Transforming Gage Data into Actionable Load Cases for Real-World Engineering Applications

Randy Bailey
(DJH Engineering Center)

Abstract

In finite element analysis (FEA) and simulation, correlating test data (strain gage data, acceleration data, etc.) to load cases used in simulations is crucial for developing reliable models that accurately represent real-world conditions. This process involves examining the data, model calibration techniques, and reliability of the data and analysis model. By converting test data into meaningful load cases, engineers can better simulate real-world conditions, leading to improved predictive models and design validation.

Processing statistical data and applying that data to load case development is the first step to having an accurate model that matches real life. In this process, test data is applied to real-world scenarios using various data manipulation techniques, simulation tools, and validation processes. These tools can be used in tandem to determine the load cases and events that are most damaging. Understanding and calculating these damaging events is a critical aspect of engineering analysis. Finding where the damage is generated during events means identifying and analyzing load cases that lead to material fatigue, structural failure, and other forms of damage. By leveraging strain gage data to calculate where the damage is coming from, engineers can develop more accurate models and focus on the largest contributors, reducing the amount of load cases needed, to predict and mitigate these damaging effects, improving the durability and safety of designs. This data can also be applied to real-world problems so that updates are made focusing on the source of the issue rather than trying to fix a symptom.

Interrogation of gage data and test data into engineering simulations is essential to bridge theoretical models with real-world applications. This presentation will demonstrate the benefit of this process and improvements in design performance using several case studies. These real-world applications demonstrate the practical benefits of accurate test correlation and load case development. They provide insight into best practices and approaches to applying strain gage data to projects. Using these methods, the accuracy of iterations is improved, accelerating the design process, and reducing the need for additional testing.

With a comprehensive overview of test correlation and load case development, the identification of damaging events, and the application of this data to real-world scenarios can take analysis beyond just analysis and start to simulate

real-world solutions. By bridging the gap between theoretical analysis and practical application, engineers can enhance the reliability and performance of their designs, leading to safer and more efficient solutions.

1 Introduction

When running analysis and simulation, accurate correlation to reality and actual usage is essential for developing reliable and robust models that can give predictions that match what is seen by users. Life, stress, and/or strain results from these models are only as good and as accurate as the inputs that they are given. Data, which is collected from sensors, instruments, and other observations, provides critical information about conditions experienced during testing that reflect what is seen when products are used. By transforming this raw data into load cases and honing the analysis, engineers can simulate real-world conditions more effectively, leading to better predictive models and enhanced design validation.

This paper explores the process of gage correlation and load case development, emphasizing the practical application of data to the virtual, to more accurately reflect everyday scenarios. We will discuss the theoretical foundations regarding analysis, and methods used to apply real-world data to analysis/simulation models and provide examples and case studies to illustrate the benefits and challenges of this approach. Additionally, we will examine the recognition, prioritization, and analysis of damaging events and load cases. We will also highlight strategies for predicting and mitigating damage in engineering designs.

Most of this paper will use general terms that can be applied to many different products. However, some will focus more on testing and simulation of heavy machines to show the pattern of the point being made. The analysis referenced in this paper is run in Abaqus and nCode but uses similar methods and strategies in most solvers.

2 Gage Correlation and Load Case Development

2.1 Data Acquisition and Calibration

There are many ways that data can be collected. The complexity and methods that are used can change, depending on the circumstances, but the goal is to get data that can be used to make decisions and drive improvement. Below are some of the types of testing that can be done.

2.1.1 Manual Testing

This involves manually collecting data through physical measurements and observations. For example, this can involve “putting the model to the test”, where a machine or prototype is built and used for its intended purpose. This try-it-out method is a good way to get an idea of how something will operate. This is useful for small-scale or limited-run tests and can be quick to get an idea of how something will perform. It can capture short-term failures, but to see the long-term effects, testing can often take a significant amount of time to determine what failures result. Manual testing alone is a great resource for impact type loads, to check fit up and look at function. As a tool for analysis/simulation, it only gives a limited amount of data that is useful in relating the virtual to reality.

