Use of Non-Contacting Strain Measurement Techniques in Fatigue Testing of Polymer Matrix Composites

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ABSTRACT

This paper presents a short investigation of the benefits of non-contact strain measurement for monitoring and control of fatigue tests on composites. Recent developments in measurement technology offer the means to effectively measure both axial and transverse strain, instantly, throughout cyclic and highly dynamic tests. Several test scenarios are examined which demonstrate potential benefits of current state-of-the-art video extensometry, for strain controlled fatigue tests on thermoplastic composites.

Live extensometry enables continuous monitoring and live calculations throughout the test and provides the option to automatically collect additional data for loading cycles with anomalous behaviour. It also allows a good control system to safely apply accurately strain-controlled loading of specimens, even where specimen behaviour is changing rapidly with every cycle.

Digital image correlation techniques can offer complimentary information on the full-field strain behaviour of a specimen, but the data processing and storage requirements are considerably too large for live or continuous measurements during fatigue tests.

Keywords:

Fatigue, Strain measurement, Mechanical testing

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Introduction

Contacting extensometers are a well-established method of strain measurement for materials testing which have been used since very early in the history of modern metallurgy and materials science [1-3]. The object is to obtain a good measure of the strain in the material, by determining the average extension of a representative length, which is subject to the intended loading conditions. The worker must accept that in tests to characterise bulk material performance, the point of load introduction is never subject to the same loading conditions as they are trying to evaluate. Likewise, for bulk mechanical measurements, it is important to take measurements from a sufficiently large volume of material that any local effects of microstructure are averaged appropriately.

Contacting extensometers can be self-supporting on a bracket or mounting, or be specimen mounted with their weight and resistance contributing to the stress applied to the specimen. In both cases a well-chosen device will provide the most precise, reliable, repeatable data possible. A wide variety of designs have been developed over some 140 years, transitioning to electronic reading devices from the 1950s onwards with the pioneering work of researchers such as Buck and Hindman [4,5]; that particular collaboration lead to the birth of Instron [6]. Although the industry continues to make incremental improvements every few years, this is largely associated with the electronics and computer systems used; mechanical and electrical performance of the physical device largely plateaued by the 1990s and new designs are mostly created to improve ergonomics or meet specific trends in customer demand.

Figure 1: Extensometers ancient and modern

(left) one of the earliest contacting extensometers produced by J. A. Ewing in Cambridge, c1890;
(right) Instron AVE2 video extensometer for dynamic measurement, released 2015.

Video extensometry is also now a moderately well-established option, the earliest systems coming into service in the late 1970s. Since the performance of these systems is predominantly governed by the automated imaging and data processing which enables them to work, improvements in this field have been somewhat more impressive. At the time of writing, the authors believe that the measurement technology is approaching practical limits of achievable accuracy and resolution. Although improvements are certain to continue in terms of ease of use and inter-laboratory

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repeatability, the current camera and processing performance are no longer limiting the measurement performance of systems for quasi-static test; rather the optical effects of specimen and environment are most significantly affecting measurement uncertainty.

Background

At the time of writing, the most rapidly growing commercial demand to implement composite materials is coming from the automotive industry. For many years this industry has used injection moulded polymers for a wide variety of non-critical components, for either cosmetic or only semi-structural purposes. However, with an urgent and legally imposed necessity to reduce carbon dioxide emissions from vehicles, one seemingly simple initiative for automotive manufacturers is to reduce vehicle mass. In consequence a vast array of schemes are being proposed and developed for using composite materials. Among those, some of the most immediately practical contributions are around using moderately established injection or compression moulded thermoplastics for components such as engine mounts, or for over-moulding much thinner metal pressings to produce hybrid structural components. The key benefit of this over more expansive (and expensive) schemes for continuous fibre body shells, is their production viability in the short term; of course such components are also still very likely to be needed in combination with grander schemes in the long term.

