Static and Fatigue Structural Test Tutorial

Introduction

Research, design, and validation of new structures requires a variety of tests from static load testing to aerodynamic testing. Ultimate strength and fatigue tests are examples of static tests that are critical for validating structural designs. Structures used in aerospace or renewable energy designs, for example, demand high channel counts in order to perform full-scale validation. National Instruments categorizes static structural testing as applications that require sample rates in the 100s to 1,000s of samples per second with channel counts as high as 10s of thousands.

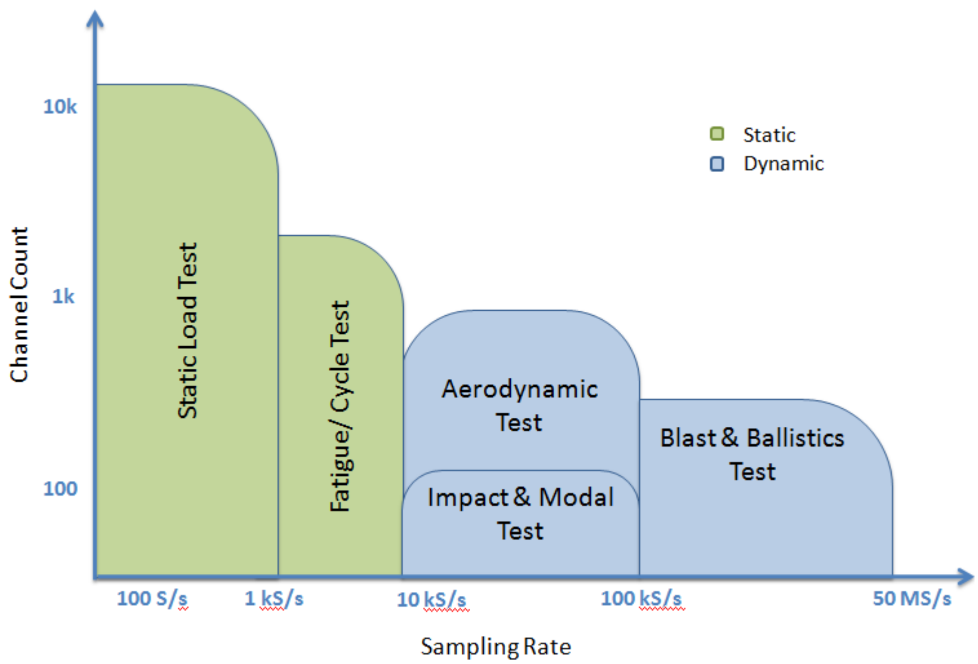

Figure 1. Structural tests are divided into static and dynamic applications.

Static Testing

Ultimate static strength tests play a critical role in ensuring a structure such as an airplane wing can withstand extreme loads caused by nature such as wind shear or other large transient forces. Although these tests are an essential part of the testing phase, it is rare that a structure ever encounters stresses of this magnitude in the real world. During static testing, the actual strength of the structure is compared to simulations and design specifications. Test data can reveal areas of concentrated stress that were not well highlighted in the simulations. This data can also be fed back into the models so that the simulations can be refined, uncovering other areas to focus test efforts on. Once this iterative process of determining absolute static strengths is well understood, the next step is to validate the durability of the structure over time.

Fatigue Testing

During design validation, a structure is exposed to both static strength tests and fatigue tests. However, once a structure is deployed, it spends the vast majority of its lifetime being subjected to smaller repeated forces that can cause cumulative damage over time. For this reason, testing the durability of a structure makes up a larger proportion of the tests that are run. Durability is one of the most important attributes that structures can posses. Consider the durability of gas turbine blades used in power generation. In this context, durability means less downtime and greater return on investment. For turbine blades used in the commercial and defense aerospace industry, durability is paramount for safety and readiness reasons.

Fatigue testing measures durability and is defined as the repeated mechanical loading of a structure to determine failure points. It requires complex analysis using the field of fracture mechanics, which is the analysis of material flaws to discover those that are safe and those that are liable to propagate as cracks and cause failure. The length of time that a structure can operate in a controlled and predictable manner is tested using a variety of fatigue methods.

