Curfew Tags: Mechanical Fatigue Tests

Reference: DPC/010/Fatigue/Issue1

James Dean

doubleprecision
fea and multiphysics

I understand that it is my duty to help the court on matters within my expertise and that this duty overrides any obligation to the person from whom I have received instructions. I have complied with that duty and will continue to do so. I have done my best to be accurate and complete.

I believe that the matters of fact stated in my report are true, and the opinions I have expressed represent my true and complete professional opinion.

Dr. James Dean,
Senior Consultant, Double Precision Consultancy Ltd.

Date: 25/07/14

Dr. James Dean

Curriculum Vitae

I am a Senior Research Scientist in the Department of Materials Science at Cambridge University and a Senior Consultant for Double Precision Consultancy. I specialise in the mechanics of materials and I am expert in the application of the finite element method and in the characterisation and testing of materials. I am the recipient of the Armourers and Brasiers' Fellowship Award and a member of the Institute of Materials. I have collaborated closely with industrialists and with scientists from government agencies including EDF Energy, Rolls Royce, the Ministry of Defence and the Atomic Weapons Establishment. My peer-reviewed work has been published in international journals and I have been invited to speak at several international conferences.

Professional Appointments

Founder and Senior Consultant, Double Precision Consultancy, 01/10/12 – Present

Senior Research Associate, Department of Materials Science, University of Cambridge, 01/09/13 – Present

Senior Engineer, Frazer-Nash Consultancy, 03/09/11 – 14/09/12

Research Associate, Department of Materials Science, University of Cambridge, 01/10/08 – 30/08/11

Consultancy Projects

Fibretech Products Ltd. (In progress): Porosity and permeability measurements on pressure-cast, steel fibre-reinforced ceramic composites.

Anglian Home Improvements (In progress): Residual stresses, viscoelasticity and creep deformation as distortion mechanisms in extruded PVC-U products.

Allen & Overy (2013 – 2014): Elastic finite element simulations of asymmetrically-loaded washing machine drums. Patent dispute.

Tata Steel (2013): Fluid flow and thermal conditions during oxygen injection lance steelmaking.

Anglian Home Improvements (2013): Measurement and finite element modelling of heat flow characteristics through PVC-U products.

Cambridge University (2012-2013): Technical and finite element modelling support for all indentation-related activities in the Gordon Laboratory, Department of Materials Science.

Solar Turbines (2012): Development of constitutive models describing single crystal plasticity and creep in nickel-based super-alloys for implementation into finite element models.

EDF Energy (2011-2012): Analysis of neutron-irradiated, reactor-core graphite data to develop mechanical constitutive models for "useful life" prediction using finite element modelling.

RIDE Magazine (2009): Aqueous corrosion performance of galvanised steel bolts

Teaching

Final year undergraduate lecture course, University of Cambridge, "The Finite Element Method", (2014)

Final year undergraduate lecture course, University of Cambridge, "The Finite Element Method", (2011)

Head of Class, Course D, University of Cambridge – Mechanical Behaviour of Materials (2011)

Final year undergraduate lecture course, University of Cambridge, "The Finite Element Method", (2010)

Part 1A Supervisions in Materials Science (2010)

Higher Education

PhD, Materials Science, Department of Materials Science, University of Cambridge, 01/10/04 – 30/09/08

MSc, Gas Turbine Technology, School of Engineering, Cranfield University, 01/09/03 – 30/09/04

BEng, Class 2.i, Materials Science and Engineering, Imperial College, London, 01/09/00 – 31/07/03

Awards and Prizes

Armourers & Brasiers' Fellowship Award (2014)

Institute of Materials Lecture Competition, Local Heat Winner and Regional Runner-up (2010)

Armourers & Brasiers' Travel Grant Award (2007)

Armourers & Brasiers' Travel Grant Award (2005)

DSTL Case Studentship (2004)

Rolls Royce UTC Scholarship (2003)

Relevant Proficiencies

Extensive experience (10+ years) in the characterisation and testing of materials:

Mechanical load frames, instrumentation, ballistic testing, nanoindentation, dilatometry, scanning electron microscopy, optical microscopy and metallography.

Research Projects/Supervision

Development of a plasma electrolytic oxidation process model (2014)

Deposition of volcanic ash within gas turbine aeroengines (2014)

Limitations in a common methodology for extraction of the steady-state creep stress exponent from indentation data (2014)

Using nanoindentation to determine the creep characteristics of metallic materials (2010)

The use of nanoindentation to measure residual stress levels in surface layers (2009)

Finite element analysis of the accelerated buoyancy test for the characterisation of cell adhesion to substrates and the resistance to mechanical cell removal (2009)

Using finite elements to characterise the thermal shock resistance of a novel, metal fibre-reinforced ceramic composite (2009)

Extracting high strain rate constitutive relations using impact nanoindentation (2008)

The impact resistance of thin steel plates and lightweight sandwich panels with metallic fibre cores (2008)

Modelling the indentation response of superelastic NiTi alloys (2007)

Characterisation of cell adhesion to substrates using forced fluid flow and computational fluid dynamics (2007)

The inception thresholds for gas turbine inlet vortices; a fluid dynamics study (2004)

Electrophoretic deposition of rutile-reinforced ceramics (2003)

Publications List:

Available at http://www.ccg.msm.cam.ac.uk/directory/jd362@cam.ac.uk

Contents

Fractography

Fractography is the *scientific* study of fractured surfaces. Its purpose is to help identify the root cause of failure in components that have fractured. The correct procedure is to document the fracture surface in a series of photographs obtained at increasing magnification. The most common tools for these purposes are the optical light microscope and the scanning electron microscope. Optical light microscopy can generate important information about the fracture process from examination of the comparatively large-scale surface features. It cannot be used to examine any fine-scale features that may or may not lie beyond the resolution of the microscope; for these features the scanning electron microscope should be used, although it is important to note that the higher resolution capability of the electron microscope does not guarantee a better understanding. It is the *self-consistent* data gathered over a range of length scales that provides a proper understanding or, put differently, 'potential explanations for cause of failure must be consistent with both macroscopic and microscopic features' [1]. This is self-evident if one understands that fracture (crack propagation) is a microscopic phenomenon with a strong microstructural sensitivity. Importantly, and as noted on page 1 of [2], during fracture surface analysis, "what one sees or observes depends on what one knows and understands".

Fatigue

Fatigue is a progressive failure phenomenon associated with the ***initiation*** and ***propagation*** of cracks in response to fluctuating loads. One of the most significant (and relevant) characteristics of fatigue failure is that the fluctuating loads generate stresses (away from the crack tip) that are lower than the static[1] strength of the material.

Fatigue failures proceed in three stages; the first stage is crack initiation – most commonly at the surface of a component – and usually at some surface defect that acts to locally raise the stress in its vicinity. The crack initiation stage is often very long in duration, although this depends to a large extent on the imposed loads and the condition of the component – particularly its surface. The second stage involves the progressive propagation of fatigue cracks. This ordinarily occurs in an incremental way, and in the simplified manner depicted in Fig.1. In Fig.1(a), a specimen (which is isotropic and homogeneous) with a pre-existing crack is loaded cyclically, with the loading history shown in Fig.1(b). Only a single cycle is considered. The crack front advances in Fig.1(c) under the action of the applied load. The crack stops when the load is removed.

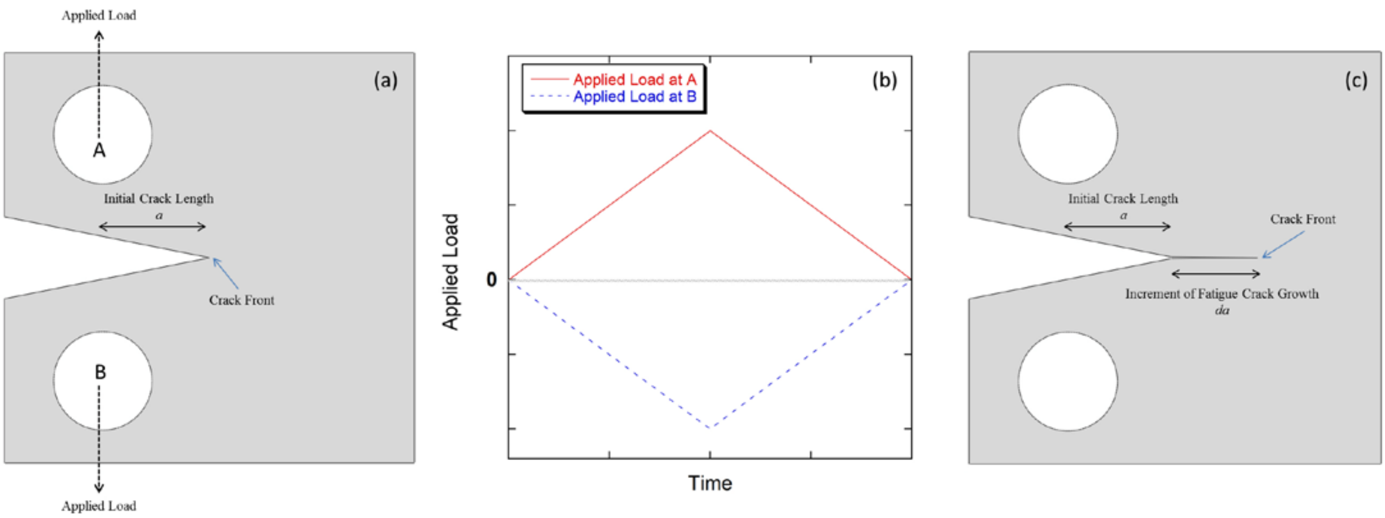

Figure 1: Schematic of a simplified fatigue test showing (a) the specimen geometry, (b) the loading history and (c) a corresponding increment of fatigue crack growth.

[1] The static strength of the material is the strength (yield stress or ultimate tensile strength) obtained from a conventional mechanical test in which the load on the specimen is continuously increased until the material yields and/or fractures

It follows that, if the applied load is small, the increment of crack advance (the value of *da*) will be smaller than if the load were high. Stage three of the process involves unsteady crack growth (fast fracture). In this regime, complete fracture of the specimen is favoured energetically since the easiest way for the material to reduce its stored strain energy is to create new surface area (which is why 'fast-fracture' surfaces exhibit hackle-like features). It is also worth noting that, if the applied cyclical load is small, then the critical crack length for the initiation of fast fracture will be larger than the one obtained at higher loads.

Fractographic Features of Fatigue Failure

Beach marks, striations and conchoidal marks indicate fatigue [1,2]. The schematic in Fig.2(a) depicts the general features of a fatigue fracture. It was obtained from [1]. The three stages of fatigue crack growth are shown; there are two initiation sites (the ratchet mark can be ignored for the purposes of this discussion), a region of (sub-critical) crack growth and a fast-fracture region. These features are observed in many classes of material including polymers. The micrograph in Fig.2(b) shows the fatigue fracture surface of a polycarbonate plumbing fixture subjected to an alternating (water hammer) load. It was obtained from [1]. The magnification was ×32.

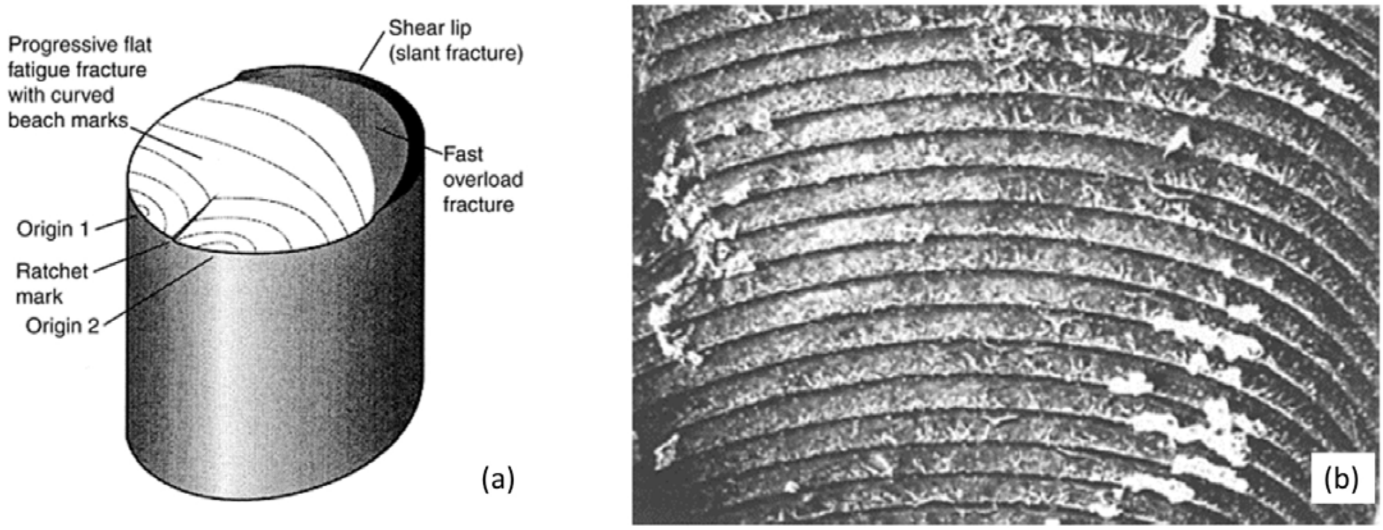

Figure 2: Schematic depiction of the fractographic features that emerge from fatigue failure events are shown in (a). Shown in (b) are crack arrest lines (beach marks/striations/conchoidal marks) in polycarbonate material subjected to an alternating load. The striations correspond to the crack front location after each increment of crack advance. The crack growth direction is normal to the crack front.

