges, which took several hours. During this time, the ship was shaking excessively from the unbalance forces. The rubber-type coupling connecting the engine to the gearbox was smoking so badly that the crew put water on it to cool it down. An experienced crewman said this had happened before. His experiences allowed us to insert a clause in the warranty that protected my company should a similar condition occur. Sometimes witnessing a failure is a good thing.

Example 1.4 A friend was designing a gearbox to adapt to a high-performance automotive engine for use on experimental aircraft. I asked him if he had performed a gear train analysis on the gearbox and bearings. Bud said that the gears and bearings had been used at lower speeds and at a horsepower twice what he would be using. This fellow was a master machinist and mechanic who had been involved in all sorts of racing activities during his lifetime. Higher horsepower at lower speeds meant higher gear loading and for his gearbox provided an adequate design margin. He didn't realize this but his wealth of experience told him it would be acceptable. A subsequent analysis showed he was correct in his thinking. Here is a non-engineer whose input I would value because of his breadth of experience based on trial and error and his logical thought process.

These examples show how input from experienced resources is so important. Of course, for your own protection, you need to screen the data yourself and don't blindly accept input as being true.

1.2.1 Summary

Utilizing others who are experts in their respected areas will allow you to better utilize your own skills. Be sure to give them credit for their contribution.

Reference

1 Sofronas, A. (2006). *Analytical Troubleshooting of Process Machinery and Pressure Vessels*, 317. Wiley.

1.3 Why Performing Calculations is Important to an Engineer's Career

This is about the value engineering calculations can have in helping an engineer's career by controlling the risks taken.

Most engineers realize they can proceed through their careers doing very few engineering calculations. Managing projects or people, selecting and procuring equipment, working with manufacturers and consultants to design products, troubleshooting equipment, pressure vessels, or structures, or using sophisticated computer programs may not require engineering calculations. This type of work can be done by talented personnel capable of making sound decisions based on the data they obtain.

However, by using engineering mathematical techniques, you can greatly enhance your abilities since you can generate the data needed. You don't have to rely solely on someone else's data which might be flawed.

Early in my career, I realized that my managers didn't want to know the details on how I arrived at my results, which were usually from an analysis I was quite proud of. What they noticed was that I was willing to make difficult decisions, meaning take a risk, solve the problem expediently, safely, and cost effectively. Usually, it meant the system design or equipment was now operating successfully.

Lack of their interest in the calculations didn't bother me since the analysis allowed the following:

- To perform a logical analysis and provide documentation that supported my decision and made me feel comfortable with the risk taken in the decision.
- To use historical failure data to analyze new designs and prevent the same type of failure from occurring again. When smaller units aren't failing but larger ones are an analysis can show why.
- To verify the analysis by using other actual failures to see if the results are the same. Cracks and failure zones show you where to center your analysis.
- To feel confident reviewing any type of unique equipment because it could be simplified, analyzed, and understood. The internal stresses, dynamics, and other phenomena are understood, something that others may not have known about. Using equations, the system can be modeled and what is happening inside an operating system observed.
- To calculate if and when something is going to fail. Analysis is exciting and like time travel. It allows you to look at a failure before it occurs or determine when it is going to fail in the future.

This will allow you to develop a strong track record of successful risk taking and decision-making and become known as someone who can help resolve difficult problems. This is what will help you advance and be recognized by management not by them having to see and understand your calculations.

Some simple examples will help explain this. Many more are in the references.

Example 1.5 Why Did the Shaft Twist?

A 20-ft long extruder shaft made of a 316 stainless steel had twisted along its length. In a meeting that was discussing the failure, there was much speculation as to what or who was the cause. It was asked if this was the original shaft. The answer was yes and with further questioning learned the motor had been increased from 800 to 1,200 horsepower several years earlier to handle a tougher product (see Table 1.3.1).

The following was put on a flip chart in the meeting [1]:

Yield strength (σ_{yield}) for 316 steel $= 35{,}000\ \text{lb/in.}^2$

Shear stress in shaft due to operating loads (σ_{shear})

$$= 321{,}000^{*}\text{HP}/(\text{D}^{3}{}^{*}\text{RPM})$$

Table 1.3.1 Data put on flip chart.

Horsepower ***D*** **= 4 in., RPM = 200**	σ_{shear}	$\sigma_{\text{yield}}/\sigma_{\text{shear}}$
800	20,000	1.75
1,200	30,000	1.17

Notice that the shaft would have required almost double the load to fail at 800 horsepower but much less at 1,200. This is why it never failed at 800 horsepower. There was enough margin to handle periodic adverse operating conditions, such as cold product start-ups. A detailed analysis was performed and the shaft was replaced with a higher yield strength 17-4 material.

This quick calculation changed the direction and results of the meeting. A repeat failure would likely have occurred with continued operation with the spare 316 shaft.

Example 1.6 Can We Start The Unit Up?

