A new apparatus for tensile testing of engineering materials

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Abstract

We develop a novel apparatus and an associated test protocol to measure the tensile response of materials. The apparatus allows testing of ring-shaped specimens, fibre yarns and tapes of arbitrary length; it can be employed to conduct experiments at different strain rates and in different environmental conditions. The technique is tested at low rates of strain on several materials, including carbon fibres, metals, polymers and ceramics; the tensile responses measured with the new apparatus are compared to those obtained from conventional measurements and found to be in good agreement with these.

Keywords: mechanical testing, metals, polymers, ceramics, fibres

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1 INTRODUCTION

Some materials of wide application in engineering are produced in the shape of thin-walled tubes (e.g. extruded metals and plastic, braided composite parts), which makes mechanical testing problematic. Cutting of dogbone specimens from the tube's wall is not always possible and several researchers developed techniques to test ring-shaped specimens under hoop tension. For example Sedlacek and Halden [1] developed a test method based on a pressurised expandable rubber bulb, forcing ring specimens to undergo hoop tension; they used their apparatus to measure the ultimate tensile strength of acrylic plastics and ceramics, however they did not measure the corresponding tensile stress versus strain responses. Holman et al [2] presented a similar test technique based on a cylindrical expandable rubber ring and used this technique to measure the strength and elongation of carbon steel; Robinson [3] developed a similar apparatus which allowed testing of rings of different height. Ainscough and Messer [4] used a similar concept to test ceramics at high temperature; their apparatus operated by compressing wax or putty by a piston, in turn inducing radial pressure on the ring specimens. Pressurised fluid was also used to test composite ring specimens (Daniel and Ishai [5]) at low strain rates.

The tests described above are suitable for experiments at low strain rates on monolithic solids; not all of them allow measurements of the stress versus strain histories on the material. In the present paper we present a test method which allows mechanical tensile testing at both low and high strain rate and which is applicable to both monolithic specimens as well as to materials in the form of tapes or fibres. The proposed method allows testing of long strands of tapes and fibres or fibre yarns, enabling investigation

of the size dependence of the mechanical response of these materials, which is a problematic task with conventional test methods. The proposed apparatus is compact in size, which facilitates performing experiments in controlled environmental conditions.

In several engineering applications materials are loaded at high rates of strains and consequently it is necessary to measure their dynamic mechanical response. While loading by hydraulic or pneumatic devices allow reaching moderate strain rates up to 10 s^{-1} (e.g. Wu et al [6]), several techniques have been developed to conduct dynamic tensile tests at strain rates of order 10^3 s^{-1} or higher, typical of impact events; these are based on tensile versions of the Hopkinson bar setup (e.g. Pellegrino et al [7]). This method yields valid measurements only after dynamic equilibrium is achieved on the sample; for elastic-plastic material, dynamic equilibrium is typically achieved at the onset of the plastic response, such that the elastic response cannot be measured accurately (Naik and Perla [8]). It follows that the test is not suitable for all materials which display an elastic-brittle response. While pulse-shaping techniques may mitigate this problem, they result in reduced strain rate.

For the case of fibres, dynamic tests are even more problematic than for monolithic materials. First, gripping of the fibres induces strain concentrations which affect the measured strength; this problem is solved, at low strain rates, by using grips like the Capstan (ASTM.F1106-87 [9]) or similar. These grips however cannot be used in dynamic tests, as their large mass would increase the time to reach dynamic equilibrium. If fibres or yarns are tested in direct tension, the imposed strain rate scales with the inverse of the gauge length, such that, in order to achieve high strain rates, the gauge

