ENHANCED FATIGUE TESTING OF COMPOSITES

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1 Abstract

A novel approach to composites fatigue testing is presented, to effectively control specimen temperature while optimising test duration. This offers improved repeatability and increased test throughput.

A fatigue test technique has been developed which employs adaptive frequency control in response to specimen temperature. Using a thermocouple or a commercial infrared detector to supply a feedback to the control system, frequency control throughout the test can maintain specimen temperature within a tight band. Comparable results are presented for various composite materials, using representative “industry standard” and our novel method.

2 Background

Fatigue testing of composite materials has become increasingly important over the last 5 years or so, led most noticeably by the wind energy industry. It is now widely recognized that these materials do accumulate damage over long periods of cyclic loading, even if the failure mode and mechanisms are radically different to conventional metallic fatigue. Thus the advent of (relatively) high strain, long service, safety critical applications, has led to a commercial need for composites “fatigue” tests to qualify materials.

Extant standards [1,2] are thorough, but not highly prescriptive, embodying conservative recommendations for test frequencies, but a generous ceiling limit on specimen temperature fluctuation. Working at a cyclic loading frequency below 5 Hz results in lengthy tests, during which specimen temperatures can still rise by as much as 20 °C. To the laboratory manager such time is undesirable and to the material scientist such temperature variation is highly questionable.

3 Experimental

3.1 Equipment

Instron servohydraulic dynamic test frames were used (100kN and 250kN capacities respectively), fitted with hydraulic wedge grips, and appropriate alignment and anti-rotation accessories (example system as see in Fig.1). An Optris PI450 infrared camera with configurable analogue output was used for non-contact temperature measurements. For contacting temperature measurement, thermocouple sensors were integrated using National Instruments USB thermocouple input units with DAQmx software which interfaces directly with Instron WaveMatrix test software. Instron's software also embodies a native extension providing real-time calculation of dynamic moduli, loss tangent, and energy dissipation.

3.2 Control Implementation

The system of frequency modulation was developed experimentally in a modified version of Instron’s test software.

The adaptive frequency control system is effectively an outer loop control algorithm, run by the test software, which adjusts the machine controller parameters. A number of approaches were tested, but monitoring the rate of temperature change relative to the target was found to be most successful. Control system algorithms and development will not be discussed further in this paper.

Instron has just implemented “Specimen Self-heating Control” as a standard extension to WaveMatrix dynamic test software, and the company holds an international patent application
[3] on the use of modulated test frequency based on temperature feedback to control specimen temperature during cyclic loading.

Fig. 1: Typical Instron 8802 test frame suitable for ambient temperature composites fatigue - 250kN capacity, fitted with hydraulic grips, alignment and anti-rotation fixtures.

3.3 Temperature Measurement and Response

It was notable that the response in measured specimen temperature is not necessarily immediate when the frequency is altered. In many cases, an appreciable lag is observed, which appears to be related to the thermal mass and conductivity of the sensor connected; larger beaded or probe thermocouples can take in excess of 20 seconds to register a change in heating rate; fine thermocouples somewhat less; infrared bolometer or thermopile measurements show an almost instant response.

3.4 Specimens and Test Regime

Specimens were prepared and tested in accordance with international composites fatigue standards [1,2], with glass fibre reinforced, medium temperature matrix, and with carbon fibre reinforced, high performance prepreg materials respectively. Initial tests were conducted in Instron’s facilities using glass fibre reinforced material. A basic thermal imaging camera was used for non-contacting temperature measurement during these tests, allowing assessment of temperature distribution (not discussed in this paper) while simultaneously providing an analogue signal for temperature to the control system.

In a more extensive case study, a standard set of load controlled, tension-tension, fatigue tests were conducted to produce an S-N curve. Peak stress values between 60 % and 80 % of static failure stress were used, with a loading ratio of R = 0.1, at a fixed frequency of 4 Hz, with temperature monitored, but not controlled. The complete test regime was then repeated using the adaptive frequency control to maintain a stable temperature. Since thermocouples are the industry standard method for temperature monitoring, these tests were conducted using thermocouple transducers as the temperature input to the control system.

4 Initial Results

These are demonstrations from the latter stages of the frequency control system development, illustrating how it responds to two likely test scenarios.

Fig.2 illustrates the start of a typical test, using glass fibre reinforced epoxy resin, loaded to 40 % of static failure stress, in tension-tension mode at R = 0.1.

Here an initial frequency of 5 Hz was set, in low ambient temperature (18 ± 1 °C), with a target test temperature of 21.0 ± 0.5 °C.

Clearly for this loading rate, 5 Hz was not sufficient to cause significant temperature rise, so the system has gradually increased this frequency until it stabilizes just above 15 Hz, having assessed that target temperature will be achieved within 20 minutes. It is also interesting to note that at around 20 minutes into this test, a lab door opening caused sudden drop in specimen temperature, so the system responded by briefly increasing frequency by a small amount to correct this.
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Fig. 3 shows the system reducing the test frequency to prevent overheating. Using the same type of specimen, this time loaded to 60% of failure stress controlled to 28.0 ± 0.5 °C. Having already seen some 50000 cycles, this is effectively the final part of the test. After an initial settling period commonly observed in composites fatigue, tan delta shows continuous increase as damage accumulation accelerates, as other researchers have observed [4,5,6] in various systems.

