Accelerated Tensile-Tensile Fatigue S-N Curve Characterization of PP-GF30 and PA66-GF50 using Block Testing and Cumulative Damage Theory

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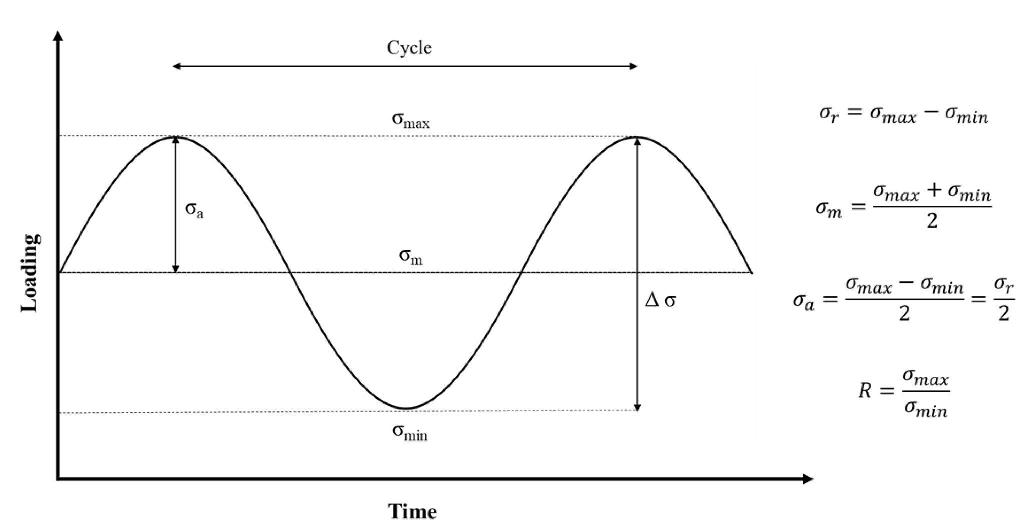
Problem

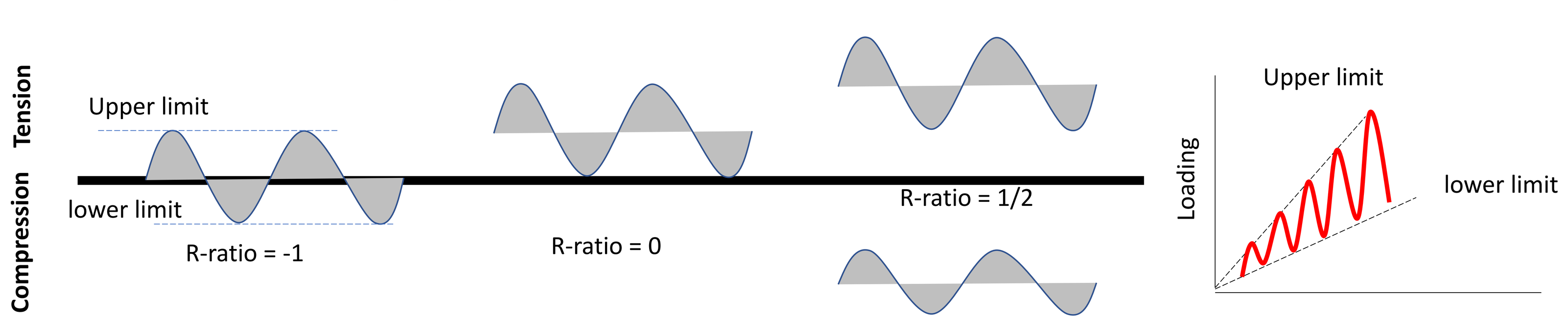
Fatigue performance is one of the most expensive features of a material to characterize. The creation of a simple S-N curve can tie up one fatigue machine for up to a month and cost thousands of dollars. The use of block fatigue testing and cumulative damage theory represent an alternative to generate the same S-N curve in less than a week. A traditionally created tensile-tensile baseline S-N curve was generated for PP-GF30 and PA66-GF50 to compare to several block testing setups with interesting results.