In fact, fatigue crack growth behaviour in polycarbonate plastic has been studied extensively and a large number of peer-reviewed articles are available in the open scientific literature. These include the studies of James et al [3,4] and Haddoui et al [5]. Micrographs obtained from these articles are reproduced in Fig.3. The characteristic traits of fatigue failure (beach marks/conchoidal marks) are clearly evident.

However, it is important to note that the absence of beach marks and striations from a fracture surface does not confirm that fracture occurred as a result of a monotonically-applied load. During repeated cyclic loading, opposing fracture surfaces can repeatedly rub against each other, grinding and polishing away historical features of progressive crack advancement. This is particularly true in soft materials like polymers.

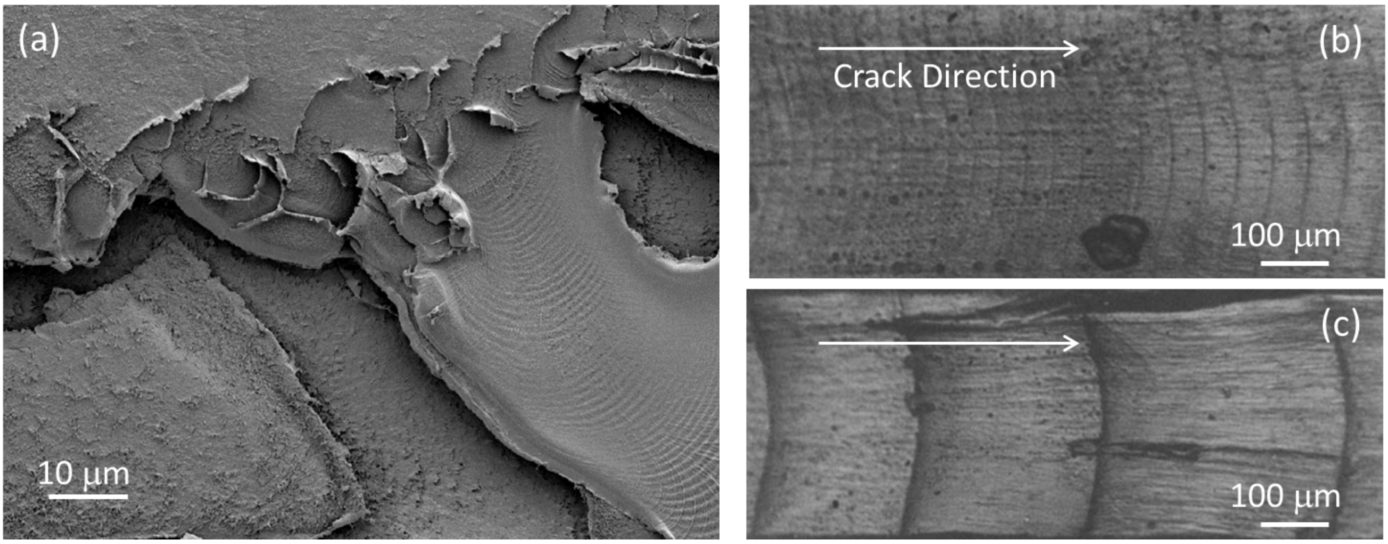

Figure 3: The micrograph in (a) is reproduced from [3] and shows fatigue-induced conchoidal marks from a cyclic loading test. The micrographs in (b) and (c) are reproduced from [5] and show fatigue-induced beach marks/striations as a result of cyclic loading tests. Image (c) is not a higher magnification image of (b). They are two separate specimens.

Wallner Lines

Some Wallner lines are shown in Fig.4. They are generated in brittle materials when transverse stress waves interact with the advancing crack front (advancing cracks generate stress waves that spread outwards from the faces of the crack). The stress waves interact with boundaries and are reflected. The crack moves therefore through a complex field of reflected waves producing changes in the fracture path, crack speed and surface topography. Their formation is favoured in brittle materials with high stiffness, and they usually occur as a result of an impact event (although this is not strictly necessary as the image in Fig.4(c) confirms).

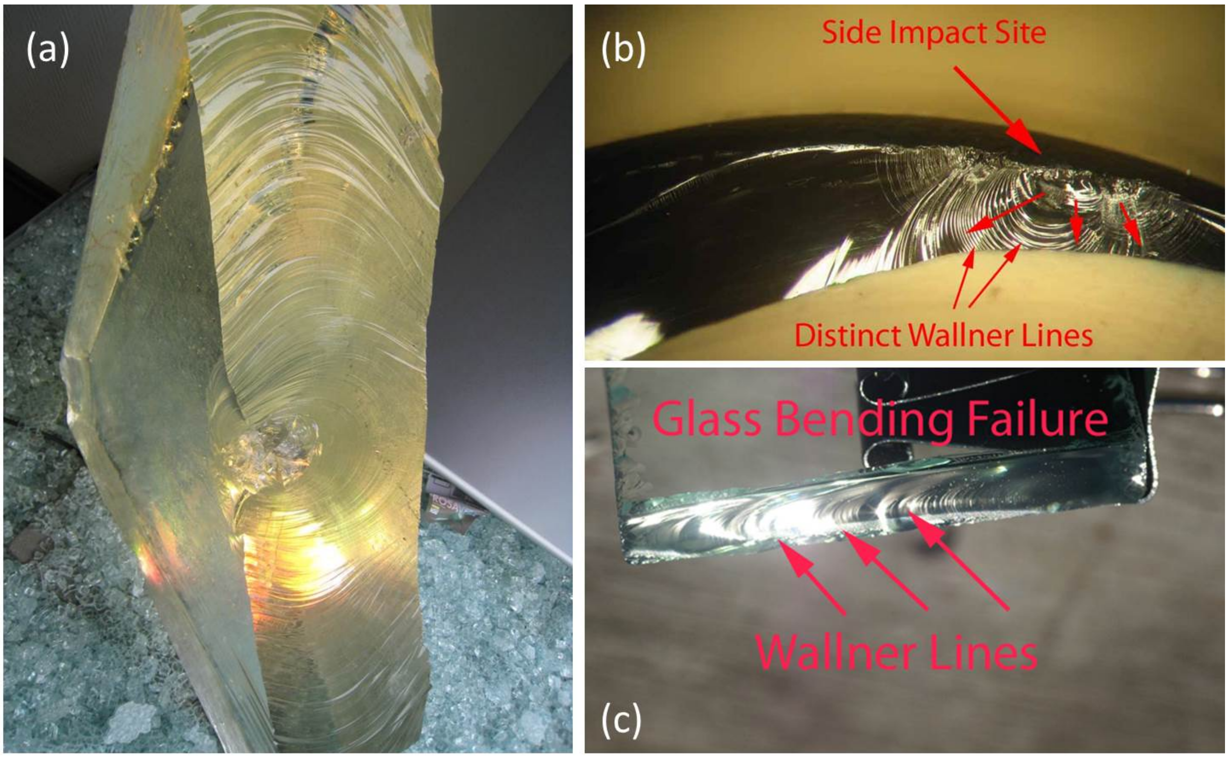

Figure 4: Wallner lines in (a) impacted glass, (b) impacted glass and (c) glass subjected to bending loads [6].

1.0 Summary

The micrographs in Fig.5 were obtained using optical light microscopy by James Dean at (a) Surescreen Scientifics Division (SSD) in Derby on Friday the 11th July in the presence of Professor Ross Anderson, James Campbell, Troy White, Paul Fearnley and Ray Davison, and at (b) Cambridge University by James Dean on Tuesday the 22nd July in the presence of Professor Ross Anderson and James Campbell. The 22nd July event was filmed by James Campbell. They are fracture surfaces from (a) the curfew tag with PID serial number PIDGCS 341525 and (b) the curfew tag with serial number PIDGC 444467. Specifically, these tags are those that were worn by Special Z in (a) 2011 and (b) 2013. After failing, both tags were analysed by James Campbell at Surescreen Scientifics Division. The corresponding SSD reports are (a) C2268 and (b) D1031. In both cases James Campbell reported the presence of conchoidal marks which is consistent with my own microscopy.

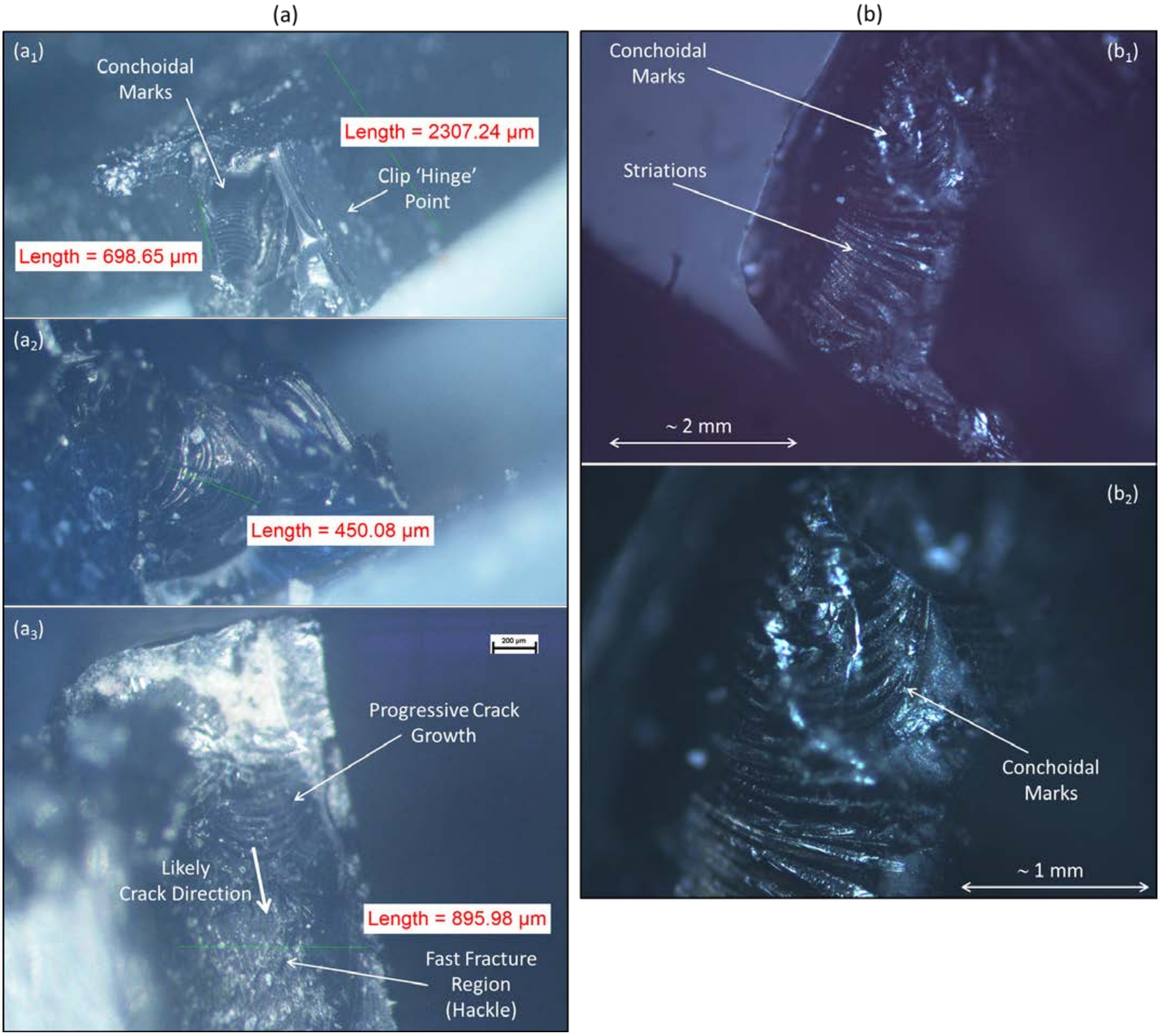

Figure 5: Optical light microscopy micrographs of (a) PIDGCS 341525 and (b) PIDGCS 444467 fracture surfaces

The conchoidal marks and the region of fast fracture in Fig.5(a_3) are consistent with those observed in Fig.2 and Fig.3. They appear therefore to show evidence of progressive crack growth. Since the conchoidal marks and striations are numerous, it would have to be assumed that a significant number of loading events occurred. This naturally implies that they occurred at a load that was insufficient to cause complete and immediate failure of the clip, although one could not say what loads exactly.