2.1.2 Automated Testing

In this case, something can be tested in a more controlled environment and because it is automated, the failure time can be accelerated to reduce the time that is required to validate a design. Because it is automated, this enables the test to be done without the need for constant monitoring, adjustments, or inputs from people. Automation of loading or tasks that are repetitive can speed up the testing process.

Both manual and automated testing can be further enhanced by condensing the loading to account for the most damaging conditions that cause failures. This is what is known as accelerated testing. Timelines can be compressed so that the damage that would normally take months or years is done in days or weeks. Shrinking this timeline saves money and speeds up the time to market.

2.1.3 Sensor-Based Data Collection

When testing becomes more sophisticated, Sensor-Based Data Collection gives a way to constantly monitor a product during use. This can come in the form of strain gages, position sensors, accelerometers, pressure sensors, thermocouples, cameras (time-lapse, standard, or high speed), or many other sensors. CAN bus data can be recorded to get information directly from a vehicle, or video of the test can also help. Special paint can be applied to areas that experience high strains, which show cracking (that indicates strain direction) to help with physical testing. All of this checks the product performance or helps to predict issues. It can also help prevent catastrophic failures and point to potential problems if designs don’t change. All this generated data can be used in analysis to make sure that the virtual model matches real life. Taking this further, it can also determine damaging loads and help with root-cause analysis.

2.1.4 Simulation and Analysis Models

The data gathered during physical testing can be used to make sure that analysis or simulation matches what happens in the physical world by anchoring it in reality. That data can describe how damage is accumulated in products and what event or load causes low life using Minor’s Rule. Simulation and physical testing work together to shorten timelines in building products and determining viability for consumers. When the model is calibrated correctly, then other variables may be changed to help determine their effects on the results to optimize fit and function. This also can help with design direction, ideally to keep from building prototypes that don’t meet criteria, because of a lack of full understanding of the load cases that lead to issues later. There has been a big push in the industry toward this kind of testing because it is generally faster and cheaper than physical testing. While there have been many advances in this field, physical testing has been reduced but currently not altogether eliminated.

2.1.5 Historical Data Analysis

This method is the most accurate way to determine how well something will withstand usage over time. With real-world application of a product, “time will tell” if it is going to meet the criteria or not. This kind of analysis is looking at how something has performed and determining if it met the criteria or not. Looking back at something that has been in service may be the most accurate method when the data is available to determine if something meets, it is already produced. This can lead to a good or bad opinion of the product, which is difficult to recover from if it is a poor performer. These kinds of studies are best suited for comparison of new products to something that is already in the market and helps to build confidence but is not great for new products on their own, or products that push the design envelope or try new inspired solutions.

2.1.6 Synthetic Data Generation

The creation of the data from a virtual model is easy to gather data without the cost of building, gaging, and performing tests. The creation of an analysis model that perfectly reproduces the physical world is known as a digital twin. The development of the digital twin helps to shrink the development time by identifying potential issues earlier in the development process, helping make better-informed decisions for structures and lifecycles, and helping identify shortcomings in products.

2.2 Gage Data to be Compared to Simulation

Calculation of life from gage data can be manually done or software can be used to calculate how long something can last, given a certain loading. The loading cycles can be simplified using a Rainflow count and then fatigue calculations can be performed on the bins either by hand, or through a fatigue calculator, and accumulate the damage using Minor’s Rule. This is discussed further in section 2.6. Alternatively, you can also run the data through a life calculator to automate the process, which you can do quickly and easily using software. A comparison between the test and simulation should be done for either stress, strain, or life. In cases where there are a lot of different loads to compare, fatigue is more convenient because it can combine the results into a single life number that can be used for comparison. In cases where there is simple loading or the damaging load is known, it can be easy to compare stress or strain and not need the extra calculation.

2.3 Statistical Methods for Data Correlation

To have accurate simulation models, there needs to be a correlation between the data and the analysis model. There are methods for correlation such as a scatter plot of the test data and the analysis data. This correlation needs to be investigated so that the reliability of the model can be improved or addressed to show result accuracy. When using the Pearson product-moment correlation coefficient method, typically a factor of 0.7 or greater is highly correlated while 0.5 to 0.7 indicates moderately correlated [1][2]. Whatever method is chosen, make sure to be aware of the advantages and disadvantages. For a simple scatter plot, ensure that the data is statistically close.