Firstly, the starting frequency is quickly reduced to prevent overheating, then gradually adjusted to correct for the increasing energy deposition rate to maintain specimen temperature which would otherwise increase significantly [6].

5 Full S-N curve generation

45 standard tensile test specimens [1,2] were prepared from a single, flat sheet of thoroughly conditioned epoxy matrix material with woven carbon fibre reinforcement. Following initial measurement of static tensile strength, the remaining specimens were split randomly into two groups.

The first group was tested at a fixed frequency of 4 Hz, in the usual manner used by NCCEF for contract testing of tension-tension fatigue.

The second group was tested at the same stress ranges, but this time employing the adaptive frequency control method. The control algorithm was given a target temperature of 30.0 ± 0.5 °C, and allowed a maximum operating frequency of 15 Hz.

These two datasets are plotted as a standard S/N curve in Fig. 4.

There was no evidence of unusual failure mode for the two outlying points observed at the lowest stress level in the fixed frequency (4 Hz) data. Since the rest of this data set does not show such broad
variability, no conclusion can reasonably be drawn on that basis.

Many commercial experimentalists apply a logarithmic fit to the S-N data from composite fatigue testing to facilitate fatigue life prediction. On an empirical basis this appears a good fit for both sets of data presented; details of the fitting parameters and resultant predictions are tabulated in Fig. 5.

Whether or not this is the best possible methodology is not the subject of this paper, but it is undeniably a simple extrapolation technique for practically obtainable data; one which will generally give conservative predictions. The range of fatigue resistance and resultant S-N curves for composites are as diverse as those seen for metals (if not more so), so it seems entirely probable that the behavior is not neatly logarithmic, and even a “no fatigue limit” might exist in some cases. Validity of this fitting procedure and rigorous assessment of confidence levels are detailed in relevant international standards for analysis of fatigue life data [7, 8].

Examining Fig. 5, there is good congruence of the fitting curves for fixed and adaptive frequency methods. It is interesting to note that both the fit quality (“R² value”) and the intercept (prediction for static failure) show a small improvement for the

<table>
<thead>
<tr>
<th>Logarithmic fit $\sigma_c = -a \ln(N) + c$</th>
<th>Gradient, $a$</th>
<th>Intercept, $c$ (% UTS)</th>
<th>Fit quality ($R^2$)</th>
<th>Predicted Stress at $10^7$ cycles (%UTS)</th>
<th>Predicted Stress at $10^8$ cycles (%UTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Hz – all data</td>
<td>3.156</td>
<td>106.7</td>
<td>0.844</td>
<td>55.9</td>
<td>48.6</td>
</tr>
<tr>
<td>4 Hz – exclude outliers</td>
<td>2.886</td>
<td>104.4</td>
<td>0.931</td>
<td>57.9</td>
<td>51.2</td>
</tr>
<tr>
<td>Adaptive frequency</td>
<td>2.651</td>
<td>100.7</td>
<td>0.966</td>
<td>57.9</td>
<td>51.8</td>
</tr>
</tbody>
</table>

Fig. 4: S-N plot for CFRE (woven prepreg) from fixed frequency and adaptive frequency methods.

Fig. 5: Comparison of data fitting and prediction
adaptive frequency data. More importantly, the predicted stress level to achieve specific long fatigue lives (a key criterion for many commercial applications) is extremely similar.

Fig. 6 gives a comparison of the time reduction and frequency variation resulting from the use of adaptive frequency control for a full set of fatigue tests on this material.

Firstly, from the authors’ viewpoint, the headline figure is that of a 27.5% reduction in total machine time to produce the data set. On the basis of the NCCEF fixed frequency testing at 4 Hz which took approaching two months of machine time, this represents a significant saving, both in time and power consumption for the laboratory.

Secondly, this time saving is achieved with fairly conservative variation in test frequency. It has been proposed that an increase in test frequency of even a whole order of magnitude may have little effect on the fatigue behavior of composite materials [9]. Composite fatigue practitioners frequently mention temperature increases exceeding 20 °C in materials with woven reinforcement; clearly this cannot be deemed a well-controlled test, or representative of operating conditions. The authors of this paper propose that closed loop frequency modulation to control the degree of specimen heating, offers a valuable and realistic alternative.

6 Conclusion

The authors had sought to increase test throughput for tests, and allow the experimentalist more realistic access to the long fatigue life data, which are often of greatest interest. In this regard, the development of an adaptive frequency control method for fatigue testing of composites can make a tangible difference.

A case study demonstrated that this new approach resulted in a major reduction in machine time requirement, without any significant influence on the final output of the test.
References