However, the automotive industry is used to working with structural materials whose behaviour is well understood, or at least easy to quantify, in severely loaded or even over-loaded conditions. Low Cycle Fatigue (LCF) testing is a crucial part of materials assessment for metals in key automotive applications. Here, tests are controlled in terms of strain amplitude including a significant degree of plastic strain, usually under fully-reversed loading conditions. Strain measurement in this case is conducted using contacting extensometers, which must press against the surface of the specimen; even for metals the contacting force must be carefully controlled, but for polymer matrix composites this could present a significant challenge in not damaging the material under such aggressive loading conditions.

Presently, a majority of fatigue testing and research in the field of composites assumes essentially pure elastic loading states in the material and is therefore conducted in stress-controlled conditions. This may well be due to the focus of interest having been driven by the wind energy industry, and more recently the aerospace sector, for whom continuous fibre technologies are key. In such circumstances strain control is possible, but not necessarily useful, since the materials of interest do indeed exhibit near linear-elastic behaviour up until catastrophic damage.

This paper provides examples of how modern video extensometry can be used to control and extract data for simulations of severe loading, where contacting extensometry would be unsuitable. It is believed that this may be a useful approach to materials evaluation for the type of smaller structural components discussed earlier.

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Equipment

The mechanical tests for this paper were all performed using Instron dynamic test equipment; higher force capacity tests using an 8801 servo-hydraulic 100 kN load frame, lower force capacity on an Electropuls 3kN load frame, both controlled by 8800 minitower controllers and WaveMatrix dynamic test software. Strain measurement was performed using an AVE2 advanced video extensometer, operating in dynamic mode in order to provide lag free data and track highly dynamic behaviour (extension rates up to 0.5m/s on the gauge length, with a data update rate of 490Hz).

Strain Rate Sensitive Behaviour of Injection Moulded Polyamide

Standard tensile test bars of a common Polyamide 6,6 injection moulding compound were tested in tension until discontinuous yield. Nominal gauge length 80mm, width 12.5mm and thickness 3.5mm. These were tested on an Electropuls E3000 3kN load frame fitted with mechanically loaded wedge grips.

It should be emphasised that for the purposes of these tests it was elected to use only a basic, standard tuning of the control system (in the elastic regime of the specimen), so no adaptive control algorithms were applied to stabilise the actuator drive through yield. At the lowest and highest test speeds used, the system was controlled by actuator velocity as for a standard quasi-static test (or indeed a very high strain rate test [7]). At intermediate speeds, the test was controlled directly from the video extensometer to achieve specified strain rates.

Figure 2 shows overlaid plots of engineering stress vs engineering strain to failure, at several test rates. Figure 3 shows an overlay of the same data up to yield with achieved strain rate as determined from optical measurement on the gauge length and rate is determined as the average between 0.45% and 0.5% engineering strain. Here it is very clear that strain rate significantly affects the performance of the material, as has been understood for some time [8], even without the need for very high speed test equipment such as that used in studies by workers such as Gude, Schlossig, *et al* [9, 10]. The initial elastic modulus is increased, as are all interpretations of yield or drawing stress.

Figure 2:
Stress vs strain (to failure) for unreinforced polyamide 6,6 at varying rate