High-Cycle Versus Low-Cycle Fatigue

Fatigue testing can be broken into two categories: high-cycle fatigue (HCF) and low-cycle fatigue (LCF). These tests characterize different modes of operation that a structure can endure. A cyclical input stimulus simulates these two operational modes. However, the number of cycles and amplitudes can differ greatly between the two approaches.

1. HCF simulates the stresses caused by online vibrations. Think of the number of vibration cycles that a turbine engine blade endures during operation. The nature of the stimulus used for this mode of testing is low-amplitude, high-frequency cycles used to test the elastic properties of a material. Test frequencies could range anywhere from 50 cycles per second to hundreds of cycles per second and the fatigue life of the structure is over 100,000 cycles.
2. LCF testing is performed at much lower frequencies but using higher forces to test the plastic properties of a material. In the example of the turbine blade, this may be a start-up/shut-down condition that exerts a large initial or final force on the blades. Fatigue life in this case is much shorter but could range from 10 up to 100,000 cycles.

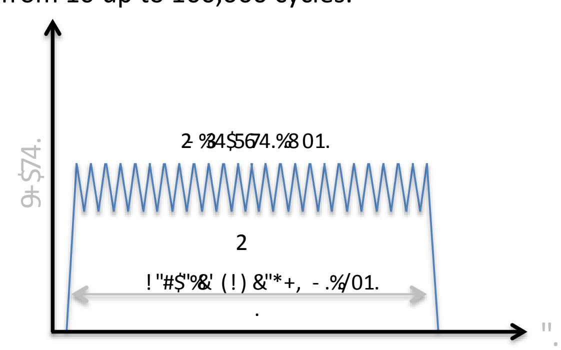

Figure 2. Pattern of Load Applied to a Turbine Blade in Service

Elasticity and Plasticity

The concepts of elasticity and placticity are based on stress and strain. Strain is the change in displacement per unit of initial material length. If a 1 m object is strained to 1.002 m, the amount of strain is said to be 2,000 uE. Stress is defined as the force applied to a cross-section of material per unit of area usually denoted in PSI. 400 lbs of force applied to a 2” x 2” piece of material would be subjected to 100 PSI. As you can imagine, strain and stress are related and can be seen in the graph below.

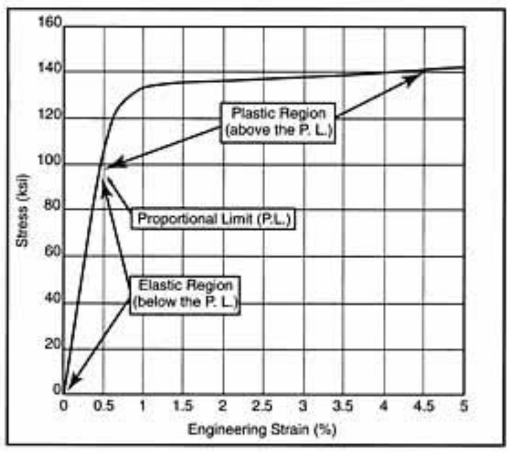

Figure 3. Material Stress-Strain Relationship[4]

The elastic region of a material is tested using HCF and refers to a region of operation where small changes in strain occur in the presence of large changes in stress. The elasticity of a material suggests that it will return to its original position once the input stimulus is removed. Think of a metal ruler fixed on one side to a desk and free on the other side so that a force can be applied with your finger. Unless you’ve exerted too much force on the ruler, the free end will return to its original position once you let go. This demonstrates the elastic properties of the ruler. It would take many cycles of these forces for the material to fail.

The plastic region of a material is tested using LCF and occurs at a point where the material will not return to its original position once the load is removed. In the example of the ruler, this could be a force that leaves the ruler permanently deformed (high strain) if you applied too much weight to the free end. The ruler could be bent back to its original position but it would require another large force to do so. Materials can usually only withstand low numbers of high strain cycles before they fail due to LCF. Large strains occur in areas of stress concentration due to mechanical features such as curves, notches, holes, and so on.