In this example, we will use a scatter plot to determine how closely life is correlated. Because life is plotted, a log-log scale is used with an acceptable correlation range of a factor of 10 (between the orange dashed lines), see Figure 1. If there is a perfect correlation, then the analysis would match the test and there is a 1:1 relationship (solid black line). A larger deviation from a perfect relationship means the correlation factor is lower, implying that the analysis and reality don’t agree. What factors are acceptable will differ from organization to organization. Perfect correlation is difficult to achieve and requires more effort and time to establish. If a factor is too low, reaching a model that is considered acceptable will be easy, but the model won't match reality very well, which will lead to erroneous results.

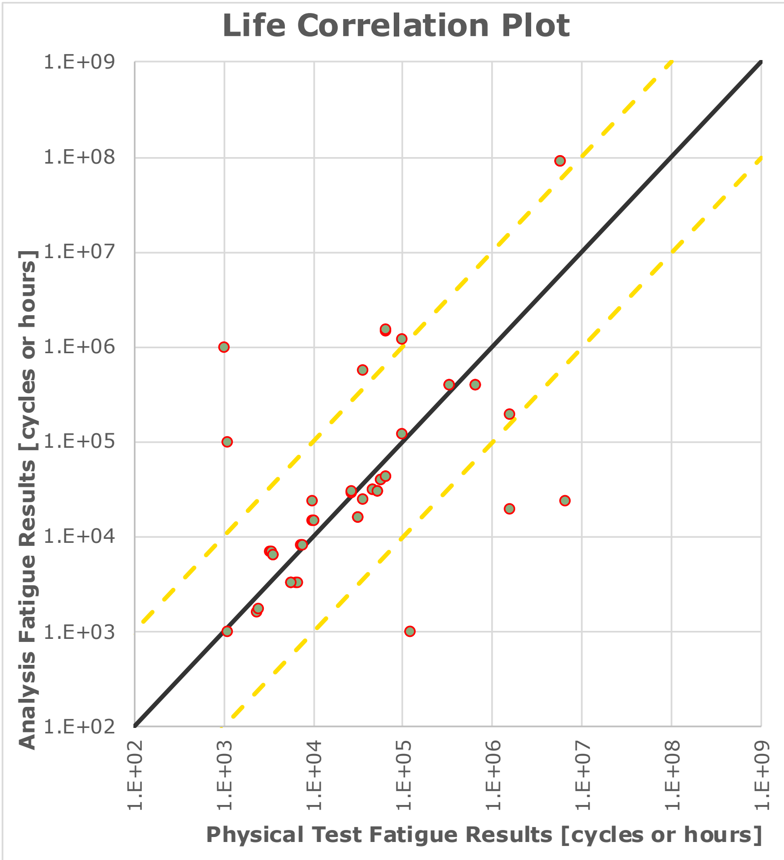

Figure 1: Life Correlation Plot

Strains (or stresses) can also be compared to test data strains (or stresses) to show how the data correlates. For example, a plot of Test Strain vs. FEA Strain could look like Figure 2, where we see the behavior of correlated results (near the black line), inversely correlated results (near the red line), and no correlated results (scattered points). In this case, the orange lines represent a 15% deviation from perfect correlation.