There are also some similarities with the Wallner lines that are shown in Fig.4 – notably in Fig.5(b_2) and I cannot reliably confirm that the conchoidal marks in Fig.5 are not Wallner lines. However, their presence is favoured in materials that are stiff and brittle, while the polycarbonate clips in this study have a low stiffness (~100× less than steel) and exhibit extensive plasticity during failure (§6.0).

In this study, attempts have been made to reproduce the features shown in Fig.5 from cyclic fatigue tests. Curfew tags were cyclically loaded using a mechanical loading frame at Cambridge University. A range of cyclic loading histories were studied – ones designed to replicate (a) the loads that tags might experience during ordinary activities (prayers, cycling, football) and (b) loads designed to replicate the effect of repeated snagging events. The tags were then tested to failure, in order to determine the residual tag strength (i.e. to ascertain if the cyclic loads had induced fatigue damage, thereby weakening the system). The fracture surfaces were then analysed using optical and scanning electron microscopy. During these tests the features shown in Fig.5 could not be reproduced, despite the application of significant axial and off-axis cyclic loads (up to 30 kg). Moreover, the residual tag strength appeared uncompromised in all instances – which is consistent with the absence of any fatigue-like conchoidal marks on the fracture surfaces of these specimens.

One important point worth noting though is this: fatigue crack growth is preceded by the initiation of cracks in surfaces. In engineering practice we often improve the fatigue life of components through various types of surface treatment which inhibit crack initiation. Once a crack initiates, or if a pre-existing crack is present, then the remaining fatigue life of the component can fall substantially. We note from inspection of SSD report D1031 that partial fractures in the hinge points of clips are possible. In these circumstances, the crack initiation stage of fatigue crack growth is bypassed, and it is then entirely possible for these cracks to continue to grow under the action of an applied cyclical load. The crack initiation event is open to speculation. In the time available, we have been unable to run tests on clips with partial fractures already present.

Finally, it should be recognised that of all the subjects we study as materials scientists, engineers and physicists, fracture of materials is one of the most complex and most poorly understood. There are an enormous number of variables and dependencies in fracture mechanics and our intuition about what we might expect to see can easily be wrong. This is particularly true for fracture in polymeric materials such as polycarbonates and, although there are some characteristic and defining features, it is imperative that the conclusions that are drawn are consistent with both macroscopic and microscopic observations, along with an understanding of the loading conditions and operating environment of the component concerned.

2.0 Curfew Tags

A curfew tag is shown in Fig.6. It consists of a rubber strap, reinforced by thin Kevlar™ fibres as in (b). There is a clip at each end of the strap that appears from inspection to be injection moulded. In Fig.6(a) they are hidden inside the plastic casing. The clip material is polycarbonate – confirmed by infra-red spectroscopy tests conducted in the Polymer Laboratory at Cambridge University. The transmission versus wavelength trace is shown in Fig.7.

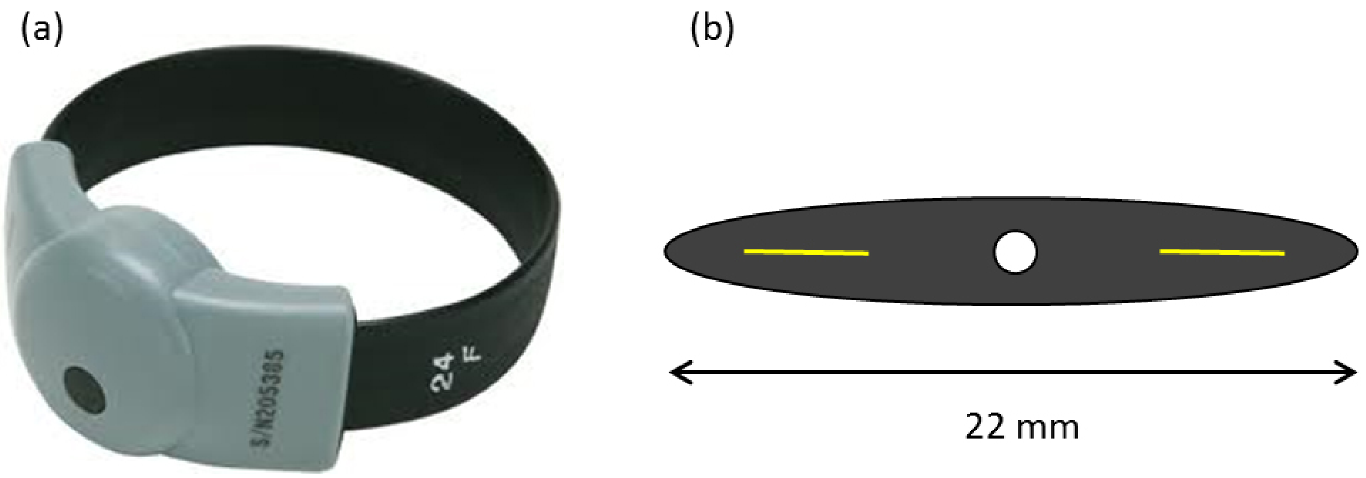

Figure 6: A curfew tag is shown in (a). The cross section of the curfew tag strap is shown in (b). The reinforcing fibre, which runs along the axis of the strap, is also shown – as is the channel down which the optical fibre runs.

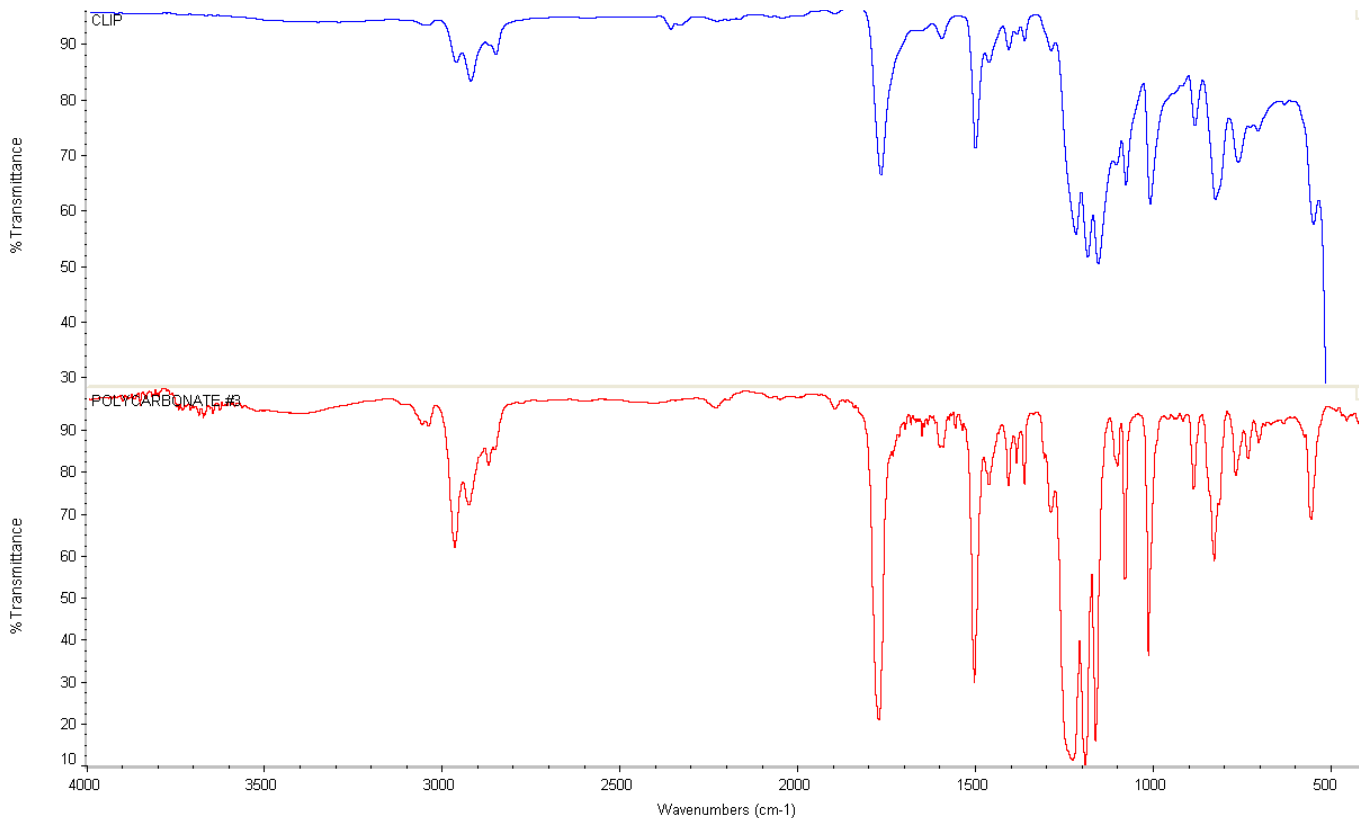

Figure 7: Transmittance versus wavenumber data obtained from infra-red spectroscopy tests on a sample of clip material (upper curve) and a corresponding trace from a known polycarbonate (lower curve).

The clip geometry is shown in Fig.8(a). It is a 3D reconstruction obtained from X-ray microtomography radiographs. There is a fracture in the left-hand uppermost arch – believed to have occurred while Professsor Ross Anderson was handling the tag. There appears also to be a hole in the lower right hand hinge location. This is an artefact from the reconstruction process. Ignore it. The recess where the 'Hinge' is located is however real, and it is there to encourage failure in this location. The same is true of the two uppermost arches which are approximately 0.5 mm thick. The clip is made from two separate components – shown in the photograph in Fig.8(b) (although sometimes there are three components and it is not clear why).

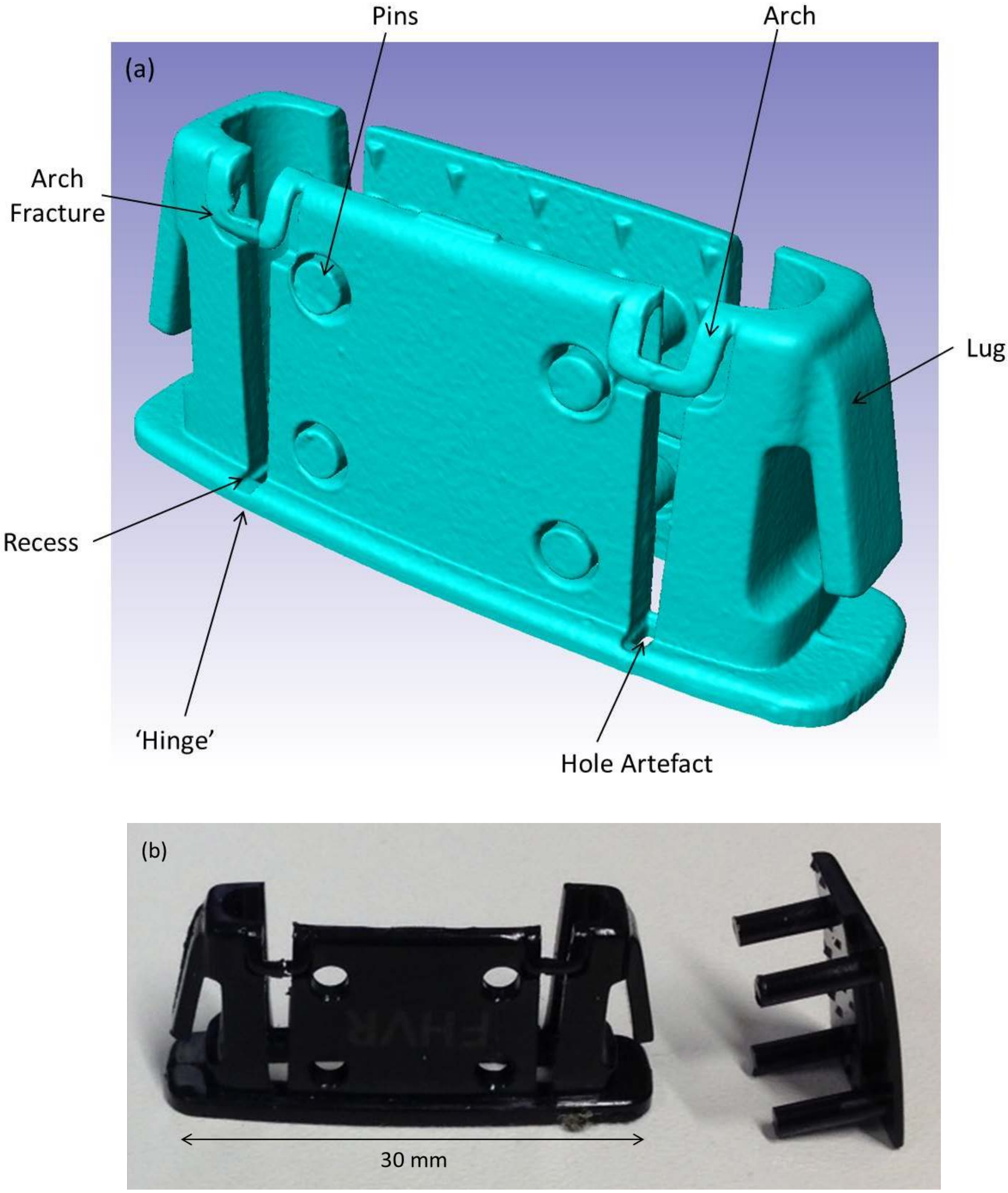

Figure 8: A 3D reconstruction of the clip assembly is shown in (a) along with some of the relevant features. The two separate components that comprise the assembly are shown in (b). The clip in (a) is not the same clip shown in (b).