length needs to be minimised; this renders testing of large specimens impossible. As a result of these problems, the literature on the dynamic properties of high performance fibres and yarns is not very wide. Several test methods have been used to measure the dynamic tensile response of these materials. For example, for the case of carbon fibre yarns, which are investigated in the present paper, Zhou and Wang [10] conducted tensile tests at strain rates in the range $10^{-1} - 10^3 \text{ s}^{-1}$, using screw-driven or hydraulic tensometers or a Hopkinson bar at high rates. The results suggested that carbon fibres were rate insensitive in this range, however evidence of equilibrium in the dynamic tests was not provided. Younes and Sankaran [11] measured the tensile properties of carbon fibre yarns with a drop tower, at strain rates in the range $10 - 80 \text{ s}^{-1}$; results suggested a mild rate sensitivity of the yarn strength; the design of their apparatus however was such to induce a transient tensile shock loading in the yarn, which again did not reach dynamic equilibrium. The test method developed in this paper is similar to those described above and is based on inducing hoop strains in ring-shaped specimens upon the application of internal pressure. The new protocol aims at addressing all current difficulties in dynamic testing of fibres, yarns and tapes: the proposed method does not involve moving grips, is not limited to short gauge lengths of the specimen, and is designed to achieve early dynamic equilibrium, allowing valid measurements at high strain rates.

In the present paper we focus on the application of the proposed test technique at low rates of strain, leaving the analysis of dynamic testing as a subject for future work. The structure of the paper is as follows: in Section 2 we describe the different material specimens tested. The new apparatus and the associated test technique are presented in Section 3; results are presented and discussed in Section 4.

2. MATERIALS AND SPECIMENS

2.1 Steel

Thin-walled rings made from annealed mild steel (Fig. 1a, carbon steel 1030) were produced by machining an extruded tube and had inner diameter 40 mm and wall thickness 1 mm; the height of the rings was 7 mm. A resistance strain gauge (of gauge length 10 mm) was adhered to the outer surface of the ring to measure strain in the hoop direction.

2.2 Poly(methy methacrylate) (PMMA)

PMMA rings were machined from an extruded PMMA rod to have 40 mm inner diameter, 1 mm wall thickness and 7 mm height (Fig. 1b). Flat dogbone specimens of gauge length $(5 \times 5 \times 15)$ mm were machined from the same rod, in the axial direction, and used to measure reference stress versus strain responses. We note that the new test method presented here induces strains in the circumferential direction of the rod, while in conventional tests on dogbone samples tensile strains are induced in the axial direction. Vickers micro-hardness tests were conducted on cubic blocks of the PMMA in both the circumferential and axial directions, and results confirmed that the material was approximately isotropic (the measured Vickers hardness was of $23^{+0.5}_{-0.7}$ and $23^{+0.8}_{-0.5}$ HV in the axial and circumferential direction, respectively).

2.3 Carbon fibre yarn

A high-modulus carbon fibre yarn was also tested in this study. The yarn was procured from Gronac (type YSH-40-A) and contained 400 filaments of diameter of approximately $7 \mu\text{m}$, as measured from SEM images. Direct tension tests were

conducted in an Instron tensometer on different lengths of the yarn; the yarn's ends were bonded between two rubber end-tabs using an epoxy adhesive, and the tabs were gripped by wedge-action clamps. In hoop tension tests the yarn was wound multiple times around a bespoke rubber sleeve (Fig. 1c), which will be described in detail below; the two ends of the yarn were then gripped using rubber-padded G-clamps onto the fixed part of the test apparatus.

2.4 Dyneema® tape

A high strength unidirectional tape from DSM (base material for the cross-ply Dyneema® BT10 material), was also tested using both a conventional test technique and the proposed new test protocol. The material was obtained from hot-pressing and calendaring of solid state ultra-high molecular weight polyethylene powder. The unidirectional tape had thickness 40 μm and was cut to a width of 2.5 mm using surgical knives. The thin strips of tape were used to manufacture ring-shaped specimen; this was done by winding multiple turns of the tape around a bespoke rubber ring of outer diameter 40 mm, while applying cyanoacrylate adhesive (Fig. 1d). The process resulted in a composite ring comprising tape and adhesive; the relative mass fraction of this composite was determined by weighing the initial strips of tape and the consolidated composite ring. The density of both tape and adhesive, as well as the specimen thickness, were also measured and allowed calculating the corresponding volume fractions, which were of approximately 50% in all specimens. A strain gauge of gauge length 10 mm was adhered on the outer surface of the composite rings to measure the hoop strain.