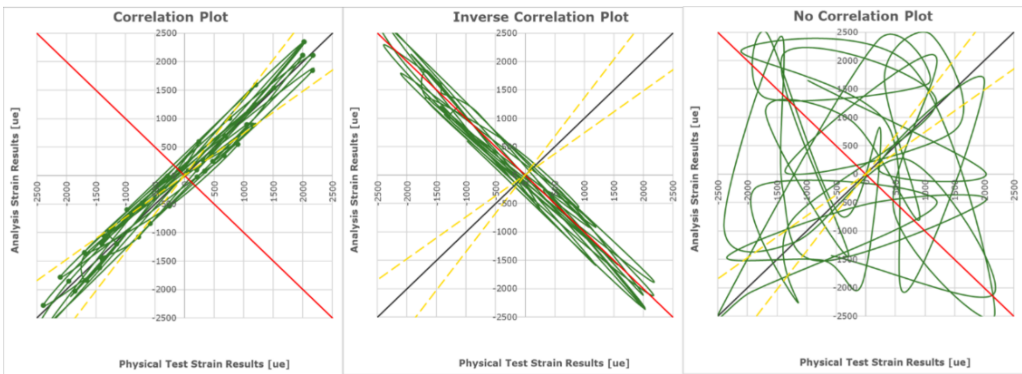

Figure 2: Strain Correlation Plots

2.4 Gage Data Verification

There are many techniques to convert raw gage data into load cases. Before beginning, make sure that the gage data is good. Common issues with gages are to check that they weren't overloaded, damaged, or have odd behavior that cannot be accounted for or resolved. Some other things to keep in mind when looking at gage data are listed below.

2.4.1 Repeatability

If there is more than one person that runs the tests, having different operators can help to ensure good data. There will be different operators when the product is in the hands of the customer, so the more varied the testing, the more it accounts for differences with consumers.

2.4.2 Calibration

While it is important to calibrate the equipment before starting a test, it is also important to make sure that there isn't drift or a zero offset during testing. If a gage is damaged or overloaded, it may move the zero and give bad data. Some of this can be corrected with offsets afterward but take care not to introduce errors.

2.4.3 Outliers

When looking at test data, make sure that there isn't something radically different from the rest. Sometimes a gage may have a small portion of bad data that can be removed while the rest remains, to get clean and useful information. This is another time when great care needs to be taken because, while this can help to make the data match the test, it can also remove critical data that is necessary to capture the true use case. This can also make or break the difference between a damaging event vs. a non-damaging event.

2.4.4 Environmental Conditions

As mentioned previously, an impact on test equipment or a vibration that feeds erroneous data into a gage can introduce error. Avoid and if necessary, remove these possible sources of error.

2.4.5 Statistical Analysis

Looking at the statistics of the data can help to locate issues as well. For example, if a test is performed in 15 minutes, but there are 3 hours of data, the data would be suspect. Conversely, if the data in this example is only 30 seconds long, the test will need to be removed, rerun, or accounted for in another way.

2.4.6 Intuitive Decision Making

Before concluding whether gage data is useable or not, make sure to review it thoroughly and check that everything makes sense and matches the expected results. If it does not, then additional verification and scrutinization may be required. Checking to make sure everything makes sense is an important step of Engineering and even running quick checks and calculations can help to reduce error and find issues early.

Only after data is proven to be correct and reliable should it be used by simulation. The gage data provides insights into machine use cases, load cases, durability, and other important aspects of what a product will experience when it is in the hands of the consumer. Data is what will drive simulations to match the real-world.

2.5 Transforming Test Data into Load Cases

Taking test data and creating actionable information can be done in many ways. There are a variety of measurements that are available during a test which can include strain gages, accelerometers, pressure readings (hydraulic, pneumatic, ambient, and others), high-speed cameras, speed, and power output, to name just a few. Other methods can give data in other ways like photoelasticity, Digital Image Correlation (DIC), X-ray Diffraction (XRD), Ultrasonic Testing, Magnetic Methods, and Thermoelastic Stress Analysis (TSA), to name a few. Whatever method is used and whatever is collected, this can be a simple process or more complex. Here are a few methods to convert data into simulation load cases.

2.5.1 Accelerometer Data

Accelerometer data is one of the easiest way to convert data into loads. The data will indicate the magnitude of g-forces the product experiences when it is in use. This data can be found in nearly all load cases but can be more important during some use cases than others. For example, with a vehicle, damage from this type of loading tends to be more prevalent during driving down a rough road than over a smooth highway due to high cycle fatigue. Damage due to accelerations can be found with any product that experiences vibration or other consistent types of motion. In some cases, where there are known loads and acceleration is not known, an inertia relief model can be run to calculate the acceleration required to balance the other loads.