A wrong answer based on someone else's opinion or erroneous data with a subsequent failure can jeopardize your career. This is where your ability to do calculations can be important. In this case, a large heated rotating disk dryer operating at a plant [1] had developed cracks at welds. Several similar smaller units hadn't developed cracks. The problem was compounded since a new much larger scaled-up unit had been shipped overseas and was waiting for installation in a new facility. The question from management was "What Should We Do Next?"

A simple finite element model was used to determine the stresses at the weld along with a cyclic crack growth analysis on the cracked dryer. After having performed these calculations on all the dryers the engineer felt confident in saying, "Based on the analysis if the new unit is put into service it will crack and fail in less than one year." It was recommended that the unit be sent back to the United States from Asia and strengthened by replacing only the first 3 disks out of 40 with thicker ones to expedite the repair. The analysis indicated that this was all that was required, along with better welding methods. Project management and the dryer manufacturer who was reluctant to modify the new unit agreed after reviewing the calculations. The decision was a low-risk one for the engineer since the same analysis was used on the smaller units and it was now known why they hadn't cracked. When you have good data from calculations, your position will usually be the strongest. Others probably have no data to contradict yours and aren't willing to take the risk. Here is a case where an analysis predicted the future and a crack growth calculation was a powerful tool.

These types of calculations are well within the capability of most engineers who look for the opportunity to utilize them. We need to recognize that this will eventually benefit our career by allowing us to take measured risks that others aren't willing to take. We could do this because we had data that others didn't. Calculations usually win over speculation when making recommendations.

1.3.1 Summary

By performing basic calculations an engineer will have new data that wasn't available. This will allow informed decisions to be made on equipment that is a first-of-its-kind design or one that has had repeated failures. A wealth of historic experience isn't necessary as new data can be calculated.

Reference

1 Sofronas, A. (2006). *Analytical Troubleshooting of Process Machinery and Pressure Vessels*, 33–315. Wiley.

1.4 How an Engineering Consultant Can Help Your Company

While engineering consultants are available for a wide range of client requirements such as developing or reviewing specifications for new equipment, this section is only concerned with analyzing equipment failures.

When a company has limited engineering resources, the failure of a critical piece of equipment and a quick resolution as to the cause can be demanding on the staff.

A consultant is a partner of the owner's failure analysis team providing valuable data to help in identifying, explaining, and addressing the failure causes.

Unique equipment failures can be difficult to troubleshoot since they may never have been experienced by the staff before. For example, a wrecked compressor housing as shown in Figure 1.4.1 or cracked welds on vibrating conveyor might be considered unique while a bearing or seal failure may not be.

One method to address the failure cause is to contact the equipment manufacturer to see if they can help provide a solution. There may be a reluctance on their

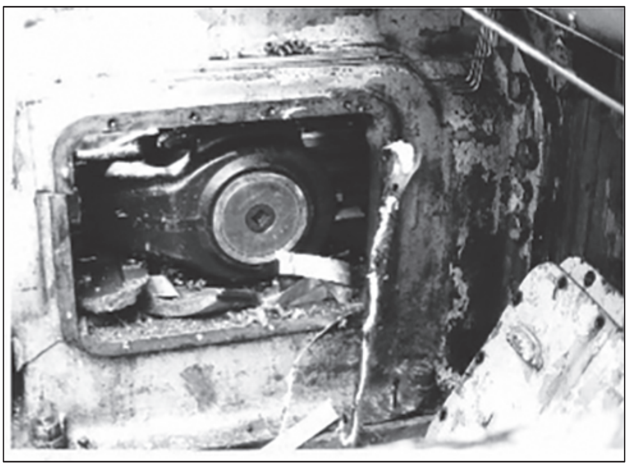

Figure 1.4.1 Wreck of a gas-engine compressor.

part if it could involve a costly warranty repair or could result in legal actions to them because of production losses or safety issues.

Often heard responses from the manufacturer are that:

- the correct operating procedures haven't been followed.
- the machine has been overloaded or abused.
- preventative maintenance hasn't been carried out.

These responses aren't helpful in getting the equipment back into operation and the owner may not agree with the manufacturer's statements.

The owner may ask for the design calculations in the failure area. The manufacturer may reply that it's proprietary information.

On new designs of larger power and geometric size, the manufacture's smaller and highly reliable unit may have been scaled up. Failures can occur in areas that don't scale up well such as welds and weld defects.

The following are some failures the author has worked where there was little design information available from the manufacture or the equipment was the first of its kind to the client company:

- vibrating conveyor structural failures
- material recycling choppers and grinder structural failures
- rotating mixer/dryer structural failures
- gearbox movement, gear pitting, and breakage
- extruder screw wear and breakage
- screw conveyor auger shaft failures
- agitator shaft, seal, and blade failures
- wrecks of gas-engine compressors
- screw compressor thermal rotor rubs
- cracked piping due to unknown vibration sources
- system failures due to torsional vibration

The consultant may have worked on similar failures for other companies and therefore has a wider experience base.

A consultant skilled in simplifying complex machines may develop an analytical model to better understand the possible causes. This allows the loads affecting the failure zone to be analyzed and explained in detail.

