Composites on the Move: Growth in the Dynamic Testing Market for Composites

Peter Bailey, PhD - Sr. Applications Specialist, Instron

Introduction

Composites are now a broad and well-established family of materials, but industry press releases frequently discuss “new and exciting” developments and opportunities. It should be remembered that there has been a commercial market in high performance, structural composites for well over 30 years, and that European automotive manufacturers have made considerable use of lower performance glass fiber reinforced polyester [GFRP] bodywork since the 1950s. Furthermore, a high level of interest from the aerospace industry has resulted in a wide range of well-established static test methods giving reliable results. Sadly, there is still only limited consensus, so test houses and machine manufacturers find themselves maintaining an extensive catalogue of fixtures, in order to meet diverse international and industry standards. From this starting point, it might be argued that there is little news in composites testing, but in fact some exciting trends have started to develop.

Fatigue Testing

Leading the way has been the wind energy industry; in the last 6 to 8 years the major manufacturers have quickly adopted fatigue testing as a key part of their composite materials evaluation. Some may find this surprising, but in fact the nature of this sector means it has greater freedom than others in terms of qualification and adoption of new materials. Furthermore, significant levels of elastic strain may be acceptable in turbine blades, and balancing design life and cost correctly can give a significant competitive edge.

The most common implementation for fatigue testing of composites is in tension-tension mode. This is generally due to the greater simplicity in terms of specimen preparation, gripping, and machine set-up. A significant number of research establishments are pressing the importance of compression-compression, or fully reversed fatigue tests on composites, since these are both more representative and more aggressive tests. However, this does present greater challenges in terms of equipment and in specimen preparation, to avoid buckling or mixed mode loading.

For all fatigue loading cases, a major concern lies in the fact that composites exhibit an unpleasant combination of temperature sensitive behavior and heat generation during loading and failure. (Fig.1) As a result, the testing process can severely affect the properties to be measured. In static tests these problems may be mitigated by carefully controlled environment in combination with very low loading rates. In a cyclic test this is impractical; considering a cyclic test to failure at 1 million cycles, then at the 1 mm/minute rate of displacement preferred in static tests, this would take around 2 years for a single specimen!

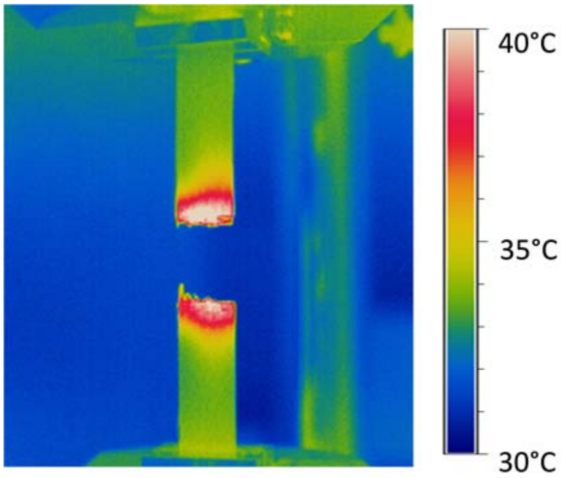

Fig.1 Thermal image showing heating at failure of static tensile test (1mm/min) of an impacted composite specimen

General practice is therefore based around practical methodologies derived from metals fatigue, using a sinusoidally varying applied stress at 3 Hz to 5 Hz frequency, typically described by a peak stress and stress ratio. Compared with metals fatigue these are very low frequencies, and yet they tend to result in surface temperature of heavily stressed specimens increasing by 20 °C to 40 °C during test, while less loaded specimens run at less than 2 °C above the ambient temperature. The outcome is a lengthy test schedule of 4 to 8 weeks of machine time to produce an SN curve for a single composite material, in one particular lay-up, with poorly controlled specimen temperature, and a high degree of scatter. Some workers have started to use frequency optimization (automatically or manually selecting different frequencies for different stress levels) to reduce the total test time. Slightly decreasing the test frequency for highly stressed specimens avoids overheating, while a small increase for lower stress levels saves considerable amounts of time. Researchers at the National Composites Certification and Evaluation Facility, University of Manchester, UK, found that it took 55 days of continuous running at 4 Hz to prepare an SN curve for woven carbon fiber composite and that specimen temperatures varied by ± 7 °C. When they used an automatic system of adaptive frequency control, surface temperatures were controlled within ± 0.5 °C on all specimens and the machine time was reduced by over 27%.