The rubber strap is fixed to the clip assembly by the four pins. When the strap is loaded axially – as in Fig.9(a) – the load is transferred via the pins to the clip assembly. Since the lugs are constrained from moving by retaining seats, the applied load is accommodated in the upper two arches and across the lower two ‘hinge points’. This type of loading condition induces bending (and some shear) in the upper two arches and in the lower two hinge points. This is an important point, since even small amounts of curvature in bending beams induces very large stresses in the surface regions.

A preliminary finite element analysis indicates that the bending stresses are highest in the hinge points at the back of the clip assembly. This can be seen in Fig.9(b) which shows the von-Mises (equivalent) stresses (in MPa) in the clip assembly when the strap is displaced axially by 0.5 mm. These preliminary simulations suggest that this is the location where fracture is first likely to occur. For reference, these locations are the hinge points nearest to the outward facing strap surface. The model assumes (very reasonably) that the polycarbonate stiffness (Young’s modulus) is 2 GPa. One should note that the stress fields shown in (b) are affected by the presence of the holes in the hinge points which are an artefact of the reconstruction process (which could be fixed with time), but the conclusions drawn about the load distribution are unlikely to change.

Although preliminary, these early simulations already convey important information about how the tags are loaded and the likely locations for failure. I specifically note that in all of the cases we’ve seen the tags do fail in these locations and there is also evidence of partial cracking in James Campbell’s report (pages 16 and 17 of D0131) in the locations circled in Fig.9(b). Such partial fractures are extremely important since if they occur and are unknown about then it is perfectly rational for these cracks to continue to grow under the action of an applied cyclical load, and at a load level much less than the level required to fully break an intact clip. This is the very definition of fatigue failure. This type of failure would also be favoured if the existing crack were sharp, and the images in D0131 are of sharp-tipped hairline fractures.

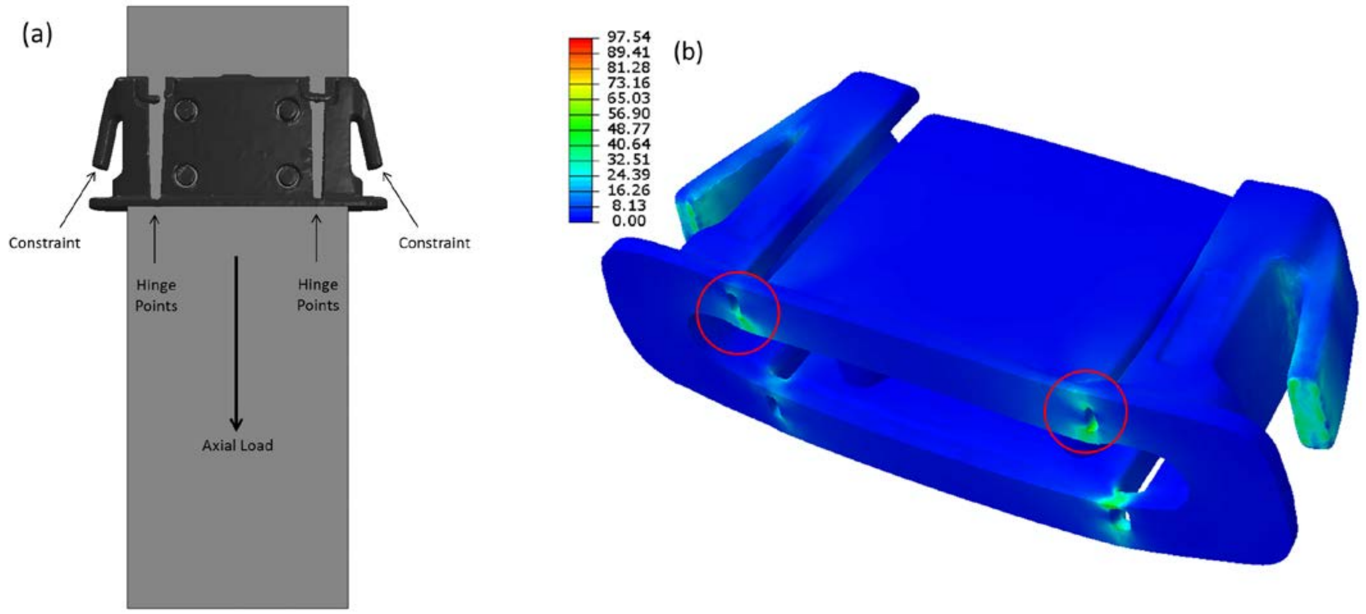

Figure 9: The reconstructed clip assembly is shown in (a). Included is a strap, to which an axial load is applied. Preliminary finite element simulations in (b) already indicate that high bending stresses develop in the lower hinge points. The simulations also suggest that the lower hinge points are likely to break first although the ‘hole’ artefacts would need to be removed in any future simulations to provide definitive proof.

3.0 Test Equipment

Mechanical tests were conducted in the mechanical testing laboratory at the Department of Materials Science at Cambridge University.

3.1 Loading Frame

A servo-hydraulic mechanical test machine with a 10 kN load cell and a 100 mm displacement range was used throughout. This is a general use machine for tension, compression and fatigue testing. A 3D-rendered image is shown in Fig.10(a). The purpose-built mechanical grips are shown in Fig.10(b). During testing, the tags are strapped around the central (plastic) cylinder which has two sections – one attached to the upper grip and one attached to the lower grip. The diameter of the cylinder comfortably fits a size 19 tag, leaving enough room for a few fingers between the gap.

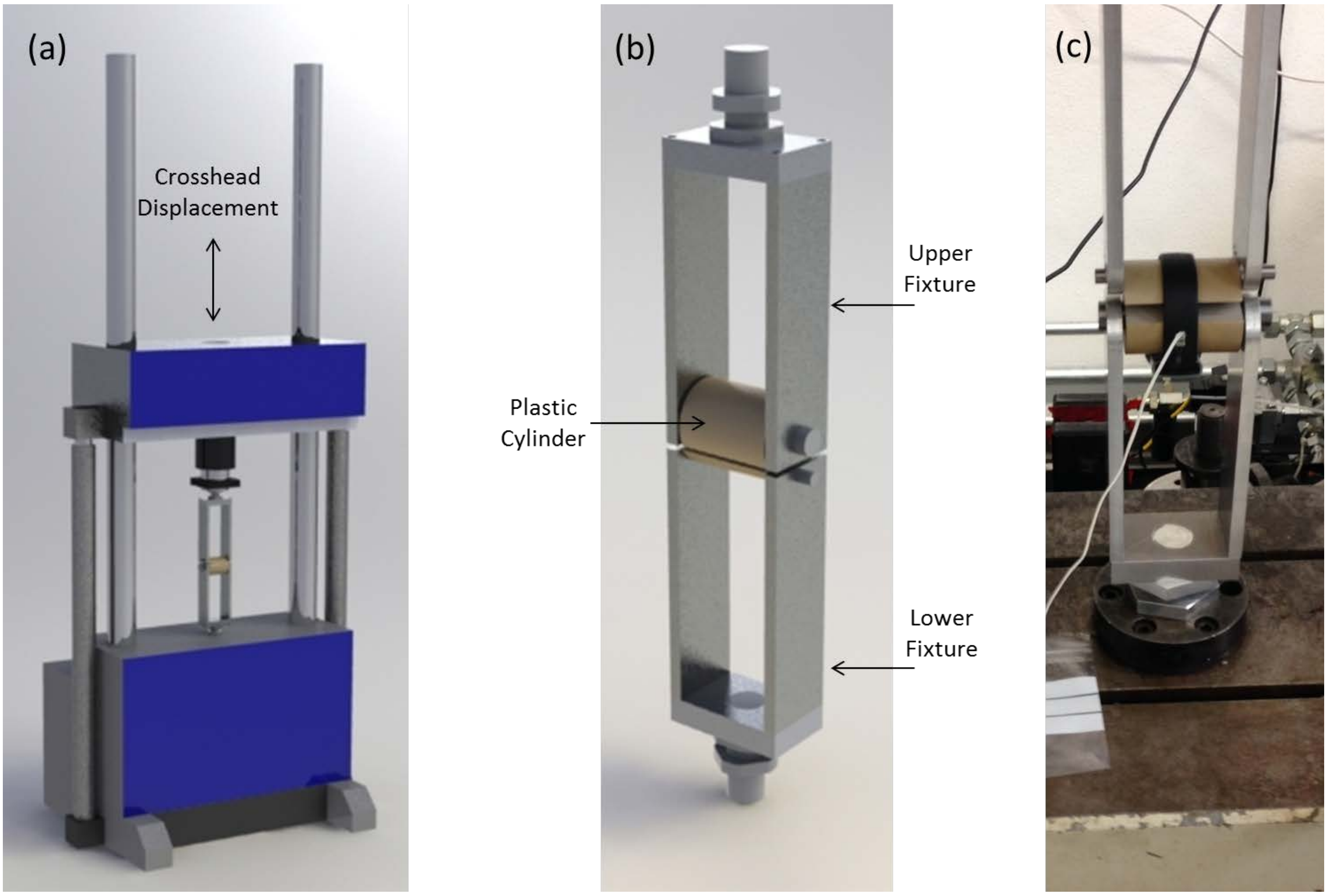

Figure 10: Shown in (a) is a 3D-rendered image of the mechanical loading frame. Shown in (b) is a 3D-rendered image of the purpose-built mechanical grips. The photograph in (c) shows a curfew tag ready for testing.

3.2 Strain Gauges

A number of curfew tags were instrumented with strain gauges (§4). These devices measure strain, which is a measure of relative distortion in a material. The gauges were attached to the straps in the locations shown in Fig.11(a). They were attached with ordinary super-glue and were aligned in a direction parallel to the long-axis of the strap. This is an important point, since the gauges are most sensitive to distortion that occurs in that direction (such as from stretching of the strap). They are less sensitive to off-axis distortion and signals generated in this way are much more difficult to interpret; they should be treated with some caution.

It was also impractical to attach strain gauges to the inside of the straps. This is common practice for gauges attached to curved surfaces, since curvature will induce an artificial strain reading. We have therefore chosen not to measure strain directly from the gauges, but to monitor instead the strain gauge signals and to correlate these signals with daily activities - (§4). For outdoor tests the gauges were covered with a protective layer of silicone rubber – as shown in Fig.11(b).