One output from such models is to determine the expected life in years due to the loads, stresses, and production rate. Defining methods to reduce these loads and stresses can increase the equipment's life.

Providing this type of data to the manufacturer will let them know you have detailed knowledge of the failure. With this they may be willing to share information on what can be done.

Experienced consultants are not inexpensive. The consultant must maintain the software and experience that a company engineer may not have. Finite element analysis (FEA), crack growth calculations, structural analysis, vibration analysis programs, and testing equipment are a few items necessary to do their job. Insurance, travel expenses are other necessities that must be included in the hourly billing.

The consultants billed work should be compared with:

- the production losses, legal liabilities, and repair costs of a repeat failure.
- the use of your engineering staff's time needed to do such an analysis.
- sharing the billed work with your company's other sites that may have experienced similar failures.

An engineering consult can be considered as an experienced temporary resource that is available at any time to help in your company's failure investigations.

1.4.1 Summary

Engineering consultants may have a wider base of experience from working with various industries. A similar failure may have been experienced at some other company. A similar approach can be used at your company.

1.5 The Benefit of Keeping Complex Problems Simple

When you are writing a technical paper for the government, a doctoral dissertation, or a consulting job, keeping things simple certainly isn't recommended. These types of jobs require a detailed analysis and they are expected from you. When you have a $100,000 budget to perform an analysis, a high-level technical analysis method is expected. It will be written for technical people who understand the complex mathematics and computer software used in the report. Finite element and structural design programs are examples. They will handle difficult structural design, heat transfer, fluid flow, and vibration problems that are difficult to analyze.

For most of my career, simplifying complex problems was important. Much of this has been in a plant environment and then as a consultant to industry analyzing failures. Something has failed and you are called in to determine why and to help fix it so it won't happen again. When the downtime is costing the company thousands of dollars a day, there's little time for long-term procrastination on an analysis. Sometimes all the analysis has to do is satisfy the investigating team with the probable cause or causes and how to address them so they don't happen again. As you will see in Section 7.1 of this book, this can become a little involved but can be done relatively quickly.

Any analysis is only worthwhile when the following are fulfilled:

- The outcome agrees with the failure data. For example, if the failure of a shaft is a fatigue failure and a materials expert says it was an instantaneous failure, someone is in error. The analysis should agree or confirm the observed data.
- It can be used to implement a fix. This means there must be results that can be used. When a shaft fails in torsion, the analysis should be able to illustrate a possible cause such as the start-up of an extruder with cold product in it. In that case, “bump-starting” to free the plug should be cautioned in the start-up procedure.
- The results of the analysis should be understandable. Complex analyses usually have nondimensional graphs and many technical terms and equations that can’t be understood by the practicing technical people, nor do they desire to. A clear deliverable with pictures of what has occurred and what needs to be done is what is needed.

Very rarely was the investigation team or management interested in how the failure problem was solved, meaning analyzed. All they want to know is, “What do you think caused it and what should we do?” This requires a very straightforward answer.

The finite element and structural programs can be used in simplified ways. For example, making a three-dimensional problem into a two-dimensional 1/4 axis-symmetric model in stress analysis, heat transfer, and fluid flow can greatly reduce the complexity, expense, and time. This makes them applicable to plant problems requiring immediate answers.

Here are some examples on where this was used.

Example 1.7 Reactor with Restrictor Head

This analysis was done to reverse a decision on installing a restrictor plate in a reactor. The plate was supposed to increase the flow velocity to reduce fouling.

This is a computational fluid dynamics (CFD) analysis of a reactor with a restrictor head plate. This 2D simplified analysis shows the high velocity in the 1-in. gap (c) region. It also shows the poor distribution and low flow in the inner tube.

Notice the simplification here. If you sweep the tubes, you have channels not individual tubes, so the results are only approximate, but did indicate the problem. Sometimes the engineer has to be creative in order to make timely decisions (see Figure 1.5.1).

Example 1.8 Extruder Barrel Distortion

A 50-ton extruder gearbox was moving on its base, even after careful alignment and bolt tightening. The simple “block” thermal stress FEA was performed.

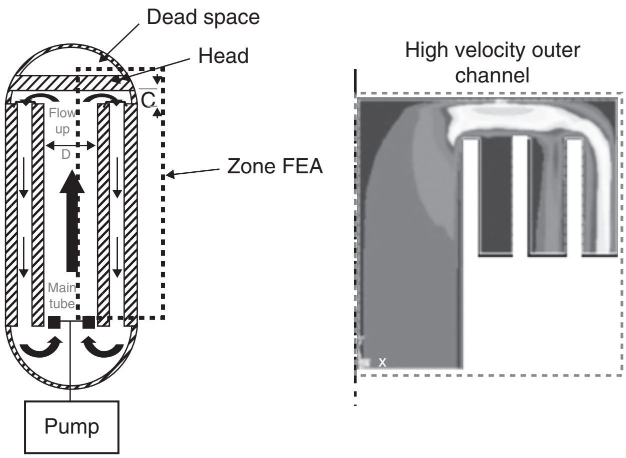

Figure 1.5.1 Reactor restrictor head.