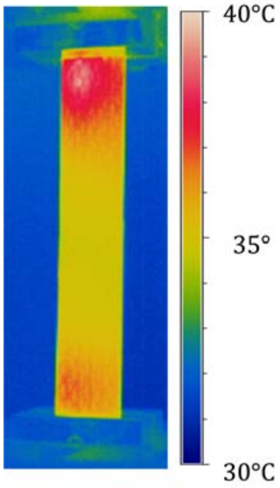

Fig.2 Thermal image of self-heating of fatigue specimen 10 minutes into test (woven carbon fiber epoxy, 5 Hz test speed)

Fatigue testing of composites is still in its nascent stages, in terms of scientific understanding of the phenomena, but it has already found an urgent industrial need. From the material scientist's view, a range of failure mechanisms at a range of length scales are interacting, and they are so different from those in metals that it could be questioned whether using the term “composites fatigue” is a misleading. The effects of processing (e.g. lay-up sequence) can be more severe than in metals, as can the results of different temperatures or strain rates, and the challenges of producing representative samples are considerable. Furthermore, there is ongoing debate on how best to define specimen “failure”. All parties agree that specimen rupture is not a good metric, yet it remains the accepted measure, since no single construction (for example xyz% reduction in modulus) has been identified which can be used comparably across the whole, diverse family of polymer matrix composites.

Recalling that metals fatigue came into being a century and a half ago, it becomes apparent that despite numerous problems as yet unsolved, by way of comparison composites fatigue is progressing rapidly after only 30 years and industrial adoption will soon result in some pragmatic improvements.

High-Speed Testing

Slightly more recently, the demand for light-weighting in the automotive sector has prompted manufacturers to investigate using high performance composites for more critical and structural parts, as a way to push mass savings even further than those available with modern metals technologies.

Some 10 to 15 years ago, strain-rate testing of metals caused a minor revolution in evaluation of automotive materials, since it gave much more informative data on differences in behave in crash scenarios. An initial phase of realization and assessment has resulted in many automotive companies concluding that greater adoption of polymer matrix composites is worthy of investment. Processing and design with structural composites has significantly different challenges, but as with fatigue testing, initial work has largely employed similar models as those for metals by way of a starting point, so experimental data is an essential input. For this area of development, existing equipment and methodologies to start from certainly seem to have helped; a number of specialized materials test systems found a new lease of life, and many new systems are being built.

By way of an example, Figure 3 is reproduced by kind permission of the Institute for Lightweight Structures and Materials at the Technical University of Dresden. This is taken from work published in 2010 as an early demonstration, showing a startling picture of just how sensitive composites can be to the very high strain rates seen by crash structures. The modulus of the material at high strain rate on the axes of reinforcement fibers shows a noticeable increase of around 15 % compared with static loading, but in the 45 ° orientation this increase is over 250 %. The Institute's commercial arm, Leichtbau-Zentrum Sachsen GmbH, provide development and contract testing of this type of testing to a variety of automotive and aerospace companies in northern Europe.