Background

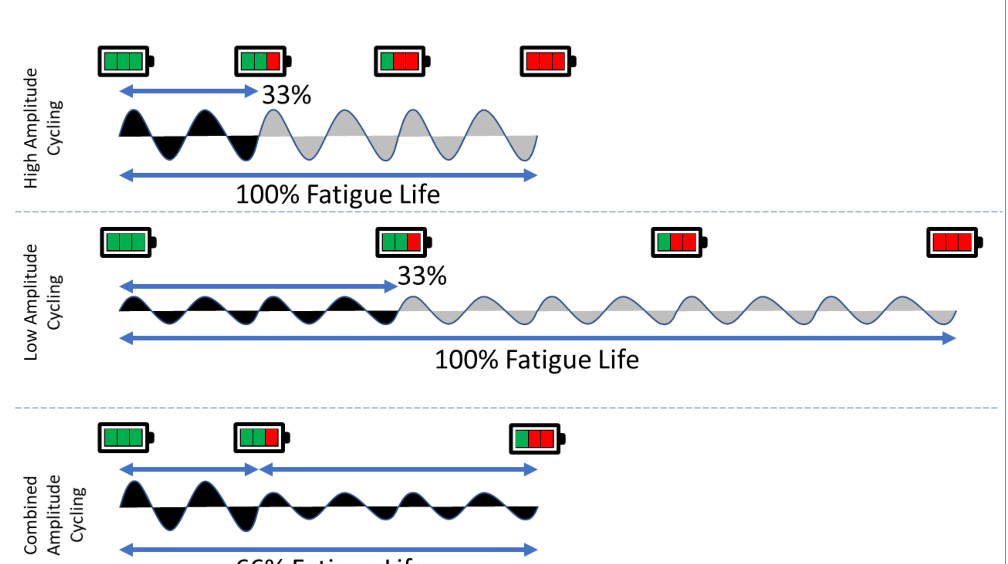
Fatigue damage occurs when an engineered material is subjected to cyclic loading, often at a stress well below its yield strength. Fatigue is the leading cause of failure in engineering systems and is particularly destructive due to its nearly imperceptible progress and catastrophic end result. Most fatigue characterization is conducted using Tensile-Tensile sinusoidal loading oscillating between a minimum tensile load and a maximum tensile load until failure.



Lab convention for fatigue testing is to use a constant r-ratio (typically 0.1) when generating an entire S-N curve to simplify documentation and S-N curve comparison. A constant r-ratio removes the need to document the minimum load/stress for every specimen tested.

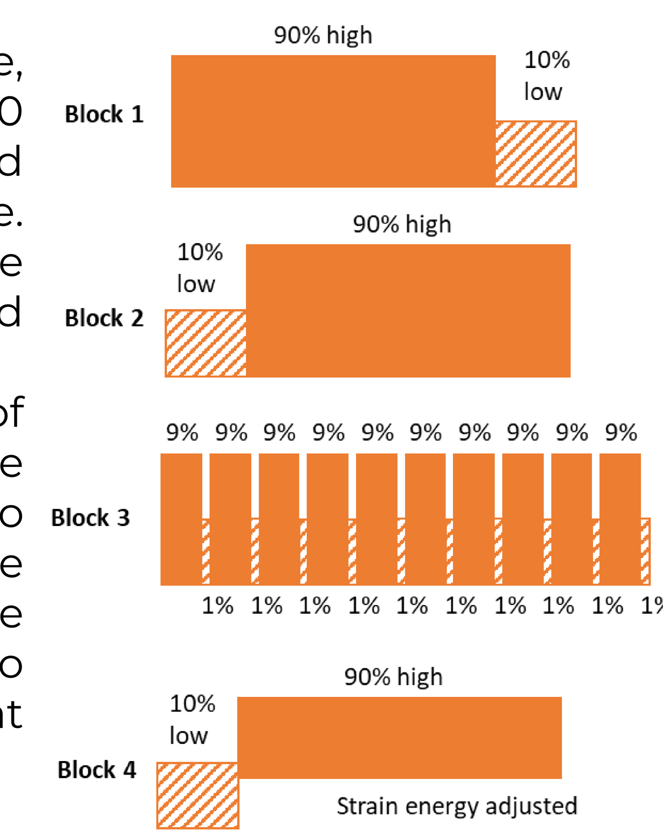


The concept of additive fatigue damage states that the same percentage of cycling to failure generates the same amount of internal damage, regardless of the applied loading. The fatigue life can be compared to a battery containing a certain amount of charge. Life can be consumed quicky at high load and slowly at low load. Consuming a third of its charge could happen quickly or slowly but provides the same end result: a remaining two thirds.