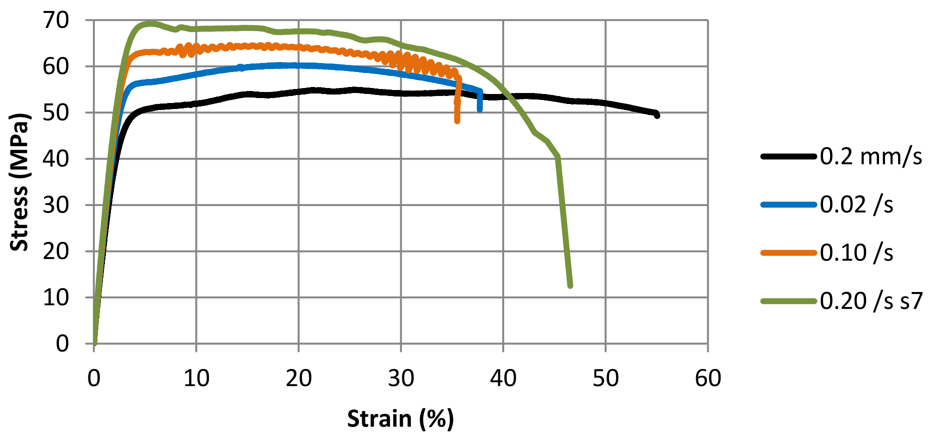

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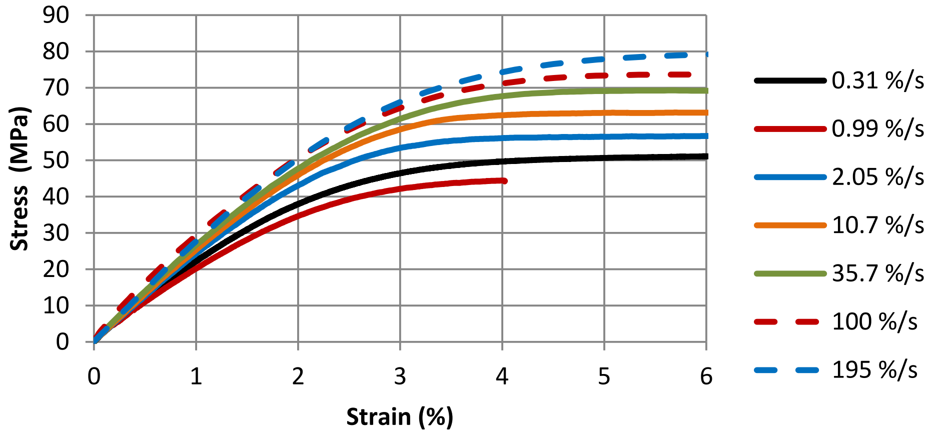
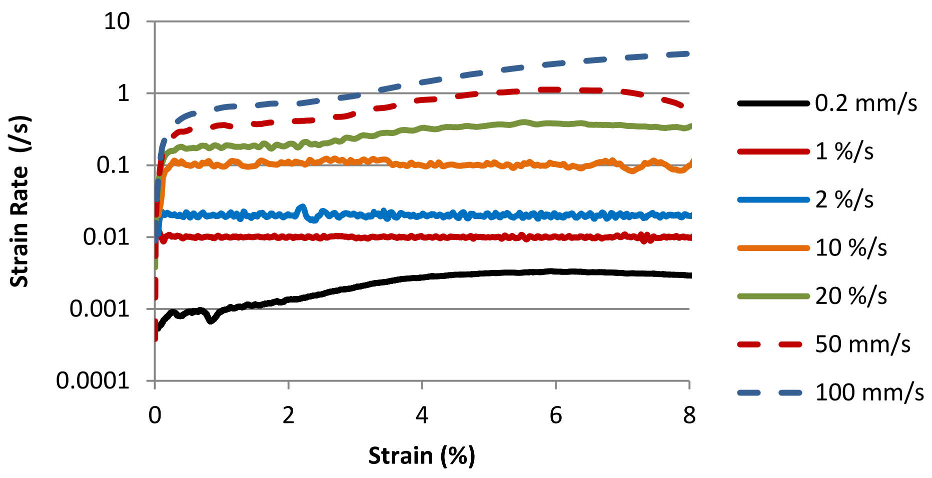
Figure 3:
Stress vs strain (to yield) for unreinforced polyamide 6,6 at varying rate



These “fast” tests are easily representative of the strain rates which might be employed in common practise for fatigue tests on polymers and composites [12, 13], yet those tests criteria are often determined on the basis of quasi-static data on ultimate strength.