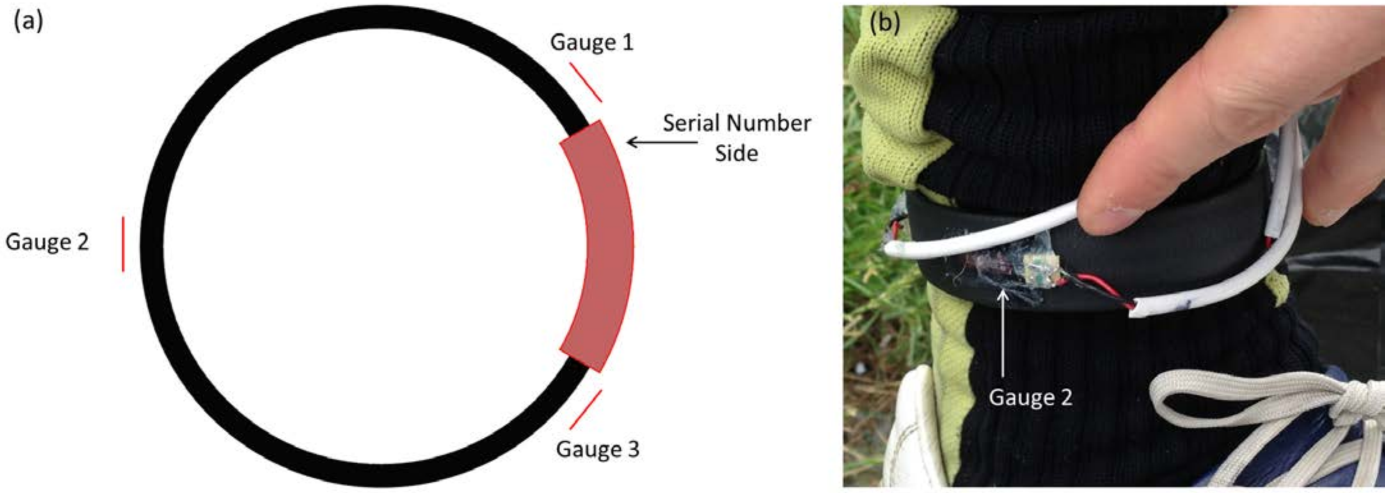

Figure 11: The positions of the strain gauges are shown in (a). Strain gauge 1 was always positioned at the serial number side of the tag. An instrumented tag is shown in (b).

The strain gauge signals were transmitted wirelessly from three Mantracourt telemetry strain gauge signal conditioners located in a rucksack carried by whoever was wearing an instrumented tag. The signals were picked up by an acquisition unit attached to a small, lightweight laptop – also carried in the rucksack. This system enabled the person whose tag was instrumented to continue with their ordinary activities, whilst simultaneously recording the strain gauge signals.

4.0 Mechanical Testing

4.1 Monotonic Loading Tests

For monotonic loading tests the tags were loaded continuously, under displacement control, until failure of the clips occurred. The load was continuously monitored throughout the duration of the test. Two tests were conducted – one at a slow displacement rate of 0.5 mm per second (**TAG 1**) and one at a crosshead displacement rate of 10 mm per second (**TAG 2**). The objective of these tests was to:

a. establish the critical load for failure
b. establish if the critical load to failure is sensitive to the rate of loading
c. correlate the fracture surface features with the type of test conducted

4.2 Cyclic Loading Tests

Four types of fatigue test were conducted.

TAG 3: Constant displacement amplitude fatigue test with a sine-wave amplitude history – 1800 cycles corresponding to ten fatigue cycles per day for 6 months. The imposed displacement amplitude (4 mm about the origin) is shown in Fig.12(a) for the first 5 cycles. The corresponding (measured) load history is included. It has a peak value of 375 N (which is approximately 37.5 kg). This is somewhat less than the loads required for complete failure of an undamaged clip (see §5.0), but a snagging event of this magnitude would undoubtedly be registered by someone wearing a tag. Note also that at zero amplitude there is an initial pre-load of ~ 1.5 kg, which was necessary to prevent the strap from rotating around the plastic grip during testing. The objective of this test was to induce a fatigue-type failure in the clip.

TAG 4: Constant displacement amplitude fatigue test with a square-wave amplitude history – 1800 cycles corresponding to ten fatigue cycles per day for 6 months. The square-wave amplitude history imposes a more vigorous impulse loading on the tag and the straps, with the intention of mimicking more realistically the effects of repeated snagging events. The imposed displacement history is shown in Fig.12(b). The corresponding (measured) load history is included also. It shows a region of compressive load, but this is due to the momentum of the crosshead generating a load in the load cell. It can be ignored. The peak applied cyclic load to the strap is ~250 N (or 25 kg). This kind of force history, if generated by a snagging event, would undoubtedly be felt. The objective of this test was to induce a fatigue-type failure in the clip.

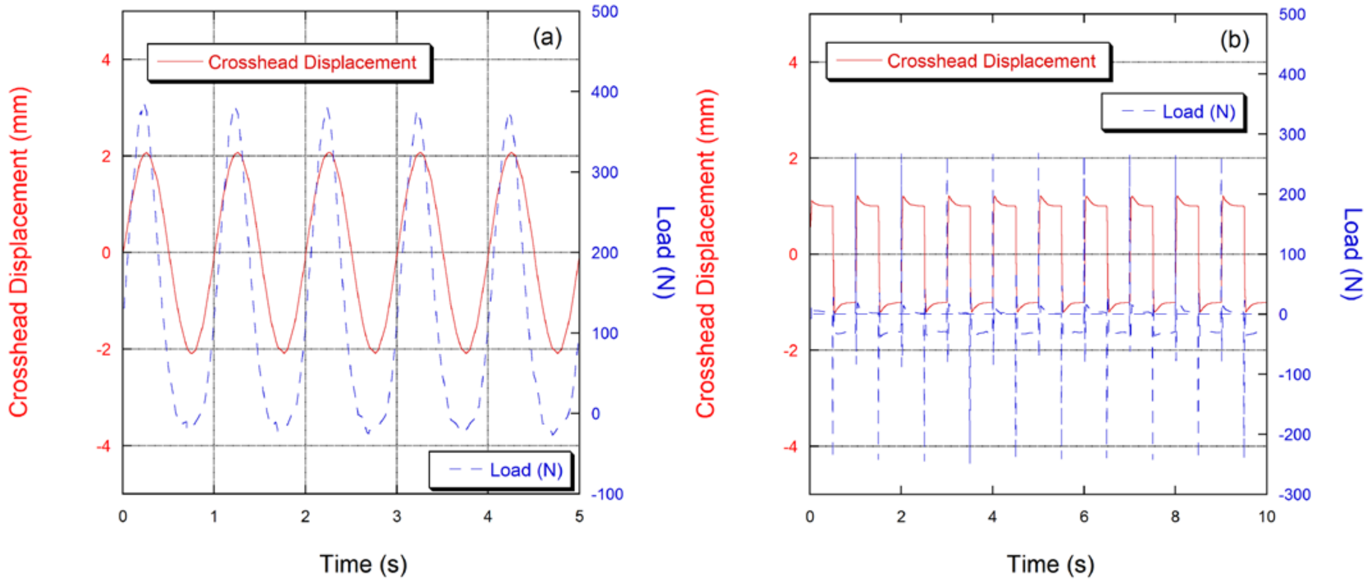

Figure 12: The imposed sine-wave amplitude history for tests conducted on TAG 3 and the corresponding (measured) loads are shown in (a). The first five seconds of the test are shown. 1800 of these cycles were imposed in total. The imposed square-wave amplitude history for tests conducted on TAG 4 and the corresponding (measured) loads are shown in (b). The first ten seconds of the test are shown. 1800 of these cycles were imposed in total.

TAG 5: Variable amplitude fatigue test with a sine-wave amplitude history. The imposed displacement amplitude histories for TAG 5 were chosen based on the test results obtained from instrumented curfew tags worn by Saad al-Oteibi and James Dean over a 24 hour period. Figure 13(a) shows the strain gauge history data that was measured during Saad's late-night prayer session on the 14th July. Saad prayed 3 times that evening. Each of those events has been captured. They are highlighted with pink overlay. Note that the signals from gauges 1 and 3 are almost identical, which is to be expected when one considers their positions (Fig.11(a)) and the symmetrical nature of a prayer (which involves bending forward whilst on ones knees). Figure 13(b) shows the strain gauge history data obtained by James Dean whilst riding a bike on the 17th July. The signals from gauges 1 and 3 correlate strongly once again. Note now however that the signals are approximately 2 or 3 times greater than they were during Saad's prayers, although this is perhaps to be expected given the more active nature of cycling. The pink overlay region corresponds to the period of time immediately after getting off the bike. Figure 13(c) shows the strain gauge history data obtained by James Dean whilst playing football on the 16th July. The data clearly correspond to a period of intense activity. As might be expected, the peak values are a little higher than those that were measured during cycling. The pink overlay region corresponds to a period in time where the signal 3 data exceeded the 3.2 mV/V limit. The reasons for this are unknown, but the signals generated before this time are sufficient for this study.

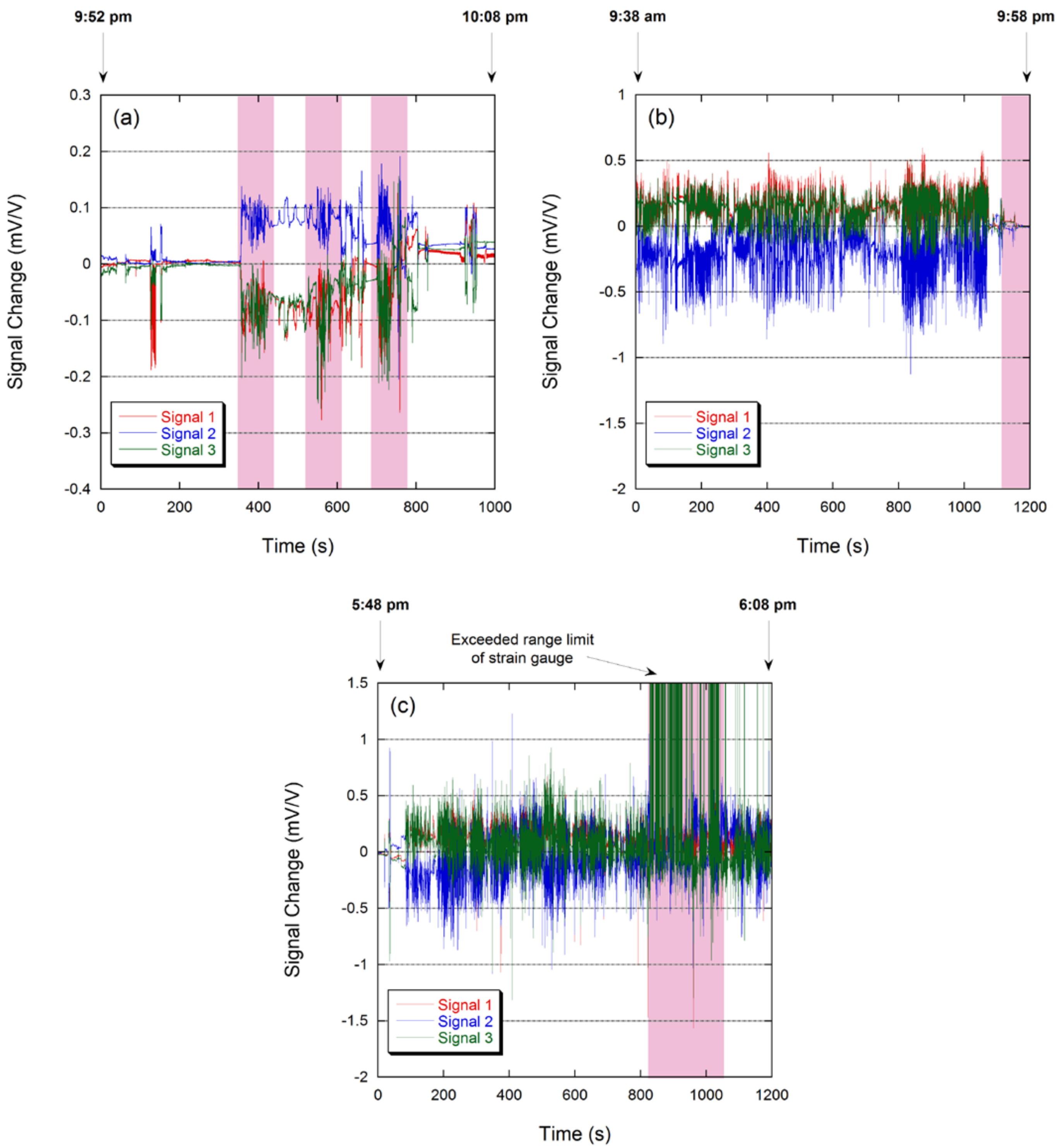

Figure 13: Measured strain gauge signal data obtained by Saad al-Oteibi and James Dean while (a) praying, (b) cycling and (c) playing football.