An application of accelerometer data is to use it to drive Dynamic Modal Superposition (DMS) analysis. This application of data simulates structures that are subject to shaking, as in transport load cases. The application of accelerometer data is an example of merging testing and analysis.

2.5.2 Hydraulic Pressure Gages

This is typically easy to convert to load cases because, with the size of a cylinder, you can use the area to convert the pressure to force. The force can be applied directly to the geometry, or it may be a connector or other type of element. Sometimes cylinders will need to be represented in different ways depending on how they are plumbed, but this should be considered in the setup, which will not be addressed in this paper.

2.5.3 High-Speed Videos

In cases where high-speed video is used to correlate data, some of this can be done to make the analysis match the video. Correlation can be done by matching time and distance of motion, or matching how an impact behaves and how much rebound is observed. A comparison can also take the form of matching simulation speeds to what is seen in the video. Data can also be measured from the video to generate "test data" that can be matched with the simulation (distance, speed, acceleration, bending, etc.).

2.5.4 Strain Gages

Using strain gage data and knowing where the gages are located can shed light on how something is loaded. When using strain gages to build load cases, there is a careful balance that needs to be addressed between using too many gages and not enough. If too many gages are used, getting a good correlation to the simulation is difficult because there are too many variables to match. If there are too few gages, then matching is easier, but the load case may not represent the data very well. Whatever matching data from a test to an analysis model, check to make sure that the remaining gages are acceptable because often the other gages may not match with the data. Decide if these differences are acceptable or not and make sure that it makes sense with the loading.

2.5.4.1 Frame Twist and Bending

Bending and twisting are very common deflection modes. The theory of beams that are loaded is similar to many structures where a beam in bending tends to have tension on one side and compression on the other. Sometimes, the bending can be vertical or it can be horizontal. When twisted (or torsion), a beam tends to have tension and compression depending on the orientation to the axes of twist. Twisting can occur in different directions or axis. Finding overall gage locations on a structure is the first step. Comparing these gages to determine if there is bending or twist will indicate what type of loading is needed (see Figure 3). Comparing gages from and a time slice that is causing damage to an analysis model will help to indicate how something should be loaded. Typically, loads can come in the forms of principal directions (Fx, Fy, Fz, Rx, Ry, Rz), or some combination of these.

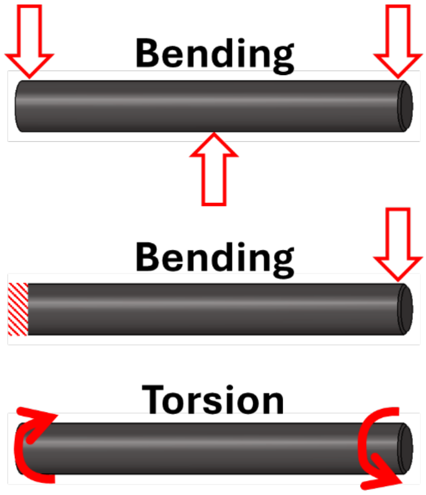

Figure 3: Bending and Torsion on a Frame

This loading can be applied to cause the bending shape seen. The loading can vary depending on the constraints, center of gravity, and load sources. An example of gage signs matching these basic concepts at locations on a loader frame is shown in Figure 4 below.