Figure 4 further illustrates an associated effect, in the resulting strain rate (calculated over a rolling window of 0.05% strain). The four tests controlled directly by applied strain rate at the gauge length have achieved very stable strain rates, which will give a more consistent measurement. By contrast, the position controlled tests do not maintain constant rate, as a larger proportion of the strain is applied in the gauge length after yield, hence fixed grip speed does not result in constant engineering strain rate. This is obviously not a novel concept in materials testing and is used commonly for evaluation of metals with deep-drawing behaviour [14], but it would be difficult to achieve at such combinations of high strain rates and large elongations.

Figure 4:
Strain rate vs strain (through yield) for unreinforced polyamide 6,6



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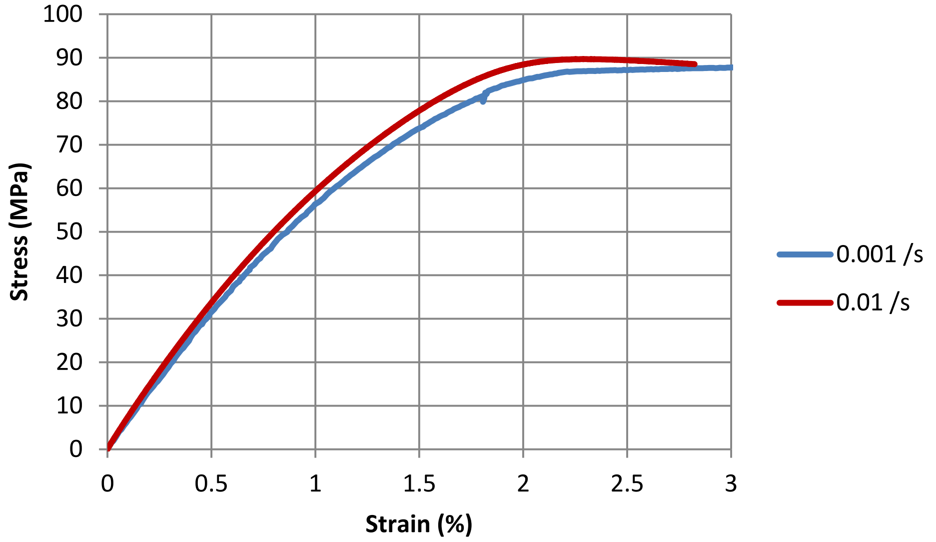
Cyclic Tests On Short Fibre Glass Reinforced Polyamide

Tests were performed on standard tensile test bars of a common Polyamide 6,6 injection moulding compound with moderately high content of short glass fibre. This is an example of material used currently in ancilliary under-bonnet automotive components. Nominal gauge length 80mm, width 12.5mm and thickness 3.5mm. These were tested on an Electropuls E3000 3kN load frame fitted with mechanically loaded wedge grips.

There is some strain rate dependency, as seen in Figure 5, but less than the unreinforced compound.

Figure 5:
Engineering Stress vs Strain for reinforced PA66 at different rates



Since the video extensometer in use is capable of dynamic measurement, these rate properties can also be evaluated for sinusoidal loading.

It becomes relatively trivial to extract more useful data from a simple stress-controlled fatigue test by performing cycle-by-cycle live calculation of phase shift between load and displacement, as per conventional dynamic mechanical analysis (DMA) calculations [11].

Here stress controlled tests were conducted at a high proportion of failure stress, with a stress ratio (σ_{min} / σ_{max}) R = 0.1, at a frequency of 10 Hz. Figure 6 plots dynamic modulus while Figure 7 plots tanδ (which can be used as a measure of damping or energy dissipation), both against elapsed cycles under sinusoidal loading.