2.5 Borosilicate glass

Borosilicate glass rings were cut from a tube using diamond-grit tools. The rings had inner diameter 40 mm, wall thickness 1.6 mm and height 7 mm (Fig. 1e). The rings were instrumented with a resistance strain gauge of gauge length 10 mm in the hoop direction.

3. DESIGN OF THE APPARATUS AND EXPERIMENTAL PROCEDURE

3.1 Design of the apparatus

Figure 2a shows a cross-section of the apparatus, configured for a quasi-static test. It consists of two steel plates, connected via vertical hollow steel cylinders and bolts, serving as a frame. The frame sandwiches a metallic base, the specimen to test, and a piston/cylinder assembly; the specimen is mounted on a bespoke rubber ring. The piston bears two holes connecting its two ends; this is to allow injection of fluid and evacuation of air bubbles from the fluid. The application of a compressive force to the piston and its consequent downward motion induces radial expansion of the rubber sleeve; the specimen to test, placed in contact with the outer surface of the rubber sleeve, undergoes hoop tension. The sizing of the metallic parts of the apparatus was dictated by considerations of structural integrity and cost minimisation.

Rubber sleeves of two different size and shape (but equal outer diameter of 40 mm) were manufactured, as sketched in Fig 2b. The axial dimension of the rubber sleeve was dictated, for solid materials, by the width of the strain gauge used. In the case of tapes and fibres, preliminary tests suggested that the height of the specimen and rubber sleeve needs to be minimised to ensure a uniform deformation in the sleeve. The large

sleeve (average wall thickness 4 mm, height 10 mm) was used in testing of solid materials (steel, PMMA and glass), while the smaller one (average wall thickness 3 mm, height 3.5 mm) was used for testing the carbon fibre yarn and the Dyneema® tape. The rubber sleeves were manufactured by 3D printing (Stratasys Connex3) from a polymer blend (of ‘TangoBlack’ and ‘VeroWhite’), which resulted in a rubbery material with compressive modulus of 5-10 MPa (at a strain rate of 10^{-3} s^{-1}).

The test procedure is as follows. The specimen is placed around the appropriate rubber sleeve, which is then placed between the metal base and the cylinder. The assembly is clamped between the two steel plates, abundantly lubricated with oil; the clamping induces axial strain in the rubber sleeve of order 3%; this induces a circumferential pre-strain in the specimen, which can be monitored via strain gauges and minimised by increasing the specimen’s cross-section; the pressure induced by the clamping facilitates sealing. Water is placed into the chamber formed by rubber sleeve, base and cylinder, and the piston is inserted; any residual air is evacuated via a bleeding valve embedded in the piston and sealed by a M2 screw. The apparatus is then ready for compression testing in a conventional test machine. The same apparatus can be also tested at high strain rates, by replacing the metal base with an additional cylinder/piston system, allowing sandwiching between the input and output bars of a split Hopkinson pressure bar (SHPB). This modified version of the apparatus will be described in a future companion study.

3.2. Mechanical Tests

3.2.1 Direct Tension tests

Dogbone specimens

Instron tensometer and wedge-action clamps were employed for the direct tension tests on PMMA, conducted in accordance to [14] on dogbone specimens of gauge length $(5 \times 5 \times 15)$ mm . Tests were conducted at strain rates of 10^{-3} s^{-1} and 10^{-2} s^{-1} and axial strain was monitored by a resistance strain gauge.

Fibre yarns

Direct tension tests of fibre yarns were also conducted with an Instron tensometer on different lengths of the yarn. The strain was measured by a laser extensometer (Manufacturer: E.I.R., model LE-05) of resolution $1 \text{ } \mu\text{m}$, which tracked the position of two reflective strips attached to the yarn. The fibres were loaded at strain rates of 10^{-4} s^{-1} and 10^{-3} s^{-1} .