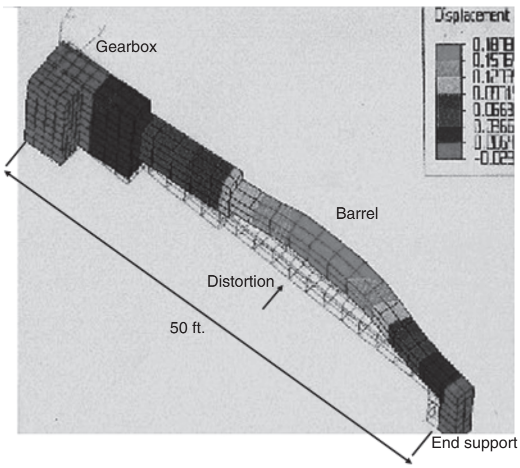

Figure 1.5.2 Extruder barrel distortion.

It showed that the fouled cooling passages in the barrel caused barrel distortion. This resulted in a thermal moment that would move the gearbox. The analysis was verified with laser measurements and thermal imaging. A better water passage cleaning schedule and temperature instrumentation solved the problem (see Figure 1.5.2).

Example 1.9 Aircraft Wind Screen Bird Strike

This was a study that reviewed the use of a thicker one-piece polymer windscreen on an aircraft. Bird strikes can cause damage such as shown, so the

FEA stress analysis looked at the stresses produced using different thickness windscreens.

The analysis required the impact loads to be calculated analytically and applied to the 3D FEA model. With large bird impacts, it was impossible to keep the windscreen from failing no matter what reasonable thickness was used. The solution is to stay away from birds (see Figure 1.5.3).

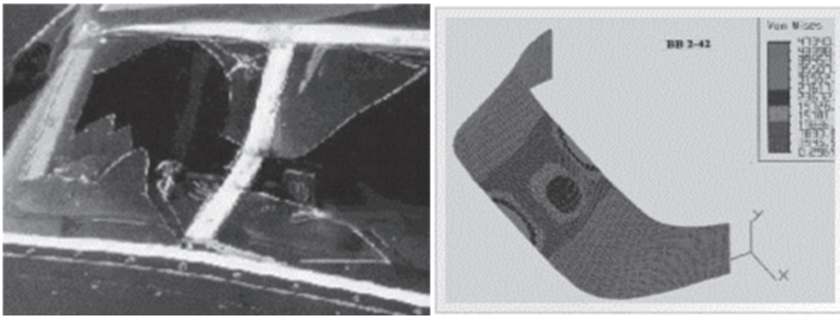

Figure 1.5.3 Aircraft windscreen bird strike.

Example 1.10 Cracking of a Cold Cycling Valve

This is a cycling valve spool piece that developed cracking over several years. An axis-symmetrical thermal stress analysis verified that it was due to the thermal cycling stress. Notice how simple the model is and that the steam jacket didn't have to be included, only the boundary temperature of the steam. Notice how cracking only developed in the high-temperature zone where the temperature cycled from −40 to +250°F (see Figure 1.5.4).

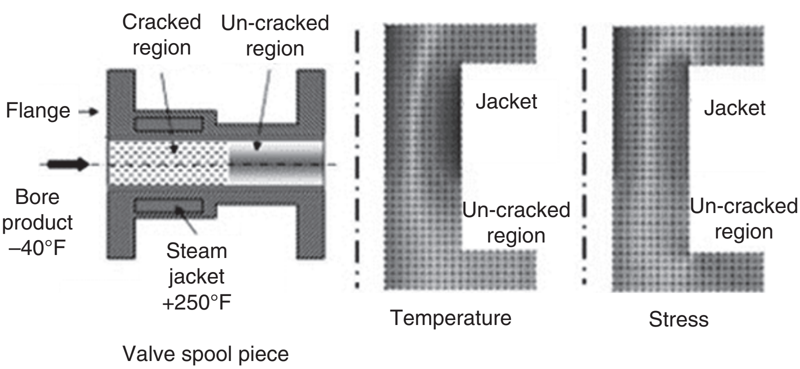

Figure 1.5.4 Cold cycling valve.

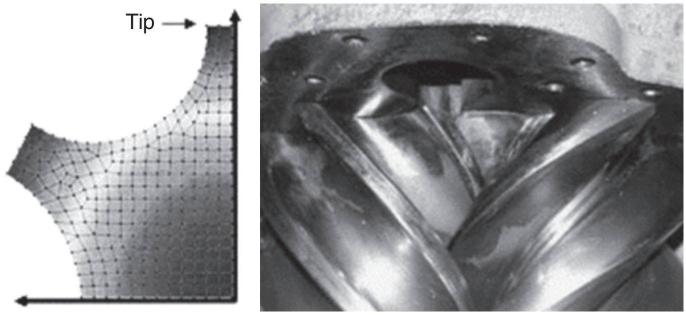

Figure 1.5.5 Rotor tip rub.