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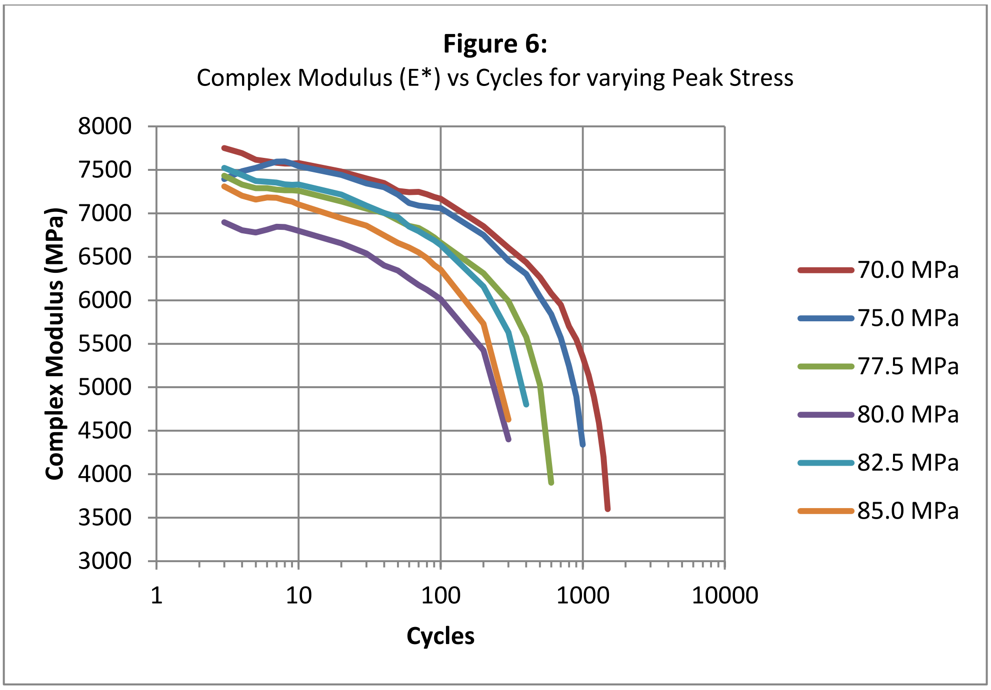

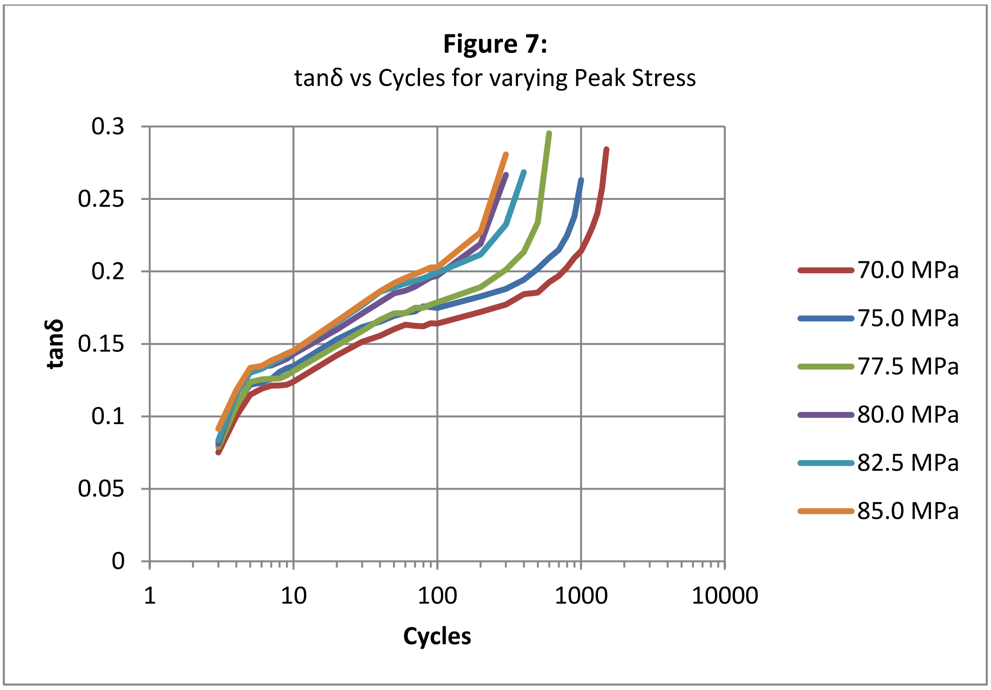

In both cases it is notable how consistent the shape of the curves are between specimens at different stress levels both Figures 6 and 7. Although this would obviously vary between materials, it agrees with the “two stage” fatigue damage model for composites, and lends weight to the suggestion which has long been debated (and is already permitted by ISO 13003 for composites fatigue [12]) that using drop in modulus or another non-destructively determined parameter, may be a more suitable determination of fatigue life for a composite than specimen rupture.

