A High-throughput Vibration-based Fatigue Assembly to More Quickly Characterize High Cycle Fatigue Life

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Abstract. High cycle fatigue testing is notoriously slow and expensive, requiring many hours to produce 1 datapoint. As a result, designers of fatigue-sensitive systems often resort to outdated materials that have been qualified by regulators, and may not take full advantage of the latest advances in material science. Vibration-based methods significantly reduce these testing times by loading at higher frequencies on the order of kHz. This work presents a novel, high-throughput approach to reduce testing times even further by loading multiple specimens simultaneously. The specimens are monitored throughout testing with Digital Image Correlation, which allows for strains to be measured independently in each specimen. The assembly vibrates until one specimen fails, during which time the remaining specimens have accumulated the same number of cycles and have less time remaining until their own failure. Thus, although the time to complete 1 test remains relatively unchanged, the time to perform an extended fatigue testing campaign is greatly reduced by the number of simultaneously loaded specimens.

Possible Sessions

Fatigue & Fracture, Novel Experimental Techniques, or Aerospace Applications

Introduction

High Cycle Fatigue (HCF) is an important design factor for turbo-machinery components. HCF tests often require many hours or days to complete – for example, a load frame cycling at 40 Hz requires almost 70 hours to accumulate 10^7 cycles – generating only 1 datapoint. Such tests must then be repeated under other relevant operating conditions to populate the rest of the S-N curve. Additionally, fatigue is highly stochastic, with results sensitive to the unique microstructures and surface finish of individual test specimens, such that they must be further repeated to obtain a statistically significant population of measurements.

One way to reduce HCF testing times is with vibration-based methods, which oscillate on the order of kHz and can therefore complete tests much more quickly. When performing these tests, one must carefully monitor strains to ensure that each specimen is loaded at the desired amplitude. Since strain gauges have fatigue lives of their own and often fail before the specimen, it is common to additionally monitor the vibrating assembly with a laser doppler vibrometer (LDV) to measure the velocity that the plate oscillates at [1]. Because the LDV is non-contacting, it can continue to monitor the plate after a strain gauge fails and can be used to construct velocity-strain calibration curves from which to estimate the applied strain.

More recently, our lab has introduced Digital Image Correlation (DIC) as a non-contact alternative to reduce dependence on strain gauges [2]. The DIC requires significant post-processing, such that it cannot provide a real-time feedback signal to the shaker; however, it can continue to monitor deformation long after a strain gauge has failed, and additionally provides full-field context for the surrounding deformation state.

In this work: we take advantage of full-field DIC measurements during vibration-based fatigue testing to monitor up to 6 specimens in parallel. The assembly is loaded until one specimen fails, during which time the remaining specimens have accumulated the same number of cycles and are therefore that much closer to failing themselves. The test is paused while the failed specimen is removed and replaced with a fresh specimen, and testing resumes. Under this approach, we can apply the same number of fatigue cycles up to 5.49 times faster compared to testing each specimen sequentially [3], such that now instead of completing 1 test in an afternoon, we can begin to populate a whole S-N curve in the same time.

Sample Results

A finite element simulation of the 6-insert assembly is shown in Figure 1. The assembly consists of 6 beam-like specimens with hourglass-shaped gauge regions that are bolted into a shared carrier plate using fasteners. The assembly is cantilevered from a rigid clamping block on top of the shaker, with the fixed end oriented at the top of the figure as shown. The left half of the figure shows the mode shape, indicating uniaxial bending along each of the 6 insert specimens. The right half shows the resulting Von-Mises stress contours, indicating a large, uniaxial bending stress in the gauge region of each specimen. The stresses are unequal, such that no two specimens are redundant on the S-N curve, but are comparable in magnitude, such that the expected fatigue lives are also comparable (meaning that we don't waste many hours waiting for lower-stress datapoints after the higher-stress datapoints complete).