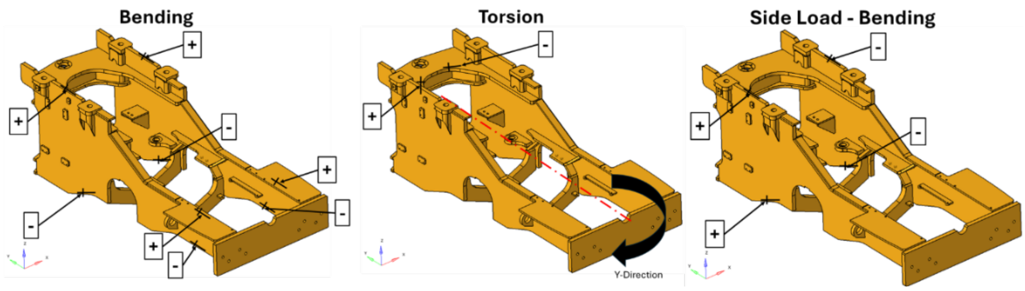

Figure 4: Load Application to Examples for Bending and Torsion

2.5.4.2 Axial Deformation

Loading on a structure can also cause deflections in the axial direction where the frame or component is pulled or pushed in a particular direction. This causes the gages to read compression or tension all the same in the same direction, see Figure 5. If the gages are 90° to the axis, they will have the opposite sign, see Figure 6. This is the same effect as what is seen in materials that cause the poison's ratio, but on a macroscopic scale rather than the microscopic. Similar to bending and twisting, this can happen on different axes.

Figure 5: Axial Loading

To match this type of deflection, the loading is in the direction of the axis.

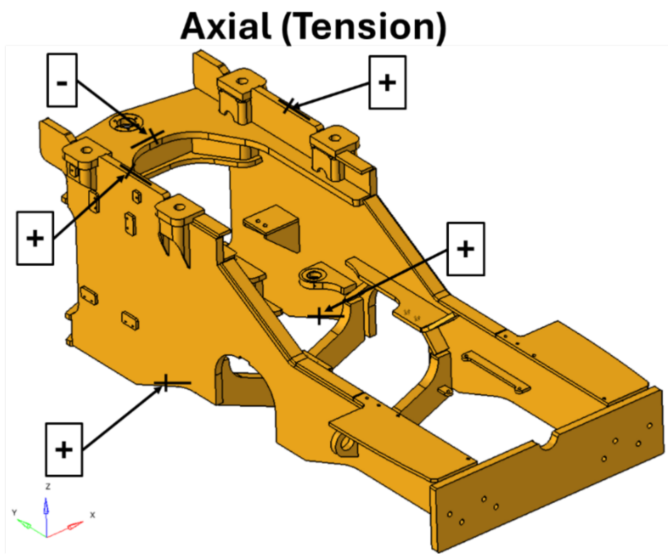

Figure 6: Loading Simulating Axial Deflection

Something to watch out for when looking at compression is Buckling. This is a special form of compression where there isn't enough section to keep the structure stable. These types of failures often result from times when plates are thinned. This would require a buckling analysis to check while running. During test verification, buckling issues are typically catastrophic and easy to reproduce.

2.5.4.3 Shear Deformation

This type of loading is not as common as bending, torsion and axial loading, but does happen. The test results would have maximum and minimum loads that look odd when compared to bending, but make more sense when shear loading is considered, see Figure 7.

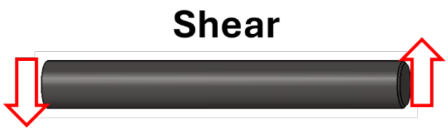

Figure 7: Shear Loading

During shear, the loading causes tension and compression on the same section of frame as shown below in Figure 8.