Furthermore, the fact that this is a non-contacting *biaxial* extensometer enables dynamic measurement of transverse strain. Figure 8 shows how this can enable the user to monitor variation in transverse strain range during the test. Signal-to-noise ratio is rather poor on smaller standard

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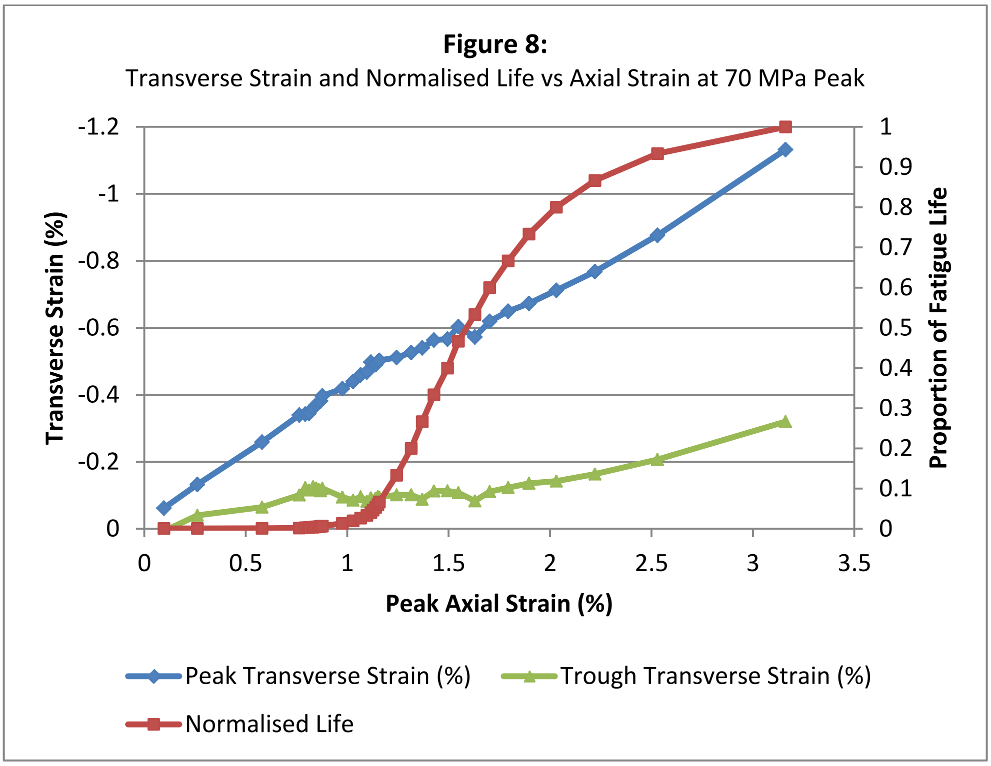
specimens, such as those used here, due to small gauge length, so the authors would not recommend attempting to determine Poisson's ratio *on the basis of a single cycle*, but by averaging the strain at a given load across a number of cycles, a useful assessment can be made. Taking peak values alone, it would appear that this particular specimen retained a ratio of around 0.31 throughout, but it would seem that the transverse strain at *minimum* force is following a subtly different trend. So an alternative analysis can be made in terms of strain ranges, as in Figure 9 (note that the stress range is controlled at 0.1 for this series of tests).