Example 1.11 Tip Rub of Rotary Screw Compressor
This represents a 1/4 axis-symmetric coupled thermal stress analysis of a screw compressor rotor. The rotor was overheated for a short period of time and it was requested that an FEA be done to see if rotor tip contact was possible due to rotor growth. It was (see Figure 1.5.5).

These simplified models with results took less than one day each. The color version of the results was clear and easy to explain to the responsible parties and the solutions were made obvious. These types of methods were very approximate and certainly wouldn't stand the test of a technical evaluation with all of the approximations made. I would not want to defend them in a doctoral dissertation review. They did successfully solve the problem and have the plant back in service so everyone could get on to their next assignment.

That's what most of this book is about. Most engineers would not care about a bird impacting an aircraft windscreen. They might be interested in using the finite element method (FEM) on a similar failure, possibly the windows of a high-rise top floor window. The impact might not be from a bird but from wind debris. The restraint conditions would show if the window would "pop-out" or "pop-in."

Even if someone is not knowledgeable in FEA, knowing that the model can be simplified will allow the technical person to mention and explore this approach with a technical consultant. The saving in time can be substantial.

1.5.1 Summary

An easy-to-explain analysis will usually be more expedient to implement a solution than a complex one. It will allow the responsible parties to understand the cause better and implement solutions with confidence.

1.6 Taking Risks and Making High-Level Presentations

As engineers we like to limit our risks. As a general aviation pilot and a mechanical engineer this has served me well over the years. I didn't do things that were too risky and always had a couple of alternate plans in case something went wrong. My requests for a design modification were always supported with adequate calculations. Usually, when someone has performed a reasonable analysis their arguments carry more weight than those who are speculating on the cause, with no supporting data.

There can be problems with this approach.

The first is that there is always some risk involved in every engineering decision and you cannot progress far in your career if you are unwilling to take calculated risks. Consider a large steam turbine vibrating slightly above normal levels with blade fouling thought to be the problem. Management wants to know if they can run one week until a planned outage with that level of vibration. Your career will not be enhanced if you say it has to be shut down immediately, with no supporting data. Likewise this is not the time to try your first attempt of online washing of a steam turbine while it is in operation. This is a risky business if you have no experience or operating guidelines to follow for this procedure. This would be a good time to monitor the vibration level, talk with the manufacturer and others with similar machines and determine the risk in just monitoring the vibration levels. Defining at what level it will have to be shut down will still require some risk, but now others are involved. Obviously, there is much more but this illustrates the need for some risk. You can expect to make some judgment errors but they should not occur early in your career or consecutively.

Correctly communicating to management what has occurred and what needs to be done is so important to an engineer. It would be wonderful if engineers had the verbal ability of attorneys in presenting data to management. An attorney job is to make juries feel comfortable with what they are telling them and the decision that has to be made with the evidence and data they have. Unfortunately, many of us don't have this type of training. Fortunately, it can be learned by experience and watching other successful engineers. Your company's senior technical personnel didn't get where they are via a lack of communication skills or poor judgment.

There are three things I have found important when discussing work with senior management. The first two items are self-explanatory but the last will require an example.

1. Management does not like to hear bad news, so present positive plans.
2. Management does not want to hear a wish list of solutions so present only your best and the most cost-effective choice.

3. Management is not impressed with complex analysis or technical terms so the engineer must simplify the cause, solution, and implementation so it can be understood and acted on.

The management team you are presenting to may not be familiar with mechanical engineering and may have their expertise elsewhere. It's useful to adjust what you are presenting to suit your audience.

Suppose you are discussing the resonance of a structure and its failure. Now as engineers we know resonance can be a highly damaging vibration caused by exciting a structure's natural frequency. Resonance could be clearly demonstrated by bringing a tuning fork to the meeting, striking it and showing the resonance of the tuning fork. With no continued exciting input, meaning striking it, the vibration dies out. However, with a continued input and without material damping the tuning fork would fail in fatigue. The fatigue failure part could be demonstrated by bending a paper clip back and forth to demonstrate and explain fatigue. At any point, you can stop bending but some of its life has been used up. This is shown in Section 8.2. Before using these techniques, it is important to know how the management team will perceive this type of explanation. Is it too simple or is it helpful?

When preparing for a technical presentation, one approach used is to make a list of all the questions you may be asked during the meeting and research them thoroughly. This allows the best possible answers for the audience you are presenting to.

1.6.1 Summary

Taking risks in engineering is necessary in solving problems. These risks can be limited in their severity by having good data either obtained or developed with analysis.

1.7 Searching the Literature for Data

Gathering accurate data is essential for failure analysis and other types of research. Writing this book required considerable research and some of the methods used are outlined here.

It's relatively easy to do a literature search today. Before electronic methods were available, informed individuals, the library, periodicals, and technical journals usually provided the results needed. Science, engineering, and technology centers provided research in most areas.