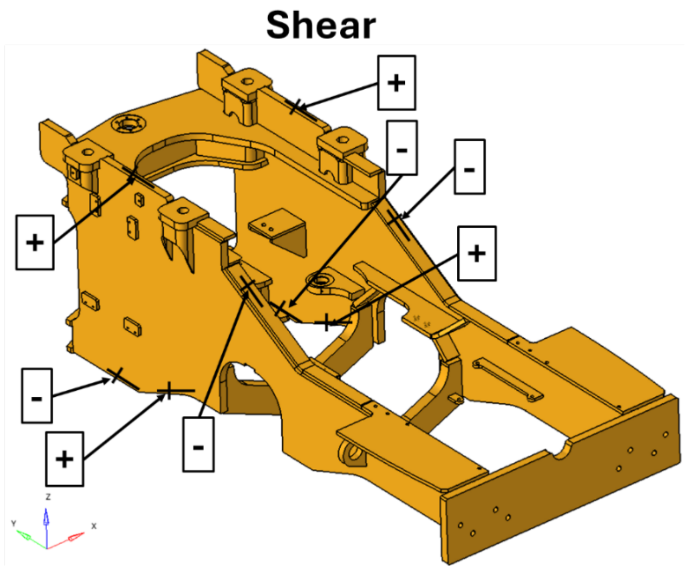

Figure 8: Shear Loading Strain Gage Locations and Signs

2.5.4.4 Deflection due to Thermal Expansion

Temperature effects can also cause loading on structures. As components expand and contract, loading can be generated. Temperature effects require gage data at different temperatures to predict how the structure is affected. While this is often ignored in structural simulation, it is a possible source of deflections, stresses, or strains to keep in mind. While this is a possible source of load, it will not be described in detail in this paper.

2.5.4.5 Combination of Loading

Something to be aware of is that all the loads described above can be combined to create the loading on a structure. It can be difficult to separate them. There are methods for doing this automatically or manually. An automatic example of this is the Load Reconstruction glyph found in nCode [3]. Whatever method is used, it is important to review, check, and verify that the loading used gives the results that are expected and match the test data.

2.6 Damaging Events and Load Cases

Often, when looking at test data, multiple load cases can be extracted from a single event. This depends on what is seen in the data. To focus design update efforts where they will make the biggest impact, the most damaging loads should be determined. Extremes in the data (Peaks and valleys) are common causes of damage, but if there are smaller cycles in the loading that occur more frequently, these can cause as much or more damage than larger peaks that happen less often. These factors can make the path for determining damage in load cases difficult to reproduce. Some tools that can help, is to run a fatigue calculation on the event to determine where the damage of that event is coming from and help focus on what load cases should be run. If stress/strain is what is being compared, looking at how the loads affect the fatigue can reveal the damaging event or load case.

For a basic load case, looking at the peaks in the strain data, acceleration, or whatever the data may be, can be a good first look at what is causing damage, but it is not necessarily the worst loading. As discussed above, if a repeat count of a load is high, even with a smaller strain reversal, the damage can be higher because of the frequency of the cycles. Some factors that cause more damage to structures are strain cycles that reverse (compression-tension) with tension influencing the damage more than compression, frequency/amplitude/mean stress of the loading, residual stresses, geometric factors, and load sequence as well as material type and surface finish. If the loading doesn't reverse, fatigue life tends to be higher than if there are compression-tension reversals. These are all considered in addition to other factors when using fatigue software. The Life Calculation Equation (1) shows how fatigue life is calculated when using the Coffin-Manson-Basquin formula for the strain life relationship [4][5].

$$\varepsilon_a = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad (1)$$

Where:
εa is the strain amplitude
εf is the fatigue ductility coefficient
σf is the fatigue strength coefficient
c is the fatigue ductility exponent
2N is the number of stress reversals
N is the number of cycles
b is the fatigue strength exponent

Another example of calculating damaging events and modes is below, where this is calculated using Dynamic Modal Superposition (DMS) that is mentioned previously. First, modal analysis is run on the structure. Then, in this example, the modes are driven with displacement data using base motions in the modal dynamic time history [6]. Combining the modal results and the driven multipliers is calculated in the fatigue solver (in our case, nCode). Accumulation of the damage is done automatically, as mentioned previously, using Minor's Rule (see Equation (2)) [5][7]. The results output are fatigue life for each of the events run as well as the total life of the structure. The individual event life can be used to calculate the life manually, or the results can be applied in another glyph that calculates the % damage per event for each location needed.

$$Total\ Life = \frac{1}{\frac{1}{Event\ 1\ Life}+\frac{1}{Event\ 2\ Life}+\frac{1}{Event\ 3\ Life}+\frac{1}{Event\ 4\ Life}} \quad (2)$$

To calculate the damage per event, this becomes Equation (3):

$$\%\ Damage\ Operation\ 1 = \frac{\frac{1}{Event\ 1\ Life}}{\frac{1}{Total\ Life}} \quad (3)$$

When the damaging event (or damaging events) are found (see *Table 1*), either manually or with software, then a virtual strain gage can be placed on the analysis model and synthetic data can be produced. Plotting the synthetic data, that has been converted to the frequency domain using a Power Spectrum Density (PSD), reveals the damaging modes. The peaks that are seen indicate what frequencies are damaging the structure as these are the frequencies that carry the most power. When the loading is understood, solutions to reduce stress/strain or increase life are much more apparent. See Figure 9 for an example data of a DMS analysis with the most damaging mode near 10.8 Hz.