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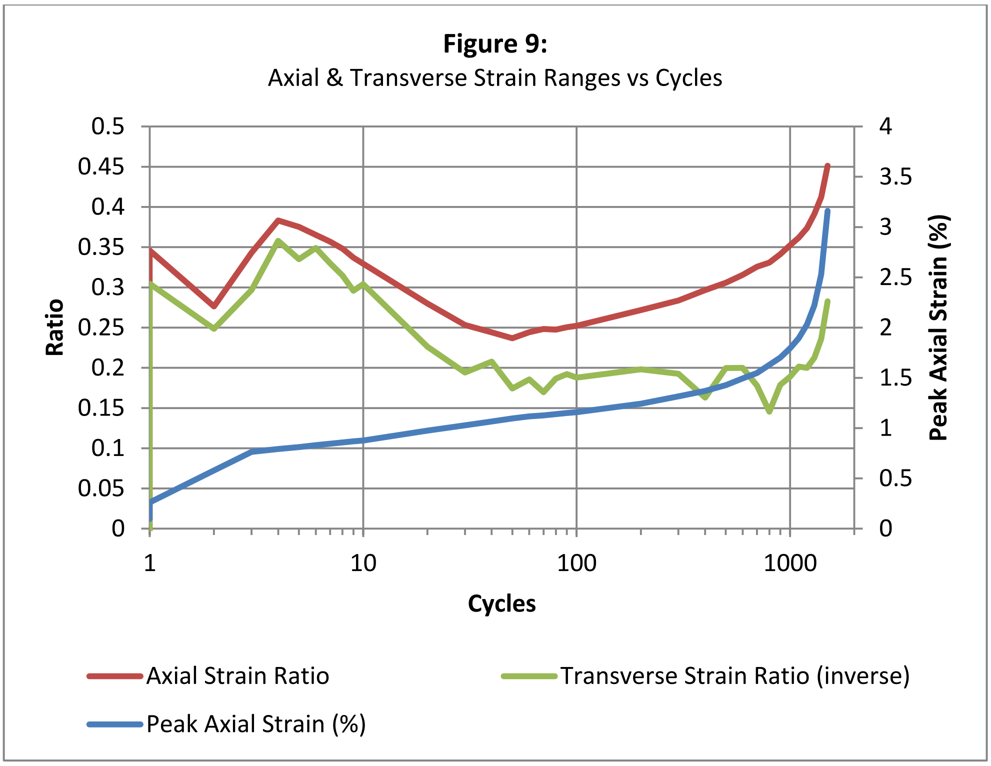

Figure 9:
Axial & Transverse Strain Ranges vs Cycles

The physical design of any contacting biaxial extensometer makes them unsuited to any significantly dynamic test. Typically their mechanical bandwidth limits their use to an absolute maximum test frequency of 1 Hz. Also the contact methods required make them more than usually likely to create fretting problems with cyclic movement and hence in a fatigue test to initiate failure at that point.

The highest accuracy biaxial measurements are achieved with strain gauges on the specimen surface, but this has the well-known problem that it only measures a small area of the specimen which leads to a risk of insufficient averaging to avoid meso-structural effects (e.g. weave in a fabric reinforced material) for a bulk property measurement. From a purely pragmatic point of view, applying strain gauges to every specimen is also extremely labour intensive and costly, meaning that most commercial workers consider it inappropriate, electing to instrument only a small number of representative specimens in a large batch for verification purposes.

Simulation Of Service Conditions on Short Glass Fibre Reinforced Polyamide

In reality, the “worst case” service conditions for a component are very rarely continuously repeated overload cycles, nor are they purely elastic at constant amplitude. One approach to this is direct application of variable amplitude loading, which, as already discussed could be conducted quite effectively in strain control, as it would traditionally have been in load control.

As an example, a “block loading” test was set up, consisting of repeatedly applying 200 cycles of sinusoidal stress-controlled loading at an amplitude of 4 MPa with a mean level of 40 MPa, followed by a rapid ramp up *in strain control* to 1.6% strain, hold for 1 second and ramp back down at the same strain rate to 40 MPa stress. Figures 10 and 11 show how this affects a “ratcheting” of mean

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strain level, but also provide an indication of how the vibration between overloads might affect recovery.