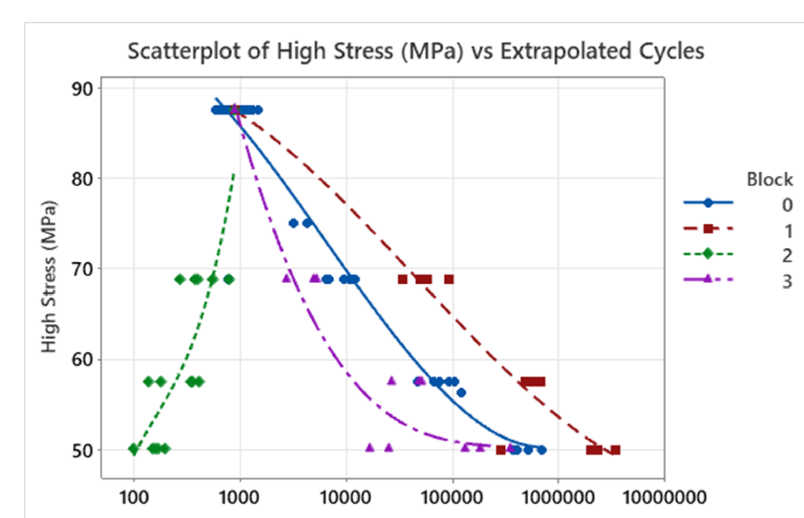
Block Testing

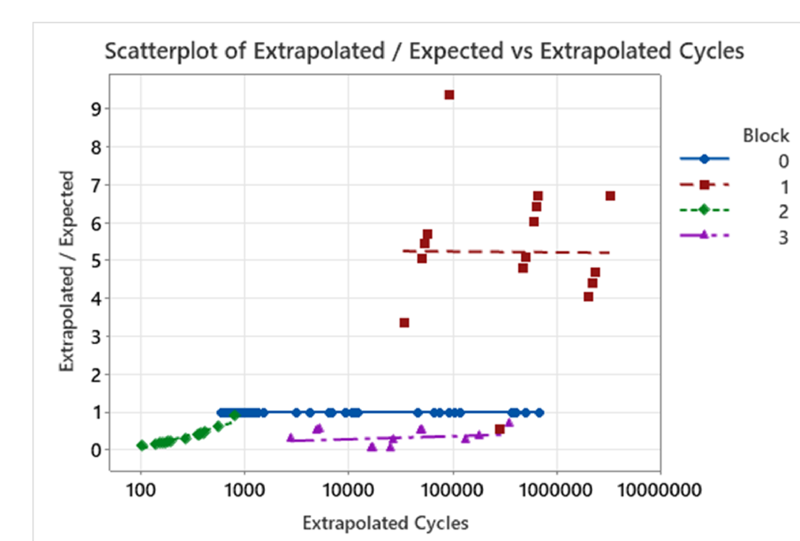
After generating a baseline S-N curve, loading was determined to achieve ~1000 cycles to fail, and 30 specimens were tested at this high load to have a statistical average. That average was used to calculate the number of cycles at high load that would consume 90% of the life of the specimen. Block 1 and 2 examined the effect of subjecting specimens to high loading before or after low loading. Block 3 was used to determine if it was more beneficial to have the high loading spread out throughout the life of the fracture path. Block 4 was used to try to better understand a few issues that resulted from Blocks 1-3.