Tape material

The Dyneema® tape was tested with Instron tensometer via Capstan grips [9]. The gauge length of the tape was 250 mm and the width was 2 mm. The specimen cross-section was measured with callipers before testing; a resistance strain gauge of gauge length 10 mm was adhered to the specimen in the longitudinal direction. The strain rate was set to 10^{-4} s^{-1} , 10^{-3} s^{-1} or 10^{-2} s^{-1} .

3.2.2 Hoop Tension Tests

Solid materials

For solid materials such as steel, PMMA and glass, ring-shaped specimens were tested. The specimen was manufactured to fit into the groove on the outer surface of the rubber sleeve; the specimen thickness was minimised to reduce radial variations of the stress state in the specimen. A strain gauge was adhered on the outer surface of the specimen to monitor strain. An Instron tensometer was employed to load the apparatus, displacing the piston at a speed such to induce hoop strain rates of 10^{-3} s^{-1} or 10^{-2} s^{-1} . The force was measured by the load cell of the test machine, of capacity 50 kN.

Carbon Fibres

A different test procedure was followed when testing fibre yarns; the desired number of turns of the carbon fibre yarn were wound uniformly in the groove of the rubber sleeve. After the sleeve was clamped in the apparatus, the free ends of the yarn were pre-tensioned manually ($\sim 10\text{N}$) and clamped around two of the hollow steel cylinders in Fig. 2, via a small rubber-padded G-clamp. A laser extensometer was used to measure the strain in the yarn, by tracking two reflective strips. The piston was displaced such to induce hoop strain rates of 10^{-4} s^{-1} or 10^{-3} s^{-1} .

Tape material

Rings made from Dyneema® tape, consolidated with cyanoacrylate, were instrumented with two strain gauges of grid length 10 mm, to check the uniformity of hoop strain; it was found that this strain was uniform throughout the test if sufficiently thick specimens

were used (3 turns of Dyneema® tape in this case). An Instron tensometer was used for loading, at strain rates of 10^{-4} s^{-1} , 10^{-3} s^{-1} and 10^{-2} s^{-1} .

3.3 Analysis of data

We now outline the procedure to obtain stress versus strain curves from the measurements taken in the hoop tests. The fluid pressure p_0 is known from measurements of the axial force on the apparatus (neglecting friction due to the contact of the piston's O-rings with the steel cylinder) and from knowledge of the cylinder's cross-sectional area A_0 . The fluid is contained within an approximately cylindrical rubber sleeve of inner radius R_0 , outer radius R_i and height h_R ; the outer surface of the rubber sleeve is in contact with a cylindrical specimen of height h_s , as sketched in Fig. 3.

The specimen consists of either a monolithic ring (for the case of solid materials) or of N windings of yarn or tape material. The fluid pressure p_0 induces radial compressive stress on the inner face of the rubber sleeve, causing the rubber and the material specimen to expand radially (axial expansion is prevented by the rigidity of the steel frame). Let p_i be the pressure at the interface between rubber sleeve and material specimen, while σ_s and σ_R are the average hoop stresses in the specimen and rubber sleeve, respectively. Equilibrium of the specimen dictates

$$\sigma_s A_s = p_i R_i h_s \quad (1)$$

where A_s is the cross-sectional area of the specimen and h_s is the height of the specimen. Equilibrium of the rubber sleeve gives

$$\sigma_R A_R + p_i R_i h_s = p_0 R_0 h_R \quad (2)$$

where A_R is the cross-sectional area of the rubber sleeve; it is assumed that the radial thickness of specimen and rubber sleeve are much smaller than the contact radius $R_i = 20\text{mm}$, such that the hoop strain ε can be taken as uniform along the radial direction. Let the constitutive response of the rubber sleeve be $\sigma_R = \sigma_R(\varepsilon)$.