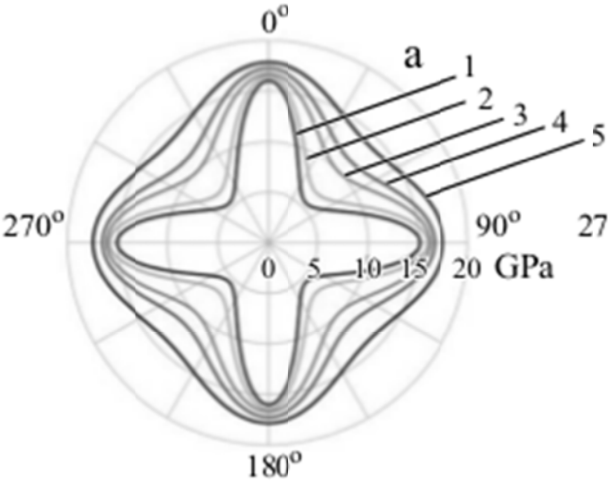

Fig 3 – polar plot of tensile modulus vs angle for a simple woven cross-ply laminate at increasing strain rate

1) 0.00044 s^{-1}, 2) 0.044 s^{-1}, 3) 0.44 s^{-1}, 4) 4.4 s^{-1}, 5) 44 s^{-1}

Gude et al*, Mech. Comp. Mat.*, Vol.45, No.5

However, high strain rate testing of composites (and of high strength metals) is not a trivial endeavor. Firstly, all the problems which might be encountered with gripping for static test tend to be exacerbated; issues such as failure at grip, effective tab bonding, or slippage of un-tabbed specimens, amongst others. Secondly, the test itself occupies a very short duration, often less than 2 milliseconds. This is due to the fact that test speeds are up to 25 meters/second, combined with the very high stiffness and low elongation at break which typify structural composites. This requires highly specialized methods of load and strain measurement, which in turn result in considerable data analysis.

Load is typically measured using a piezoelectric transducer within the load-string, which converts applied stress directly to a potential difference (voltage). These devices provide extremely high stiffness and near instant response, ideal for the necessary data acquisition rate. However, those features come with the penalty that this type of "load cell" offers almost no damping, so the shock loading with sudden failure and recoil of the test piece results in strong, but repeatable, resonances which must be filtered out appropriately to determine the true applied load on the specimen. A few workers use strain gauge based load measurement, but the mechanical damping inherent to a device which must necessarily be mechanically compliant raises questions over the fidelity of the load trace and the bandwidth of signal conditioning.

Similarly, strain cannot be measured by conventional contacting methods used in low speed tests. It is possible to apply strain gauges to the specimen and connect them to high bandwidth amplifiers, but firstly, it is easy to question whether the location and area is representative of the specimen bulk, and secondly, the gauges do not remain adhered to the specimen throughout the test. A more successful method for general strain measurement is to use a high speed optical extensometer; these are still based on relatively old technology which tracks a simple line of strong contrast at either end of the gauge length. The most popular and effective method is to apply a speckle pattern directly to the whole area of interest, then trigger a very high speed digital camera to collect a series of images, which are then post-processed using a Digital Image Correlation (DIC) technique. Although considerably more expensive, DIC systems have great advantages in terms of understanding strain distribution during failure and the influence of edge effects.

Once again, this is a technically demanding test, the data from which requires considerable care in interpretation, but these issues are outweighed by the importance of providing crucial insight, which cannot be obtained by other means, into the material behavior.

New Analytical Techniques

At this juncture it is necessary to comment on the increasing impact of thermography on dynamic testing, and on composites testing in general. As discussed earlier, composites exhibit a significant energetic response to loading, but this can be observed both in damaging and in purely elastic conditions.