Results – PP-GF30

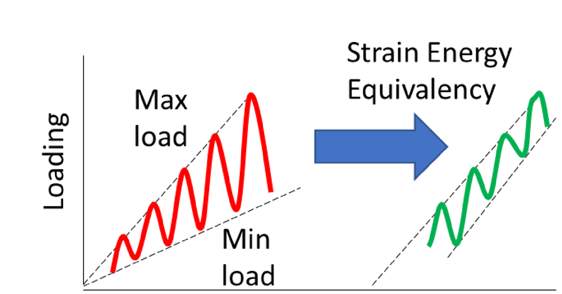
Block 1 testing would be the most practical method used of the approaches examined in this study, but the extrapolated fatigue life was 5.3 times higher than baseline curve (Block 0). Block 2 is impractical because it requires the use of a baseline S-N curve, which is what this research aims to eliminate. The results were the reverse of Block 1 and had less accurate predictions as the low load oscillations were lowered.





The results from Blocks 1 and 2 indicated that the order of loading for this fracture mechanics problem mattered, which is why Block 3 was examined to space high and low loading out throughout the nucleation, steady state, and non-steady state phases of crack growth. This was better than Block 2, but also seemed to result in lower values as more load changes occurred. Detailed analysis of the results from Blocks 1-3 seemed to indicate that the culprit in this case Is the use of a constant r-ratio. The imposed strain energy and strain rate with a constant r-ratio will shift as the material transition from high to low block loading.

A few bars were tested using Block 4 to determine if the data needs to be shifted due to non-equivalent strain energy resulting in data that shifted closer to expectation. Adiabatic heating or Thirion polymer chain creep may be causing this discrepancy.

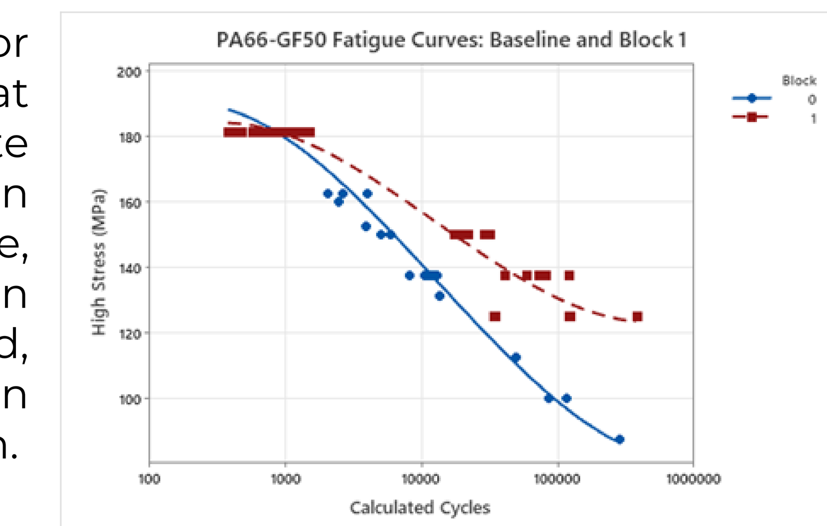


$$Strain\ Energy = \frac{1}{2} \times \frac{1}{E} \times \sigma^2 \longrightarrow \frac{1}{2} \times \frac{1}{E} \times {\sigma_1}^2 = \frac{1}{2} \times \frac{1}{E} \times {\sigma_2}^2$$