TAG 5 was instrumented with strain gauges. The gauges were located in the positions shown previously in Fig.11 – i.e. in the same locations that they were fitted on the tags attached to Saad al-Oteibi and James Dean. TAG 5 was then fixed to the loading frame as in Fig.10. A small and cyclic (sine-wave) displacement amplitude was specified, with the amplitude being altered until the recorded strain gauge signals were similar to those obtained in Fig.13(a). The amplitude was altered once more until the recorded strain gauge signals were similar to those obtained in Fig.13(b). The amplitude was altered one final time – this time to generate strain gauge signals similar to those obtained in Fig.13(c). These amplitude histories, which are designed to mimic as closely as possible the measured strain gauge signals in Fig.13, give the TAG 5 strain gauge signals shown in Figs.14(a-c). These data were used to impose on TAG 5 a variable amplitude fatigue cycle. This is in contrast to the constant amplitude fatigue tests conducted on TAG 3 and TAG 4, with the intention of generating a more realistic tag loading history based on the daily activities reported by Special Z. The resulting TAG 5 loading history is shown in Fig.14(d). It comprises 3640 cycles of low displacement amplitude fatigue testing, generating strain gauge signal changes (Fig.14(a)) similar to those in Fig.13(a) to simulate the effect of regular praying (20 prayers a day for 6 months). There then follow 187,200 cycles at an intermediate displacement amplitude to generate strain gauge signal changes (Fig.14(b)) similar to those in Fig.13(b). This corresponds to 20 minutes of cycling (with a pedal rotation of 2 Hz), three times a week for six months. There are a further 124,800 fatigue cycles at a (relatively) large displacement amplitude to generate strain gauge signal changes (Fig.14(c)) similar to those in Fig.13(c). This corresponds approximately to one 25 to 30 minute session of football per week for six months, assuming the tag gets loaded ~3 times per second.

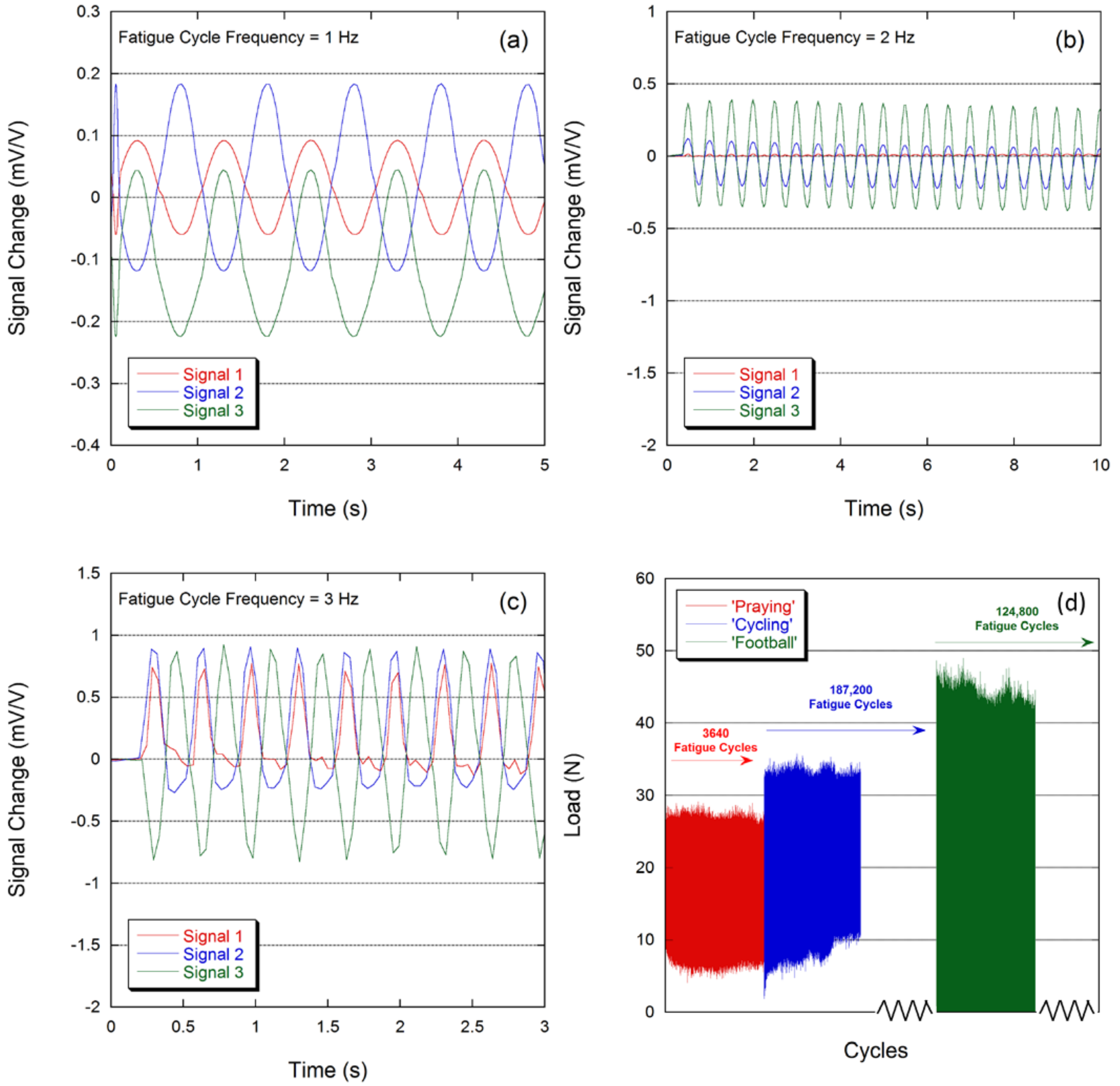

Figure 14: Measured TAG 5 strain gauge signals. The signals in (a) were obtained during simulated prayer cycles. The signals in (b) were obtained during simulated cycling cycles. The signals in (c) were obtained during simulated football cycles. The corresponding TAG 5 loading history is shown in (d).

It should be noted that the amplitude histories imposed on TAG 5 that yield the strain gauge signal changes in Fig.14 can only approximately reflect the loading histories experienced by tags in service. The measured signal change histories in Fig.13 are far more random than can be generated in the laboratory and they almost certainly include an element of strap twisting and rotation. These effects are difficult to replicate experimentally although the signal change histories in Fig.14 are reasonable approximations. Furthermore, the corresponding (measured) loading histories in Fig.14(d) are sensible and don't exceed 5 kg, which provides some confidence in this approach.

TAG 6: Constant amplitude fatigue test with a square wave amplitude history with the tag oriented in the manner shown in Fig.15(a). In this condition, the applied load is distributed non-uniformly through the clips, such that any damage is likely to be located in the lower parts of the clip as we view it in the figure. The imposed displacement history is shown in Fig.15(b). The measured load history is included in the figure. The peak applied load is ~300 N (~30 kg). This corresponds to a significant snagging event. 3640 of these events were simulated – i.e. ten snagging events per day for one whole year. The compressive loads in Fig.15(b) are generated from the downwards momentum of the crosshead during testing. They can be ignored.

The image in Fig.15(c) shows TAG 6 after the completion of the test. There is a clear amount of permanent distortion, and the strap now exits the tag at an angle. There were no obvious indentations in the strap edge.

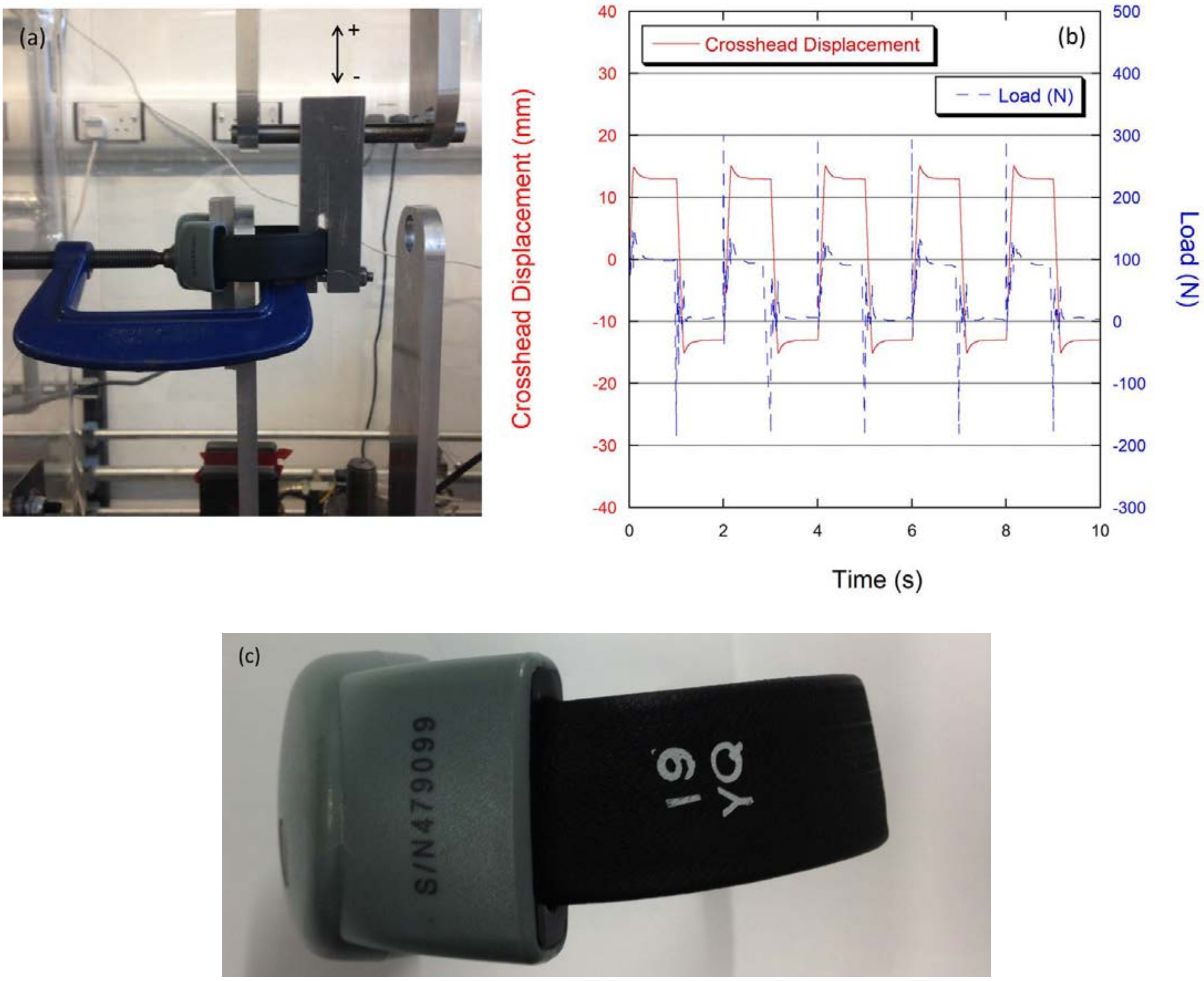

Figure 15. The testing arrangement employed for the off-axis TAG 6 fatigue test is shown in (a). The imposed square-wave amplitude history for the tests conducted on TAG 6 and the corresponding (measured) loads are shown in (b). The first ten seconds of the test are shown. 3640 of these cycles were imposed in total. TAG 6 after testing is shown in (c).

4.3 Residual Tag Strength Tests

TAG 3, **TAG 4**, **TAG 5** and **TAG 6** were loaded monotonically after their respective fatigue tests had ended. The objective of these tests was to establish if the mechanical integrity of the clips had been compromised from the accumulation of fatigue damage.

5.0 Mechanical Test Results

The mechanical test results are shown in Fig.16. They are curves of crosshead displacement (see Fig.10) versus load. Each of these curves was obtained from a monotonic loading test – i.e. the load was steadily increased until the tag failed. TAGS 3, 4, 5 and 6 were first subjected to the fatigue tests described in §4.2.