Combining eqns. (1) and (2) and using $F = A_0 p_0$, the hoop stress in the specimen is obtained as

$$\sigma_s = \frac{1}{A_s} \left[\frac{R_0 h_R F}{A_0} - A_R \sigma_R(\varepsilon) \right] \quad (3)$$

Solid material specimens had rectangular cross-section and $A_s = h_s t_s$; for fibre yarns and tape material specimens, the total cross-section depends on the number of windings N , such that $A_s = N A_F$, where A_F is the cross-sectional area of the yarn or tape. As the rubber sleeve was much softer than the specimen, the negative term in the parenthesis of eq. (3) was found to be negligible compared to the positive term; in other words, the presence of the rubber has only a minor influence on the stress measure performed. Equation (3) however allows to correct the measurements if the response of the rubber $\sigma_R(\varepsilon)$ is known.

The apparatus was designed to operate at fluid pressures up to 50 MPa; in this regime the compressibility of the water can be neglected; the rubber used for the sleeve has Poisson's ratio of order 0.49, therefore its compressibility can also be neglected in first

approximation. Considering both rubber and water as incompressible, and assuming small displacements, the hoop strain ε induced in the specimen can be related to the piston displacement δ by

$$\delta A_0 = 2\pi R_i h_R \varepsilon R_i \Rightarrow \varepsilon = \frac{\delta A_0}{2\pi R_i^2 h_R}. \quad (4)$$

It must be noted that for the case of the tests on Dyneema® tape the specimen consisted of a composite of tape and cyanoacrylate adhesive. The stress in the composite σ_c is $\sigma_c = V_f E_d \varepsilon + (1 - V_f) E_c \varepsilon$, with V_f the volume fraction of Dyneema® tape, index ‘d’ represents Dyneema® tape and ‘c’ represents cyanoacrylate adhesive. V_f is typically 50% and the modulus of cyanoacrylate, is below 1 GPa, while the modulus of the tape is of order 100 GPa. Therefore the presence of the adhesive was neglected in the analysis

4. RESULTS AND DISCUSSION

4.1 Preliminary tests

A preliminary set of tests is presented to illustrate the role of the rubber sleeve in the test, to highlight the test repeatability, and to discuss strain measurements.

Figure 4a presents load versus piston displacement curves obtained loading the larger rubber sleeve, absent any specimen, at different speeds; a measurement taken during a test on PMMA is shown for comparison. Clearly even at relatively large speeds, deforming the large rubber sleeve requires a small force, compared to the case of a real

test on a relatively soft specimen (the PMMA has the lowest modulus and strength among the materials tested in this study). Figure 4b presents the hoop stress versus hoop strain histories for the same tests in Fig 4a. The hoop strain of the rubber sleeve is measured by strain gauge attached to its outer surface; frictional forces are neglected to calculate the stress in the rubber. The data shows that the rubber undergoes a non-linear convex stress versus strain history, with a viscous response. This measurement provides the constitutive relation $\sigma_R(\varepsilon)$ used in eq. (3).

Several steel ring specimens were tested to validate the data analysis method; steel is chosen as the modulus of this material is known accurately, and its response can be considered as approximately rate-independent. Results are given in Fig 4c, where three repeated tests are shown, to illustrate scatter. Modulus and yield stress of steel are measured with sufficient accuracy; as the response of steel is quite repeatable (within 1% in flow stress), from a comparison of the three repetitions we deduce that the proposed technique introduces an uncertainty in flow stress of order 5%.

Figure 4d shows stress versus strain curves for a Dyneema® tape specimen; these are recorded from a test in which strain is monitored with both a strain gauge and a laser extensometer, to allow direct comparison. Clearly the use of a strain gauge results in much lower noise; for this reason, the laser extensometer was only used where using a strain gauge was infeasible (i.e. when testing the fibre yarn).

We proceed to summarise the results of the tensile tests and to compare measurements by the proposed method to those from conventional test protocols. All results are

summarised in Table 1. The tensile properties measured with conventional test protocols are shown in parentheses.