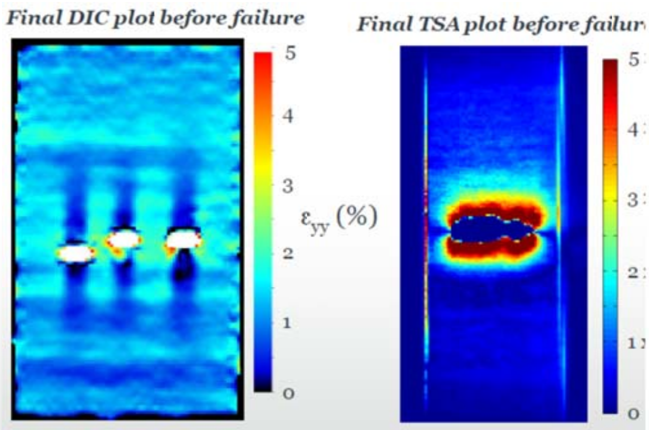

Fig 4 – Comparison of maps of axial strain from D.I.C. (left) and local stress from T.S.A. (right) on the same specimen giving complementary information. Here an impact damaged composite specimen has been subjected to fatigue loading.

Crump et al*, Engineering Integrity*, No.35

In the simplest sense, imaging the infrared emission from a specimen can give useful qualitative information on location and evolution of heating and damage during a test, as seen in Fig. 1 & 2. With appropriate calibration it can also be used to directly measure surface temperature, but this must be approached with some appreciation of the factors which affect measurements. Firstly, materials which are chemically or visually similar can have significantly different values of emissivity, which determines the intensity of infrared light released by the specimen. Secondly, emissivity can vary with temperature, this is generally only a subtle change for polymers, but when monitoring metals at high temperature quite serious changes can be observed due to formation of oxide layers. A final consideration is that almost all specimens will also reflect radiation from the surrounding environment, so readings from an unshielded test area at ambient temperature can be affected simply by reflected radiation from people walking around the laboratory.

On a more advanced level, which is rapidly gaining traction within the research sector, the University of Southampton pioneered a new technique of thermo-elastic stress analysis (TSA), which can be applied to all types of material, using cameras with much higher sensitivity. Here the relationship between temperature and mechanical dilation is used to analyze the stress distribution in a system, by comparing the surface temperature difference between two load levels. Stress mapping generated in this manner can be conducted in parallel with strain mapping generated using digital image correlation, and these two independent techniques used for mutually verification. To date, this approach has been used most effectively with very high performance cameras, to maximize the data extracted from very high speed tests. Although this is largely academic research at present, it is paving the way for application of less expensive equipment to more routine studies of damage evolution in the future.

Moving to Higher Capacity

So far in this article, the aerospace sector has not been mentioned with regard to new areas of composites testing, and it has historically been criticized by some researchers for its necessarily conservative, cautious approach. Flight-ready technology does take a long time to pass through approvals, but that does not correspond to a lack of applied research activity. Personnel from the R&D departments of major aerospace manufacturers expressly publicize the fact that a large part of their development work is centered on composite technologies. In addition to developing their production technologies, these groups are working to identify robust, repeatable approaches for dynamic performance evaluation. Meanwhile as China and India prepare to enter the commercial aerospace market, their new research institutes have invested heavily from the beginning in a full range of dynamic testing capabilities for both metals and composites.

Another recent market development is an increasing demand for very high capacity servo hydraulic test frames. Although the tests for which these are used often do not require highly dynamic performance in terms of frequency or number of cycles, their use is definitely not confined to high force monotonic tests. In this case, the aerospace industry is foremost in generating this requirement, for two reasons. Firstly, large, high strength structures are produced from thick composite laminates, with complex lay-ups; this means that a representative test specimen must often be the full thickness and only a finite width reduction is possible without undue influence of specimen edge effects. Obviously, if the specimen cannot be made smaller, machine capacity must be higher. Secondly, for similar reasons, the influence of laminate design and processing means that there is no alternative but to test whole structural elements.

True Progress

There is no doubt that the structural composites market is only going to keep growing for the foreseeable future, and that certainly is interesting. However, it may be argued that some of the most commercially exciting developments are starting to be achieved by industrial acceptance of different design needs, which must in turn be supported by even more rigorous and demanding mechanical test techniques.

Ultimately this commercial demand comes from the power generation and transport industries which have become central to our era, since they must now evaluate various aspects of the dynamic performance of composites in order to use them in safety critical, moving structures.