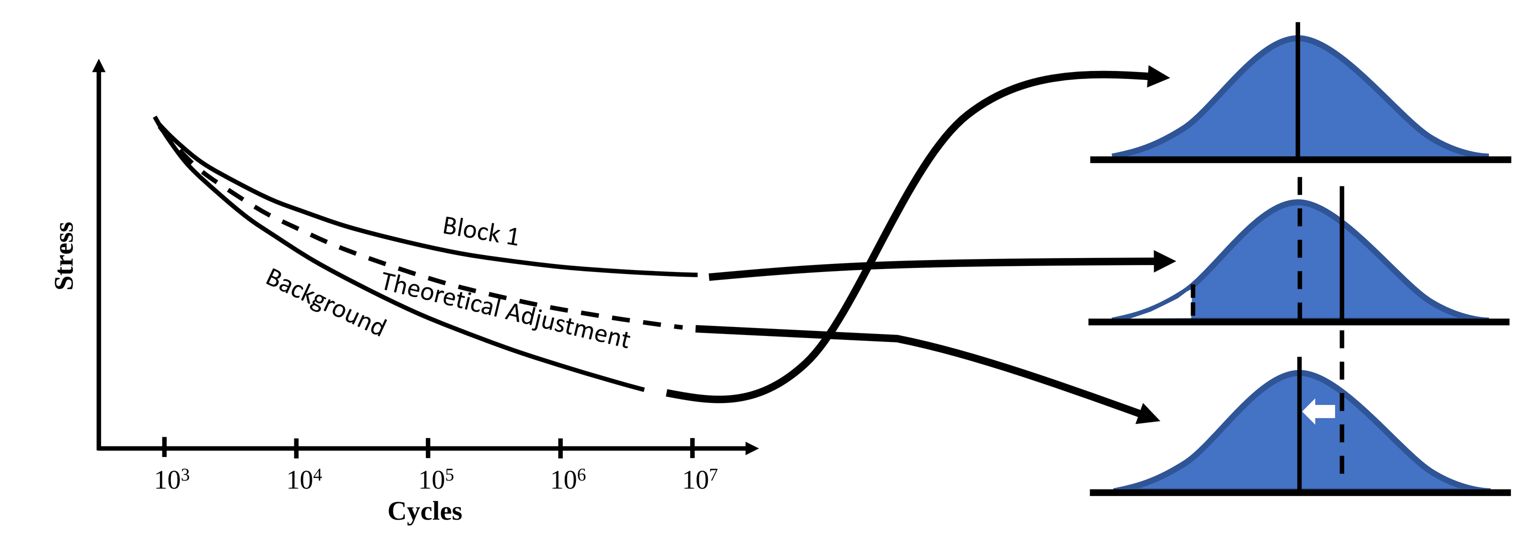
$$\left(\frac{Max\ Load - Min\ Load}{2 \times Bar\ Area}\right)_1^2 = \left(\frac{Max\ Load - Min\ Load}{2 \times Bar\ Area}\right)_2^2 \longrightarrow \boxed{\left(\frac{2000\ N - 250\ N}{2 \times 40\ mm^2}\right)^2 = \left(\frac{3500\ N - x}{2 \times 40\ mm^2}\right)^2}$$

Results – PA66-GF50

Only Block 1 was examined for PA66-GF50 as it was the setup that was the most promising to create an accelerated S-N curve. When compared against its baseline, extrapolated results were again consistent across the loads tested, but the constant was higher than PP-GF30 at 6.45 times expectation.



The time savings of this test is highly dependent on how much fatigue life is removed at high loading, but every material has a standard deviation associated with its mechanical performance. This means that some bars will last longer and some will fail sooner, but the average is what is documented on a S-N curve. Consuming 90% of fatigue life first for PP-GF30 and PA66-GF50 resulted in some bars failing prior to reaching the second block in the test. The test setup would cull bad material/specimens from the analysis and shift the results artificially higher than a normal grouping of baseline. A test method developed from this research may need to be adjusted back to account for the statistical removal of the normal data set in addition to other correction factors related to strain energy, strain rate, and adiabatic heating.



A side-by-side comparison of the PP-GF30 and PA66-GF50 is shown below. GF30 results in a very even distribution of fiberglass, while a GF50 is near the limit of fiber loading resulting in a higher Coefficient of Variation.

PP-GF30
- 30 specimens used to generate highest loading
- Line Shift Coefficient = 5.30
- COV = 25%
- 33% of bars "screened out"
- 2 Hz
- Lower Fiber Content

PA66-GF50
- 30 specimens used to generate highest loading
- Line Shift Coefficient = 6.45
- COV = 34%
- 43% of bars "screened out"
- 1 Hz
- Higher Fiber Content

Future Work

Fatigue properties are used to design parts and many engineers have a surface knowledge of the topic. Peeling back a few layers as to how this testing is conducted and delving into the material response has been very interesting. Many things line up with general theory and many things do not line up with general theory. The next step for this research is to examine what affect latent strain energy has on this topic.