Table 1: Example % Damage per Event

Operation	% Damage
Operation 1	15%
Operation 2	22%
Operation 3	0%
Operation 4	63%
Total Damage:	100%

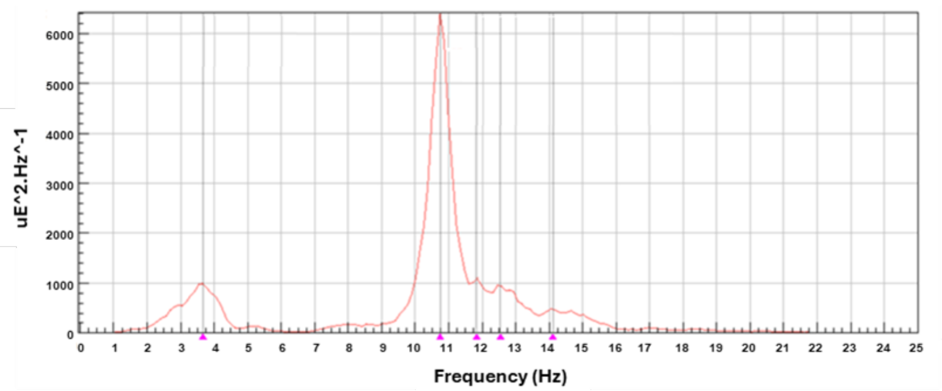

Figure 9: Example of DMS Damaging Mode for Event 4

Peaks of the PSD show the power per Hz, which indicates where the damage is occurring. Matching these frequencies to the modal results suggests what modes are responsible for the damage. In the example above, a mode near 10.8 Hz would be the shape of the deflection/strain/stress that would be the focus to improve.

3 Applying Gage Data to Real-World Scenarios

The integration of gage data in simulations is key. Taking an instant in time from the data and looking at the overall picture can establish how a structure (in the examples shown, a frame) is loaded. When you apply the analysis shown above, you can determine how a frame is stressed. There is often a combination of forces and moments in different directions and magnitudes that make up a load case. Look at the data available and decide how to differentiate what loads are applied.

Taking the simple bending shapes into account, often, is a good starting point for decoding the loading from the gage data. Run unit loads (near the same order of magnitude as what loads are expected) on the structure. These loads are added together in the analysis to create load cases that can be compared back to the test data. Combine the unit loads in different directions to get the behavior that matches best. Start with getting the signs of the results to match, while merging the loading, and scaling magnitudes to create better correlation to the test. An event of a machine is made up of one or more load cases and the events are then combined into a duty cycle to form a life calculation (in the case of fatigue calculations).

Software, like nCode, helps to integrate gage data with analysis models and predict life as well as generate other results. In addition, some tools can take gage data and predict load cases from unit loads that are applied to FEA models. These tools can allow engineers to simplify the process, speedup the processing and creation of data, load cases, and results while minimizing errors and mistakes.

4 Conclusion

This paper explored the process of transforming gage data into load cases and simulating real-world applications. This is essential to creating accurate models that mimic reality and reliably predict results. By accurately correlating data, engineers can develop reliable and robust models that can predict results that reduce testing, improve products, and reduce the time to market.

We discussed aspects of data acquisition and calibration, the application of statistical methods used for data correlation, and the transformation of raw gage data into meaningful load cases. The identification of damaging events and load cases (or in the DMS example above, damaging modes). The theoretical foundations and statistical techniques along with gage correlation were also reviewed. The data used for the analysis must be accurate and reliable for all the data to work correctly.

In the future, research will need to focus on refining the data collection methods and exploring new approaches to further improve the accuracy of load case development. By using these advancements, we will be better at predicting and mitigating damage which will ultimately lead to safer and more resilient designs.

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