In addition to the above sources, much of the data utilized now is located on the Internet. The data can be used to verify analytical models, develop new ones, or read about lessons learned.

Data is also available as unclassified government reports on the Internet. When you use the correct search topics, they will usually show up. For example, Ref. [1]

was found searching under NASA REPORTS. Such reports also contain valuable references and test data to help you widen your search. The results are quite reliable since these types of reports have been thoroughly reviewed. When a document has multiple contributors, the review process is even more thorough. Unfortunately, brevity and simplicity do not usually prevail in such documents.

There can be problems with some of the sites on the Internet and other social media sources providing information. Many have been found to contain erroneous information which could be dangerous if believed and used.

When a site has an experienced contributor who can comment on erroneous data the site holds more value. When someone is using questionable language, give the site a low score on believability. The site probably is not being screened for substance. Here are some other problems I've noted on some Internet sites.

1.7.1 Equations

Even in my own works, when an equation is converted from one type format to another errors can occur. For example, when converting from a Word document to a PDF document, some of the symbols in the equations may not be recognized. Always verify the equations you use and ask for a final review when they are converted. It's also useful to do a dimensional check on the equations to ensure the units are correct.

1.7.2 Facts

One person's statement of a fact may only be someone else's opinion and that opinion may not even be their own. What they are citing may have been obtained from another source and that source may have been incorrect. When researching for an article on pneumatic testing I've read, "If it blows up just get out of the way". My first thought was that this would be hard to do when fragments are flying at 2,500 ft/s. People want to have something to say but without good data it's just an opinion.

1.7.3 Credibility

You may know nothing about the person who is presenting the information. At least in a technical publication, the background of the author is known. A contributor may have valuable information based on their experiences, however, you won't be able to verify its value unless you cross-check it against other sources.

1.7.4 Accuracy of the Data

Much of the work I do doesn't have to be highly accurate. Getting the unit back-up and operating safely and cost-effectively along with eliminating the possibility of a repeat failure was the goal. Usually, the details on how this was done are not as important to management as that it got done safely and cost-effectively.

An overload can be 300% or 800% and break gear teeth. The exact percentage isn't as important as knowing why there was an overload and what should be done to keep it from reoccurring.

This is the reason obtaining test data from the literature is so important. Here are some additional suggestions for obtaining information:

1.7.5 Sources to Search

For locating test data for comparison with calculated data, one source is technical journals of societies that specialize in that type subject matter. Various journals such as published by the American Society for Mechanical Engineers usually have papers on most subjects in mechanical engineering. Other technical societies do the same. Government research publications usually contain test data. I have also used online Masters and Doctoral thesis of specific topics that will show up if you are persistent enough.

For general subject matter or information on scientists and people of interest, I have always found Wikipedia on the Internet and other such sources to be quite useful. When the information is incomplete, they will mention this. Usually, these have a good number of references to follow up on. For example, I searched Amazon books for [2] and then got it as an interlibrary loan.

It's amazing how much information there is online for learning different subjects. I taught myself CFD for use with the ANSYS program I had with online courses by just searching the web. Khan Academy [3] is an online source and a wonderful learning aid for brushing up on statistics and other subjects.

Your own experiences are a valuable source of information. I've made it a habit to write down sources used and where to get this type of data again. It may have been at a trade show, a lecture, reading a technical journal, book, or article or asking someone a question in a machine shop. Anything of importance would be saved. Most of my books have been written using this type of material. One good technical paper can generate many valuable references.

1.7.6 Summary

Advice to those new to engineering or the sciences is to record all the work you do. Especially important are failures that you have witnessed because eventually it will be useful to you. Most companies don't like to admit their failures and how they solved them, so this type of material is scarce.

References

1 Columbia Accident Investigation Board (2003). *National Aeronautics and Space Administration*, vol. 1, 248. Government Printing Office.
2 Newton, I. (au.), Cohen, B., Whitman, A. (trans.), *The Principia: Mathematical*
3 Khan, S. (2009). *Birthday Probability Problem*. YouTube: Khan Academy.

1.8 Cautions to New to Industry Technical Personnel

There are some cautions everyone should be aware of when in industry. Here are some actual cases that may help you learn from the errors of others.

1.8.1 The Wrong Frequency

A bearing failure problem kept occurring on an overhung pump similar to that shown in Figure 1.8.1. It was taken to an outside shop for bearing replace.