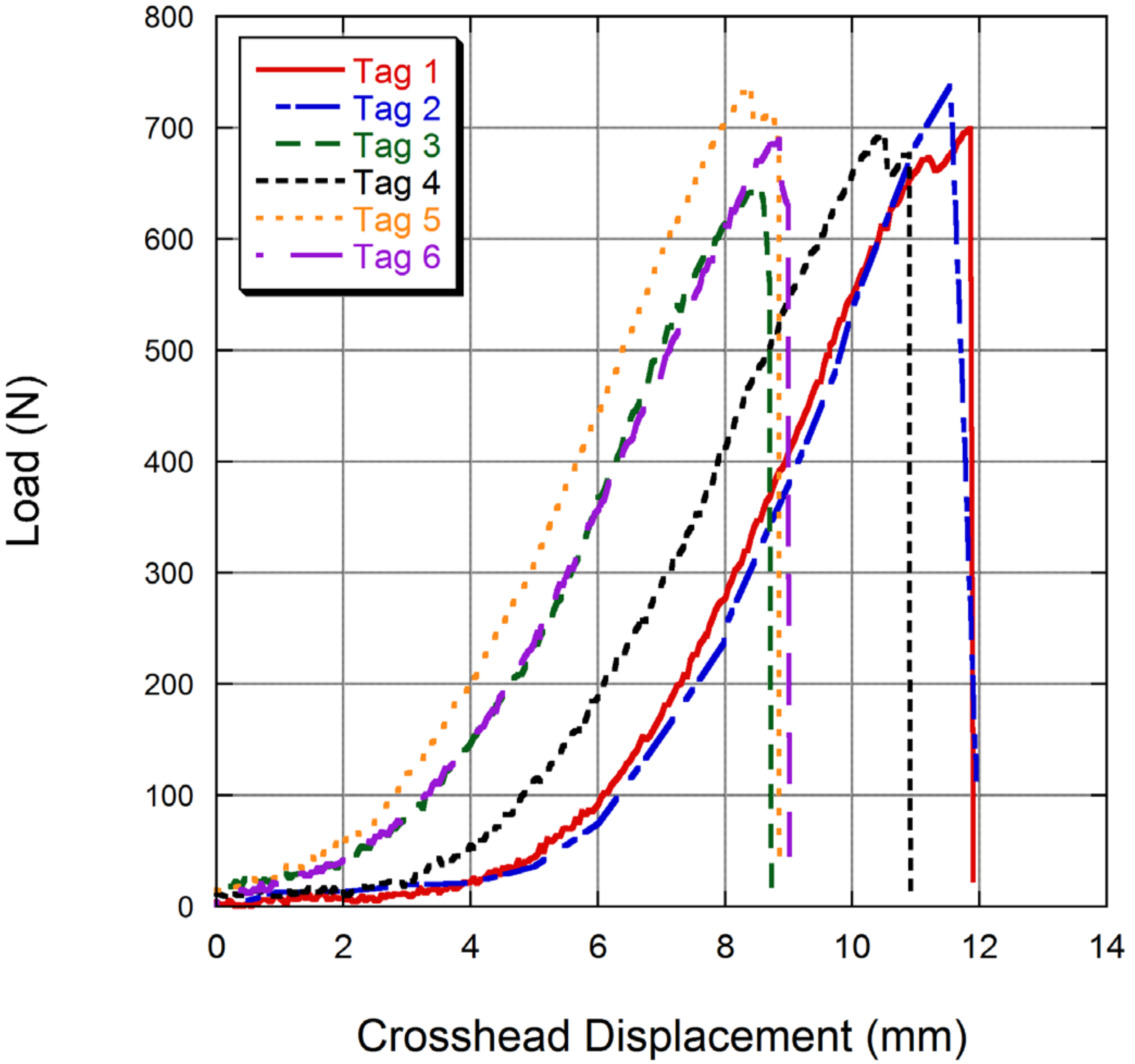

Figure 16: Measured load versus crosshead displacement data for TAGS 1 to 6. These data are from monotonic loading tests. TAGS 3, 4, 5 and 6 were subjected to the cyclic loading histories described above.

In each case, the load at failure was ~700 N (or ~70 kg). The only exception to this was TAG 3 with a failure load of ~650 N. However, these values all lie within the range specified by Surescreen Scientifics Division – even TAG 6

(Fig.15(c)) which displayed clear evidence of permanent distortion after testing. Although limited in number, these data suggest that any damage from fatigue was negligible. This tentative conclusion appears to be supported by the fractographic analysis in §6.0.

6.0 Fractographic Analysis

Some scanning electron microscopy micrographs are shown in Fig.17. They were obtained from TAG 4 and TAG 5, but the predominant features were observed in all of the tags tested. They show extensive local tearing and plasticity but no evidence of fatigue crack growth. There was also no evidence of conchoidal marks during examination of the fracture surface using lower resolution optical light microscopy. For instance, Fig.17 is a micrograph of a fractured arch from TAG 4. It also shows evidence of ductile fracture including a shear lip in the upper left hand corner. These observations are consistent with the observations of ductility at higher magnification.

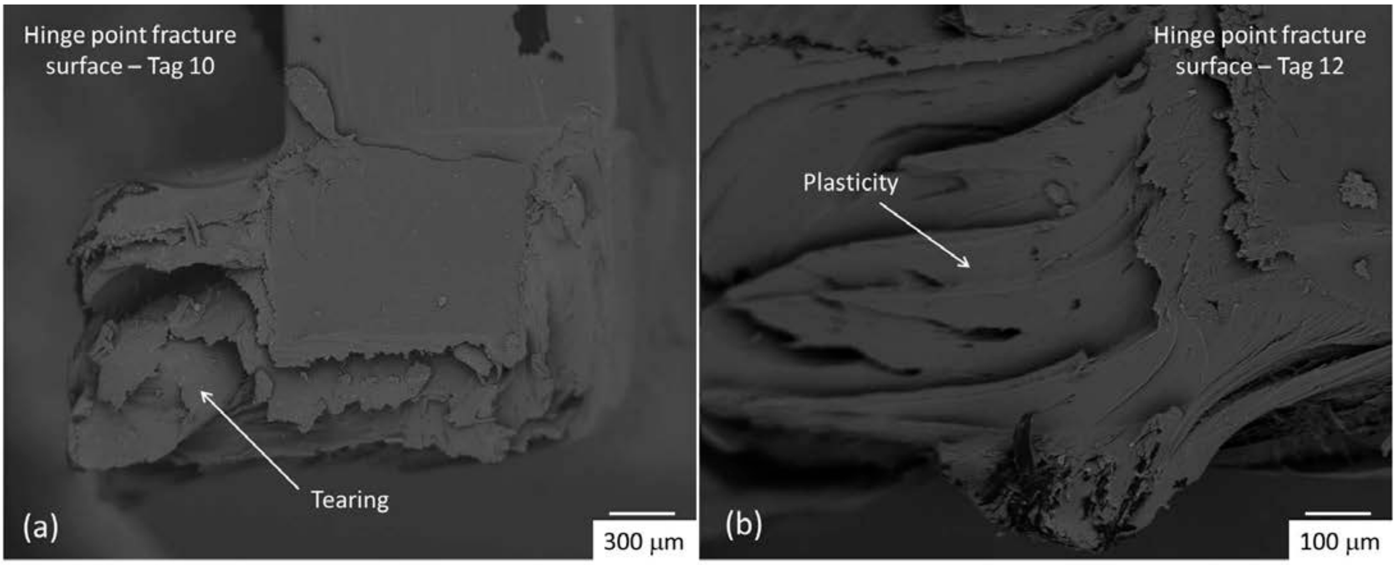

Figure 16: Scanning electron micrographs of the hinge point fracture surfaces of (a) TAG 4 and (b) TAG 5 showing tearing and plasticity.

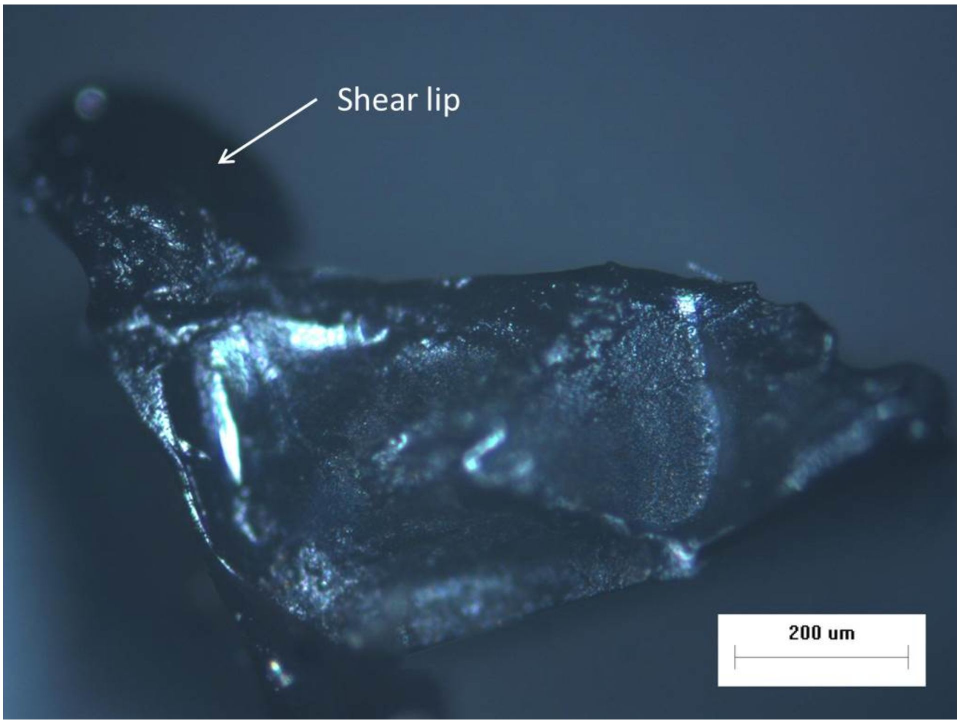

Figure 17: Optical light microscope image of a fractured arch surface showing ductile tearing and a shear lip.

7.0 Conclusions

The conchoidal marks in Fig.5 resemble fatigue crack growth marks such as those shown in Fig.2 and Fig.3. Their location is consistent with our understanding of how the loads are distributed during loading of the strap. Our understanding has been aided by some simple finite element modelling. We have attempted to recreate the features shown in Fig.5 by conducting our own fatigue tests. The applied cyclic loads were designed to simulate the everyday activities of Z. They included therefore some simulated prayer cycles, some simulated cycling cycles and some simulated football cycles. The tests were accelerated in order to induce approximately 6 months' worth of loading. Some further, more vigorous loading cycles were imposed also. These were designed to simulate accidental snagging events. It is accepted that the ordinary loading cycles incurred by Z's tag cannot be reproduced to high precision in the laboratory. The same is true of an accidental snagging event. Our simulated loading cycles are approximations only.

We found in all instances that we could not generate the features shown in Fig.5. The residual strength of the tags remained comparable to the values recorded for tags that had not been fatigue tested. One has to assume therefore that we did not induce fatigue damage, and this is consistent with the fractography. The effect of an initial (sharp) partial-crack (such as those seen on page 17 of D0131) on the fatigue performance of these tags has not been studied, but it could be important.

The possibility that the marks in Fig.5 are Wallner lines cannot reliably be ruled out, although these features are favoured in materials with higher stiffness and low ductility.

8.0 Personal Curfew Tag Experience

I wore a curfew tag for 4 days. The tag was not intrusive and most of the time I forgot I was wearing it. I occasionally snagged the tag while undressing but the imparted loads were small – I estimate that they were less than 5 kg. The tag was not uncomfortable while cycling or playing football. I did not notice any excessive loadings on the tag during my game (which lasted 20 minutes), but the tag was struck by the ball on a few occasions. The following morning, after the strain gauge trials had finished, I attempted to forcibly remove the tag from my ankle. I pulled the strap at an angle and in a direction away from the floor. I was surprised at how easily the tag came off. Having read some of the previous reports of James Campbell and Troy White I expected the tag to offer much more resistance than it did. Since this was not a scientific test, I cannot say with certainty what the applied load for failure was. I am however very confident that the exerted load was substantially less than 35 kg. I would estimate that it was no more than 15 kg. The fracture surfaces showed no signs of fatigue damage so the low load for failure remains unexplained. A video of me pulling the strap off is available on request.

I also note that the upper two arches (see Fig.8(a)) are very fragile. Professor Anderson appeared to fracture one while in my presence and without exerting much load. There was an audible crack while he handled the tag. I then X-rayed the tag – without removing the clip assembly from the tag – and found that one of the arches was indeed fractured. The scan in Fig.8(a) is from Professor Anderson's tag. The possibility that these two arches can fracture during installation of the tag should therefore be explored. My handling of the clips and my preliminary simulations suggest that this is indeed possible. I am not aware if this has previously been considered and, by their own admission, SSD cannot remove the clips from the tag without breaking the arches. I suggest therefore that a number of assembled tags and straps be analysed with X-rays. It also seems apparent that these two clips could fracture without causing any significant misalignment between the optical fibre and the light receiver. In my opinion, even if these arches had fractured, I would not expect to see any significant reduction in the load required for failure when the tags are loaded axially. Their contribution to this load is, in my opinion, very small. It would have been very helpful to have received the spare sets of unassembled clips and tags as we initially requested.

9.0 Critical Appraisal of SSD Reports C2268 and D0131

Report C2268

Paragraph 5:

"Whenever a load is applied to a case or a strap, the load has to be shared by both ends of the strap because the strap is a loop, so both clips see this load. When a load is applied to break the strap clip, both clips see this load and the intact clip becomes deformed. The extent of this deformation allows the trained eye to observe how this load was applied. On the intact clip there are signs of distortion that signify that the clip has also been loaded."

It is true to say that both clips become loaded when the strap is pulled or snagged. The language used by James Campbell implies that the applied load is shared equally between the clips. This is clearly not the case.