As you can see from Figure 3, in the elastic region, a large change in stress translates to very little strain. For this reason, HCF testing is accomplished by controlling the stress or load applied to the structure. This can be done using a closed-loop system that applies force using a hydraulic actuator and closes the loop by measuring a load cell sensor. In LCF testing, the strain levels can be very large for a small change in stress or load. Therefore strain is controlled in the very same manner but using a strain gage to close the control loop instead of the load cell. See the Measuring Strain With Strain Gages tutorial on the NI Developer Zone website for more information about using bridge-based sensors.

Fatigue Life Methods

Total Fatigue Life/Stress-Life (S-N)

The Stress-Life (S-N) or Total Fatigue Life method is widely used for HCF applications. During HCF testing, a material spends the majority of life in a state where the cracks are very small, the growth is controlled, and the structure integrity is retained. As noted earlier, the applied stress stays within the elastic range of the material. Total Life is determined by running multiple specimen tests at a number of different stresses. The objective is to identify the highest stress that produces a fatigue life beyond 10 million cycles. This stress is also known as the material's endurance limit. See the Fatigue Analysis in LabVIEW tutorial on the NI Developer Zone website for more information about the Stress-Life (S-N) method.

Crack Initiation/Strain-Life (E-N) and Crack Growth

The Strain-Life method uses LCF testing to measure when a crack will form. This happens when layers of a material slide past each other in a shearing process called slip. A crack forms along these slip bands and begins to grow more rapidly as seen by the nonlinear relationship in Figure 4. These cracks can be measured in a variety of ways using optical inspection, electrical resistance tests, and even estimated using strain gages to create a curve like the one shown in Figure 4.

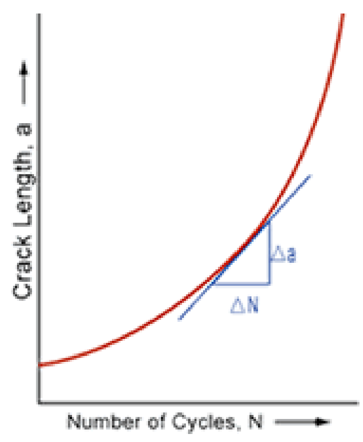

Figure 4. Increasing Crack Length Over N Fatigue Cycles[3]

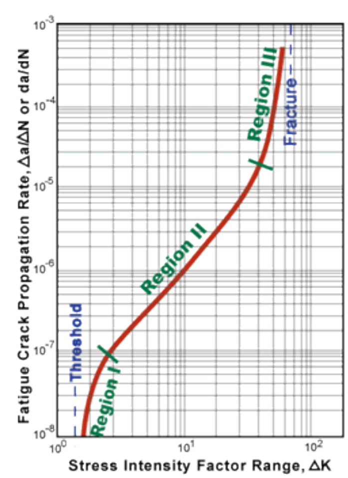

Figure 5. The Lifetime of a Crack[3]

This process can then be repeated by varying the magnitude of the cyclic loading to create a series of crack growth data as seen in Figure 5. The crack propagation behavior of many materials can be divided into three regions. Region I is the fatigue region where the force is too low to propagate a crack. Region II describes a behavior where the rate of crack growth changes roughly linearly with a change in stress. In region III, small increases in the stress produce relatively large increases in crack growth rate since the material is nearing the point of unstable fracture.[3]

Some structures like those found in aerospace and defense may spend the majority of their life in the crack growth stage. Due to the complex and repeated forces that an aircraft endures throughout its lifetime, material cracks are a way of life. Rivet joints are an example of components that need routine inspection, but in-depth analysis can predict the expected life of components like these. For this reason, it is imperative that designers understand the behavior of these cracks. In addition, design decisions could be made to delay crack initiation by adding new mechanical features during design. The analysis helps to ensure the design of structures that support slow stable crack growth until the crack reaches a length where it can reliably be detected.[3]

Conclusion

Static and fatigue tests are a critical means to understanding the durability of a structure over its lifetime. Despite the seemingly benign characteristics of fatigue, testing requires an understanding of fatigue theory as well as measurement and control considerations for prediction and improvement of a material's fatigue life.

References

1 http://www.designnews.com/article/2207-How_to_predict_fatigue_life.php

2 http://en.wikipedia.org/wiki/Fracture_mechanics

3 http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/FatigueGrowthRate.htm

4 http://files.asme.org/IGTI/Knowledge/Articles/13048.pdf