The opportunity was taken to use a newly acquired spectrum analysis measuring system to determine the natural frequency of the rotor assembly. The rotor was mounted as shown in Figure 1.8.1 with an accelerometer mounted on the shaft. The impeller was "bumped" with a soft mallet and the frequency analyzed. It indicated there was a resonance concern at the operating condition. The new to industry engineer reported this back to his mentor who didn't believe the results. He came to the shop took one look at the setup and said, "Your measuring the frequency of the table the pump is mounted on!" The pump was remounted on a heavy baseplate that resulted in the frequency being several times higher than

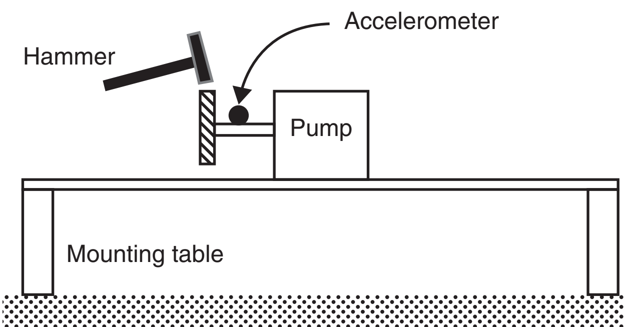

Figure 1.8.1 Overhung pump.

when on the table. This was very embarrassing and why it's mentioned here so others can learn. It would have been much worse if the results were in a technical paper.

1.8.2 Using the Incorrect Measuring Technique

Become a consulting after retiring from industry is a learning experience. On one job while reviewing the vibration data taken by site personnel, it was noticed that it was lacking the low-frequency harmonics that were expected based on an analysis that had been performed. Out on the equipment, you could feel these vibrations. A technique used when there is no measuring equipment present is to place a piece of paper on the machine and pull a line across with a pencil for a second or two, recording the time. Low frequencies will look like a sawtooth pattern, in the direction of the vibratory motion, so just count the peaks and divide by the seconds. The pencil and your body stay rigid and the paper on the equipment moves with the equipment. This will produce cycle/second, and while not very accurate it produces the peak-to-peak amplitude also. Crude but effective on low frequencies with fairly large amplitudes. This resulted in about 10 cycles/s. The analysis group said they would retest. Taking one of the team aside it was mentioned that the frequency range of the setup should be reviewed first to make sure the system was effective at such low frequencies. The next day at a review meeting the reanalyzed vibration data was presented to management and the low frequencies were present and agreed with the analysis. This is a good time for a consultant just to say "Good job!" It's always wise to discuss the results with the consultant before a meeting with management.

1.8.3 Never Under-Estimate the Value of Experienced People

Early in my career, I was witnessing the start-up of a large diesel engine and was standing on the west side of the engine. The Chief Engineer and Test Shop Superintendent were standing on the east side. The superintendent waved to me to come to their side. I had a much better view from where I was so waved them off. It was a little strange that the floor on my side was dark and their side looked like freshly painted gray. The engine started up, an oil line broke and sprayed oil on my front. I turned and ran and it sprayed oil on my back.

The next day the superintendent came to my desk and said, "Always stand behind the most experienced person at the test." Similar advice was given at a fire drill at an oil refinery. "Always follow the Machinists, they're running from the fire, the Operators are running toward it to shut things down." This wasn't such good advice since some of the machinists were also volunteer fire men.

1.8.4 Check and Double Check Your Design

Early in my career, I was given the job of designing an oil level measuring device for one of those large mining trucks used for carrying ore out of open-pit mines.

The sketch shown in Figure 1.8.2 is similar to one of the trucks and the driver, for scale reference, is about 6 ft tall. The company I was working for designed the motorized wheel the oil indicator was going on. It wasn't a complicated design but since there were several different versions many dimensions had to be verified.

After designing it, I had my colleagues follow the instructions to install it on a truck. It seemed acceptable so I took it to my manager. He gave me an airplane ticket and said, "Go to the ore mine out west and show them how to install it." When I got there I went to the Mine Supervisor, he looked at the instructions, chuckled and called in "Tiny" the welder who was going to install it. Tiny was 6 ft 6 in. and weighed about 300 lb. He drove me out to truck # 265 and I immediately knew what the chuckle was all about. The truck was parked in the normal 4 ft of mud and the top of the newly designed level was set at 3 ft. It would be 1 ft under the mud. Pretty difficult to pull out the level indicator to check the fluid level. The worst part was when Tiny asked, "Do you want me to get started or do you want to think about it for a while?"

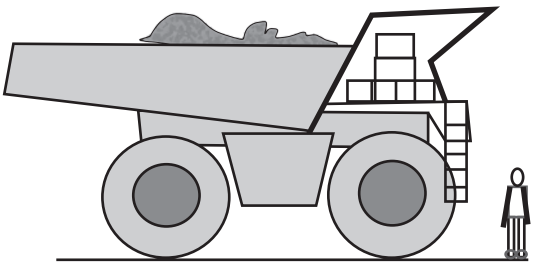

Figure 1.8.2 Off-road mining truck.

This is where I learned, early in my career, to always understand all of the operating conditions on whatever you design.

1.8.5 Some Understand the Equipment Much Better Than You

An automated brake grinding machine produced the finish grind curvature on truck-type brake linings. It would periodically produce out-of-tolerance linings. The machine was fast and ground the shape in about 1 s after automatic fixturing. In order to observe the operation a video at 5,000 frames/s was taken. The key point is that the personnel responsible for operating, adjusting, and maintaining the equipment were invited to a meeting along with the plant manager and supervisors, to view the video.