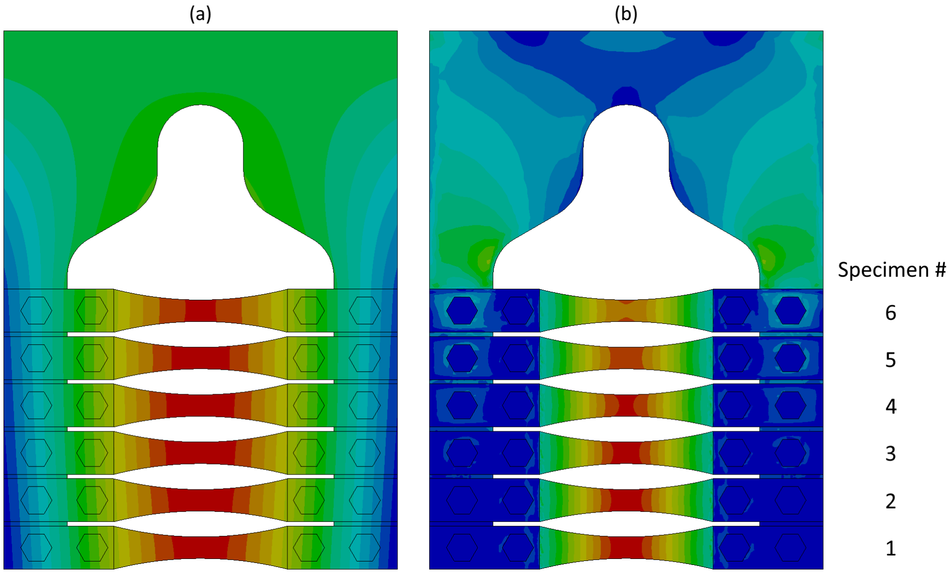

Figure 1: (a) Out-of-plane displacement contours for fatigue mode of six-insert plate. (b) Von-mises stress contours of the same resonant mode.

A preliminary S-N curve obtained using the assembly is shown in Figure 2. The figure compares three different vibration-based measurements for 6061-T651 aluminum. The “Six Insert” data (shown in blue) is obtained using the assembly in Figure 1. The “Two Insert” data (shown in black) is obtained using a similar assembly which contains only 2 inserts and is much easier to monitor using strain gauges. The “Bruns-Zearley” data was published by the US Air Force Research Laboratory, involving an assembly with only 1 insert [1]. Although all 3 methods perform comparably within the 95% confidence intervals of the single insert assembly, it should be noted that the 6-insert plate has a visibly much steeper slope, owing to interference from another resonant mode that has yet to be isolated.

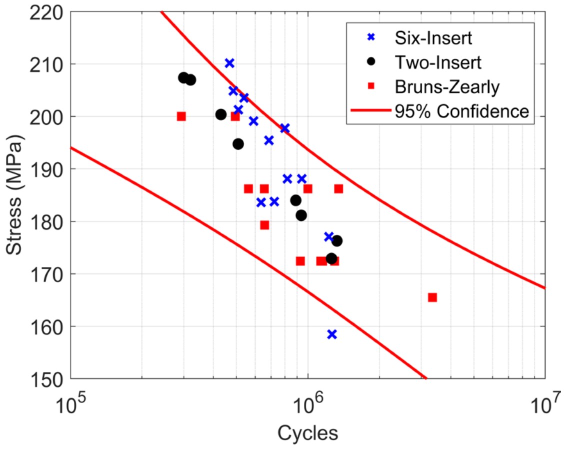

Figure 2: Fatigue life measurements for samples from the six-insert, two-insert carrier, and the single-insert carriers. Results for the single-insert carrier reproduced from [1].

Conclusion

In summary, the high-throughput assembly is estimated to accumulate fatigue cycles up to 275 times faster compared to axial testing at 40 Hz [3]. This will greatly accelerate the characterization of fatigue-resistant materials, such that designers of fatigue-sensitive systems can take fuller advantage of new advances in material science.

References

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