Figure 10:
Hysteresis for cycle 200 in first 5 blocks

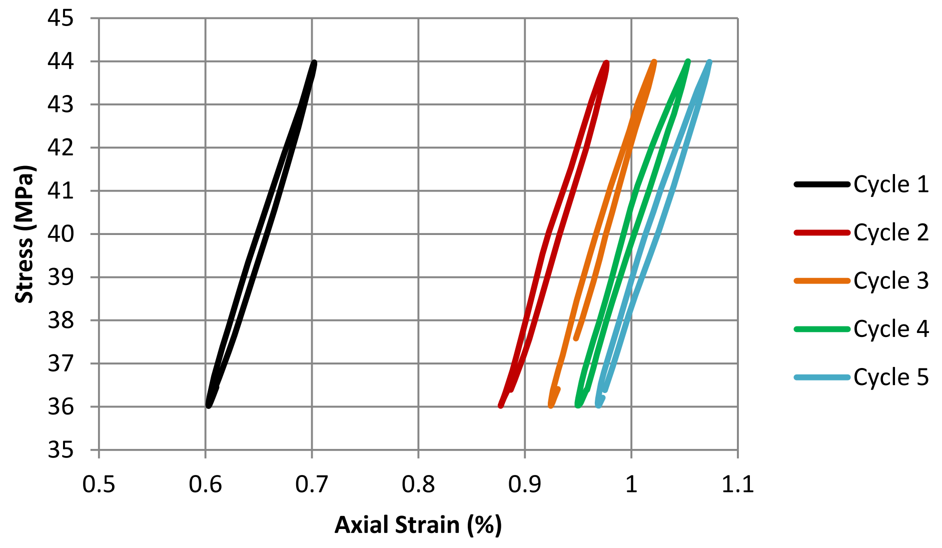
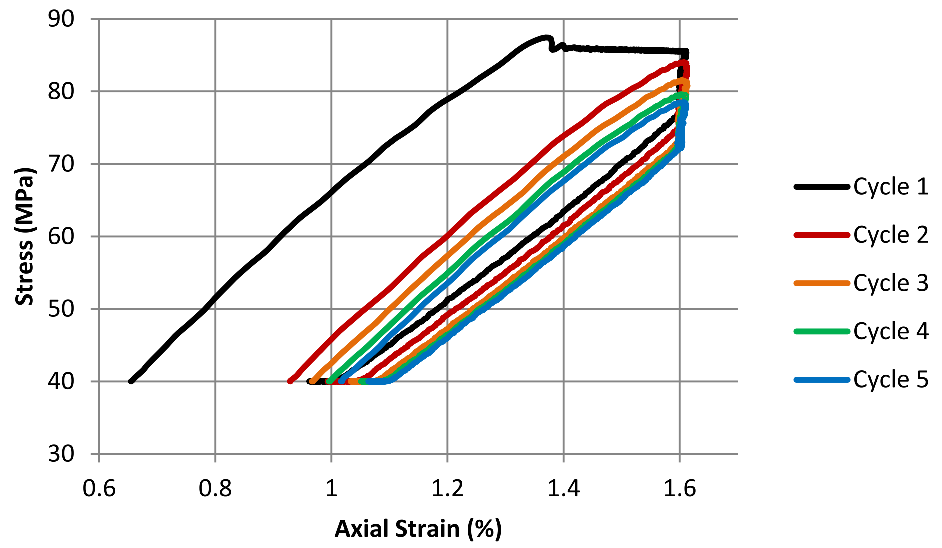


Figure 11:
Hysteresis for first 5 overload cycles



Conclusions

This paper has presented a demonstration of how state-of-the-art (at time of writing) dynamic video extensometry can be utilised in the measurement and control of tests on composites. With appropriate control systems and software, this has the potential to provide the experimentalist with much greater insight into the strain rate sensitivity of composite materials, and to facilitate better simulations of in-service loading conditions.

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