In the middle of the session, the technicians and operators started talking to each other. It seems that they saw the problem in slow motion. An adjustment indexing arm would periodically work itself loose. It corrected itself when the next piece was clamped in place. This caused the product deviation. This was a random occurrence and happened to be caught during this video capture. This was fixed on several machines and solved the problem.

Those who are around equipment continuously usually understand it better than the manufacturer does.

1.8.6 Summary

It's important to learn lessons from others both good and bad. Only in this way can they be followed and not repeated.

1.9 A Method for Analyzing Catastrophic Type Failures

A portion of my consulting career involved investigating catastrophic type failures on machines, pressure vessels, and structures in industry. Causes and solutions were required quickly so the equipment could be safely restarted and production resumed.

While collecting and analyzing the damaged and mangled parts, my involvement has been to propose and test theories on the most probable causes. Some form of an analytical analysis is used based on the available data. The analytic methods used are usually taken from one of the Refs. [1–3]. I share this information with the investigating team and modify this as new information is obtained. This helps focus the team on all the confusing debris and input from interviews and helps in understanding what might have happened. Testing the theory in this way will either validate it or provide reasons to dismiss it. This is similar to what is done using the scientific method. In the scientific method, a theory, hypothesis, or best guess, on how something has occurred is proposed based on the data available. As additional data is gathered, such as metallurgical/material evidence, interviews or a mathematical analysis, it is tested to see if it agrees with the theory.

This approach is different than speculating on a possible cause. Speculating is saying what you think may have happened without this being verified against all of the available data. You are not trying to prove or disprove your thought.

It has been my experience that several events usually have to occur to result in a failure. Lack of or delayed maintenance, overloads due to exceeding operating or design specifications, faulty repairs, or modifications are typically the causes. Major design deficiencies from the manufacturer are rare if built to their specifications. A long history of successful operation before a failure of the type experienced would direct attention to one of these possibilities.

Consider theorizing on the wreck of a 2,000 HP gas engine–reciprocating compressor as shown in Figure 1.9.1 (1).

A sampling of the data assembled is shown in Table 1.9.1 to help in verifying the theory.

After reviewing the data shown in Table 1.9.1, which is only a small sample, the following theory was proposed.

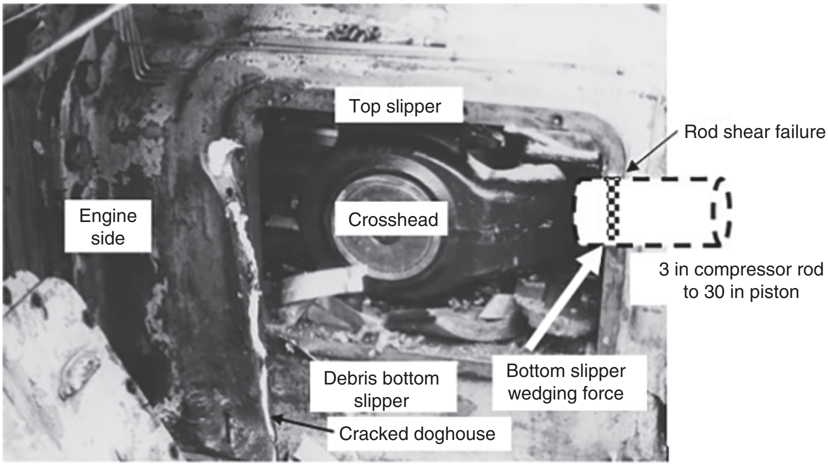

Figure 1.9.1 Wreck of doghouse section.

Table 1.9.1 Data to help verify theory.

Observation	Source
1. An experienced operator heard an unusual continuous tick-tick-tick and then a bang-bang just before the failure.	Interview
2. The compressor piston rod had sheared off due to wedging of the broken slipper.	Calculation performed along with metallurgical analysis. One million pound-force possible to do this.
3. The slipper bolts had all sheared off due to dynamic impacting.	Calculation performed along with metallurgical analysis. Loose hold-down bolt torque and shear probable.
4. The slipper bolts hadn't been torque checked for many years.	Maintenance records and interviews.
5. There were two bolts with low torque on the six other slippers out of 24 bolts.	Torque wench
6. The safety wire was still in place.	Observation
7. The slipper was cast iron and was broken into pieces and the 3-in. diameter piston rod had sheared. The nut was tight.	Observation and torque wrench
8. This type of failure had happened to the same type of unit at another division.	Interview with a colleague at a gas compression plant

The slipper bolts had become loose over time and that was the tick-tick-tick heard by the operator. The dynamic load impacted the body of the bolts and caused them to fail in shear. The loose slipper wedged itself against the piston rod and when the cross-head came forward it sheared the rod. This was the bang-bang the operator heard.

There were several other causes suggested by others, however, the data didn't support them.

The solution was to install dowels to secure the slippers in addition to the bolts. This eliminated the cyclic load on the bolts that loosened them. Periodic torque inspections were recommended as a maintenance item.

There were no failures of this type for 15 years after the modification at which time the machine was replaced with a centrifugal compressor.

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