Paragraphs 6 and 7:

If the clip has distorted, but not fractured, then the clip has plastically-deformed (permanently changed its shape). This is not consistent with the material being brittle, which is an assertion that has repeatedly been made. I also noted during my own studies that the clips could plastically deform and the fractography in §6.0 shows extensive local plastic deformation around the fractured regions. Since plastic deformation precedes fracture, it occurs at loads that are less than those required for fracture. Since plastic deformation of the clips involves a permanent shape change, the strap will not necessarily return to its original position when unloaded – adopting instead a new position. It is therefore conceivable that multiple indents on the edge of a strap appear progressively over time as the clips plastically deform and expose new strap edge. One might expect their appearance and occurrence to be a little irregular and for the microscopic surface features to exhibit some signs of scuffing and abrasion. I am not aware of any electron microscopy studies on the strap edge indents, but my advice would be to perform these tests as a routine part of their examination.

Paragraph 8:

"Strap connections are very strong and clips cannot fail from normal wear and tear"

What is meant by "strong" is not well defined. The strength of the clip is determined by the material it is made from (i.e. its microstructure). This value is fixed (notionally). The load at which the clip and its components fail ***is variable***, and it depends on the loading conditions, the loading rate, the test temperature and even the environment. One cannot state with absolute certaintly that the clips cannot fail from normal wear and tear. All materials are vulnerable to wear and tear. The extent of any wear and tear damage depends on the material type and the loading conditions/environment. There are of course scenarios in which the loads are so small that the rate of wear and tear is imperceptibly slow. From wearing the tags myself, I suspect that the rate of clip wear and tear, from ordinary daily activities, is also very slow. I would expect the rate to increase if my activities were energetic enough to more substantially load the clips and from repeated incidents of snagging also. The presence of a partial crack, however it occurred, could also encourage more rapid failure of the clip via fatigue crack propagation mechanisms.

Paragraph 10:

"Straps are designed to break at between 35 and 40 kilograms load (about 6 stone) when loaded accidentally."

This statement is true for tags that are loaded from the centre of the strap in the direction normal to the plane of the tag (see Fig.10(c) and Fig.16). This is likely to be lower for a strap that is loaded off-axis.

Paragraph 13;

"I am guided by the fact that it is extremely difficult to fracture only three out of the four quarters of a clip by overloading alone."

It is difficult to fracture only some of the clips when exerting a high load. Jim Campbell explains why this is so in Paragraph 14. However, progressively accumulating damage may well explain why this difficult-to-produce event appears to have happened in this instance.

Paragraph 15:

"It is a misconception that something will be weakened by prior damage and will fail progressively, piece by piece."

I am not entirely sure that I understand James Campbell's analogy, but if he is suggesting that damaged materials retain their undamaged strength then he is wrong. If he is suggesting that materials cannot fail from the progressive accumulation of damage then he is wrong. If he is suggesting that materials can't progressively accumulate damage then he is also wrong. His statement needs clarifying.

Paragraph 16:

"It is also a misconception that a tag will simply fail by snagging and fall off."

The loads required to break a fatigue-damaged clip won't necessarily be substantial. It would depend on the degree of damage and the manner in which the loading event had occurred.

Paragraph 17:

"I cannot think of any circumstances in which such an action could load a strap sufficiently to break a strap clip in the manner I have described yet leave behind no tell-tale marks on the strap or case."

A clip that failed by the progressive accumulation of damage would not leave behind any "tell-tale" signs of external damage.

Report D0131

Paragraph 9:

"The right side of the clip has bent to form a hinge point."

This demonstrates that the clip material is not brittle.

"…the presence of a fragment of the fractured plastic attached to the broken clip suggests to me that it is more likely than not that the strap has not been pulled out and replaced, otherwise I would have expected that fragment to have become dislodged and lost"

James Campbell has previously said that it is very difficult to break just a few of the clips if a significant and deliberate load is applied to the strap (paragraph 13 of reportC2268). Might this suggest therefore that the clip was damaged progressively and over a long period of time? This is consistent with the fracture surfaces in Fig.5.

Paragraph 10:

"Conchoidal marks are seen in strong materials like plastics when they are overloaded."

What does James Campbell mean by "strong"? Does he mean they have a high stiffness? Or a high yield stress? A high hardness? Maybe a high tensile strength? In general they have none of these qualities. They can of course be tough? Is this what he means? It is also possible that the conchoidal marks are Wallner lines – which are generated when stress waves interact with an advancing crack front. These features are favoured by materials that are stiff and brittle (glass, for instance) whereas this polymer has a low stiffness and exhibits extensive plasticity during failure. However, I cannot reliably confirm that the markings in Fig.5 are not Wallner lines.

Paragraph 11:

"These clips are designed to fracture at a particular load, but they will start to deform when the load becomes excessive."

This is an admission that the clips can plastically deform and are not therefore brittle.

"Since the strap is a loop, loads applied to it or the case will be shared, in effect doubling the strap strength"

This is only possible if the load is applied in a very particular way.

Paragraph 13:

"…I cannot think of any other possible situation in which the strap could be overloaded without leaving behind physical damage except deliberate loading of the strap by soft tissue….

The progressive accumulation of fatigue damage is one such scenario.

Paragraph 14:

"I have found that it is possible to break these clips with the fingers but it requires significant effort to do so."

This is not consistent with my own attempt to forcibly remove the tag.

"I have been unable to exert a sufficiently controlled overload to break one part of the clip while allowing the other part to remain intact. I believe this is because the amount of exertion required in a single determined effort is difficult to apply in a controlled way, such that as soon as one side of the clip breaks, the same applied load then goes on to break the other side of the clip because the clip is now weakened by the failure of one side of it."

If this is the case, how could Z possibly apply a controlled overload? After all, only a few of his clips were broken and by Campbell's own admission the clips had not come out and been replaced. In my own example, all of the clips broke when I overloaded the sample and I agree that it would be difficult to break just a few if the applied overload was deliberate because of instantaneous load transfer to the remaining intact clips.

Paragraph 18:

"Then after some 20 or so exertions at almost the limit of my capability with the fingers, I had deformed the clip sufficiently for one side to fracture, leaving the other side as a hinge and still intact."

James Campbell performed therefore a fatigue test – albeit unknowingly – and demonstrated that, after a sufficient number of loading cycles, he was able to fracture the clip. He also states that this type of test generated conchoidal marks like the ones seen in Z's tag yet he has provided no images for comparison. We should absolutely see these images.

Paragraph 20:

"…I have by experimentation shown that deliberate and repeated excessive forcing of the clip can result in one side of the clip failing…"

He has therefore demonstrated that these tags can fail from fatigue.

Technical Report Statement (28th January 2014)

Paragraph 2:

"The type of fracture seen on the device in question contains river marks (fanning out from the point of failure) and conchoidal fracture marks (radiating out from the point of failure) which indicate it is NOT related to stretching or fatigue.

This simply is not right. It cannot be said with absolute certainty that these are NOT fatigue marks.

10.0 Critical Appraisal of SSD Reports

Report D0095

Paragraph 8:

"Finally, the plastic was overloaded and fractured in a brittle manner at the speed of sound."

This cannot be said. Crack propagation speeds are highly variable (even during a single crack event) and they are very sensitive to microstructure and to local crack tip plasticity (even in brittle materials!). In the tests that I have conducted I see extensive plastic deformation in the fractography (§6.0). SSD might possibly have seen this if they had conducted some electron microscopy. The failure features I have observed also show extensive crazing and crack bridging from polymer ligaments which undoubtedly reduce the crack propagation speed. What speed of sound is he referring to? The dilatational wave speed? The transverse wave speed? These take different values. The wave speeds are also sensitive to material anisotropy and injection moulded polymers exhibit significant anisotropy. This statement has clearly not been thought about and its sole purpose is to sound authoritative. This statement is repeated again in paragraph 8 of D0111 and paragraph 12 of D0310.

Report D0111

Paragraph 10:

"….and the device was installed correctly because of the conchoidal markings on the fracture face."

There is no supporting image of the conchoidal fracture features.

Report D0116

Paragraph 5:

"There are conchoidal markings, also reversed [referred?] to as river markings on the fracture faces…"

I cannot see any conchoidal markings – only river lines – in the image. Also, it seems that Troy White thinks that conchoidal marks and river lines are the same thing. They are not.

Report D0129

Figure 6 shows a partial crack. This is an ideal location from which a fatigue crack could grow.

Report D0200

Paragraph 5:

"This is because the PID is a closed loop so if a force is applied to anywhere on this closed loop, then both clips will share this force almost equally. As a result of this statement, the force that has caused the clip to fracture must have gripped to PID case or strap as to only apply forces on one clip."

It is not correct to say that the load is shared equally when a force is applied to anywhere on the closed loop. It is also a contradiction to claim that the load is shared equally regardless of where the strap is pulled and to then claim that the force that caused fracture of the clip must have been applied to one clip only.

Paragraph 11:

"I have also carried out all of the environmental…tests."

Polymer materials are sensitive to their environment and crack tip phenomena are sensitive to local environmental conditions also. Have SSD considered the effects of UV embrittlement on the polycarbonate clips? Do they know that the ingress of water/solvents/chemicals etc. into crack tips can accelerate crack growth rates and encourage early fracture? Can we see the environmental test data? What does it comprise?

Report D0164

Paragraph 6:

"There are conchoidal marks, also known as river markings, across the face of the fracture."

This demonstrates that Troy White does not realise that conchoidal marks and river marks are two different things, with two distinct morphologies.

"This shows that the material has been overloaded in a brittle fracture and the bonds that keep the material together have been forced apart."

This is the most elementary-level description of fracture possible.

Paragraph 7:

"Due to the brittle nature of the plastic clip and the stress/strain curve of these materials, the misconception that the tag could have been hanging on by a thread is not possible."

If the stress-strain curves exist then we need to see them. We would also like to see their temperature dependence and their strain rate dependence since the mechanical behaviour of polymer materials is sensitive to these variables. My fractography shows extensive plasticity (which may be confined to the crack tip region), but the stress-strain curves should help identify if the polycarbonate is brittle or not). In fact, polycarbonate is often considered to be a relatively tough plastic, hence its common use in crash helmets.

Report D0310

Paragraph 18:

"Only one clip has seen significant loading and when these devices are caught, the load is shared between both clips, as the device is a closed loop."

The loads are not necessarily shared equally when a snagging event occurs. In fact it would be very difficult to snag the strap in a way that caused an even distribution of the load between the two clips.

Report D0310

Paragraph 11:

"Examination of the fracture faces of the broken clip reveals river markings and conchoidal indications."

These pictures are not provided in the report.

Paragraph 15:

"This is because a large force is required to cause a fracture…."

This is not necessarily the case if there exists some fatigue crack damage prior to an accidental snagging event.

Report D0369

Paragraph 11:

"…as the device is a closed loop so the forces are shared equally between the two clips when caught."

This is not true for almost all possible snagging events.

Report C2515

Paragraph 16:

"Since the strength is substantial, the clips cannot break through normal wear and tear."

This is incorrect. Most metals have substantial strength but they do still fail from fatigue.

The image on page 12 demonstrates plasticity, which contradicts the previous assertions that the polycarbonate clips are brittle.

Report C2549

Paragraph 4:

"The clip fractures all have a conchoidal surface, that is, their fracture surfaces are covered in stress marks known as river markings; these show that the material was overloaded."

These images are not provided in the report, yet they are the basis on which the conclusion of a deliberate tamper is formed. There is again some confusion about the difference between conchoidal marks and river marks.

Report D0045

Paragraph 9:

"The fracture face has conchoidal characteristics suggesting there were no defects in the material….."

No images of the conchoidal marks are shown in the report.

References

[1] Failure Analysis and Prevention, ASM Handbook Volume 11

[2] Observing, Measuring and Interpreting Fracture Surface Topography, D. Hull, ISBN 0 521 64082 2

[3] Fatigue Crack Growth and Craze-induced Crack Tip Shielding in Polycarbonate, M. N. James, C. J. Christopher, Y. Lu, E. A. Patterson, Polymer, Vol.53 (2012) 1558 - 1570

[4] Crack Path Support for Deformation Mechanisms in Fatigue of Polycarbonate, M. N. James, Y. Lu, C. J. Christopher, E. A. Patterson, Engineering Fracture Mechanics 108 (2013) 89-97

[5] Ductile Fatigue Crack Propagation in Polycarbonate, N. Haddaoui, A. Chudnovsky and A. Moet, Polymer, Vol.27, Issue 9, 1986, 1377-1384

[6] http://www.flachglas-service.de/en/practical_example_cases_of_damage.html#wallner_lines (24/07/14)

[7] http://readconsultingblog.blogspot.co.uk/2010/11/glass-expert-performs-bottle-failure.html (24/07/14)

[8] http://readconsultingblog.blogspot.co.uk/2012_10_01_archive.html (24/07/14)