Material Name	Strain rate (s^{-1})	Young's Modulus (GPa)	Failure Stress (MPa)	Failure Strain
Steel	10^{-3}	197^{+2}_{-1}	/	/
PMMA	10^{-3}	$3.43^{+0.34}_{-0.30}$ (3.50)	84^{+3}_{-4} (84)	$0.038^{+0.002}_{-0.002}$ (0.041)
	10^{-2}	$3.57^{+0.08}_{-0.14}$ (3.75)	80^{+6}_{-5} (88)	$0.030^{+0.001}_{-0.001}$ (0.032)
Carbon Fibre	10^{-4}	424^{+40}_{-20} (401)	2162^{+55}_{-32} (2305)	$0.0058^{+0.0001}_{-0.0001}$ (0.0059)
	10^{-3}	585^{+93}_{-102} (521)	2150^{+83}_{-122} (2448)	$0.0054^{+0.0003}_{-0.0004}$ (0.0054)
Dyneema® Tape	10^{-4}	141^{+8}_{-11} (134)	1270^{+43}_{-34} (1314)	$0.0108^{+0.0004}_{-0.0003}$ (0.0109)
	10^{-3}	164^{+15}_{-16} (157)	1474^{+19}_{-13} (1486)	$0.0106^{+0.0002}_{-0.0001}$ (0.0108)
	10^{-2}	174^{+5}_{-8} (162)	1624^{+65}_{-47} (1540)	$0.0106^{+0.0004}_{-0.0006}$ (0.0107)
Borosilicate Glass	3×10^{-5}	50^{+1}_{-1}	29^{+1}_{-1}	$0.00067^{+0.00001}_{-0.00001}$
	10^{-4}	56^{+1}_{-1}	33^{+1}_{-1}	$0.00068^{+0.00001}_{-0.00001}$
	10^{-3}	65	39	0.00071
	2×10^{-3}	81^{+4}_{-4}	43^{+1}_{-1}	$0.00070^{+0.00005}_{-0.00005}$

Table 1. Summary of mechanical properties measured with the proposed apparatus (in parentheses: result of conventional tests).

4.2 Response of PMMA

The stress versus strain curves of PMMA tested at two different strain rates are shown in Fig 5. The measurements taken in the hoop test (dashed lines) are compared to the results obtained from a conventional test method (in this case tensile testing of a dogbone specimen); clearly the two sets of measurements are in agreement. The material has an initial linear response, followed by a non-linear behaviour up to failure.

The flow stress increases and the ductility decreases with increasing strain rate, in accordance with measurements from Wu et al [6].

4.3 Response of carbon fibre yarns

The results for this material are presented in Fig. 6. For these tests strain was measured using a laser extensometer; Figures 6a and 6b compare results obtained via a conventional test method with those achieved with the proposed hoop test; three hoop stress measurements are shown, to illustrate scatter, together with their average. Despite the problems with noise in strain reading, the hoop test method allows measuring similar stress versus strain histories as in conventional tests. The stiffness of the carbon yarn and its ultimate strength increase mildly with strain rate, while the failure strain decreases slightly.

4.4 Response of Dyneema® tape

Figure 7 presents stress versus strain measurements for this material at strain rates of 10^{-4}s^{-1} , 10^{-3}s^{-1} and 10^{-2}s^{-1} . At all strain rates, the response measured with the new hoop test coincides with that measured by conventional test methods. The tensile response of the Dyneema® tape has a significant strain rate sensitivity; the stiffness of the material and its ultimate strength increase as the strain rate increases, while the failure strain is approximately insensitive to the applied strain rate.

4.5 Response of borosilicate glass

Hoop stress versus strain measurements at strain rates in the range $10^{-5} - 2 \cdot 10^{-3}\text{s}^{-1}$ were performed on glass rings and results are presented in Fig 8. Conventional tests in this case were not performed, due to the difficulty with machining glass. Measurements

suggest that the glass exhibits strong strain sensitivity in the range investigated. As the strain rate increases, the failure strength and Young's modulus increase, while the failure strain remains unchanged at approximately 0.7%.

4.6 Sources of errors and discussion of uncertainties

In this section we discuss in more detail the possible sources of errors for the proposed test. These are: (i) frictional effects between piston and cylinder, (ii) frictional effects between rubber sleeve and steel surfaces, (iii) inhomogeneity of the radial strain in the specimen, (iv) asymmetric deformation modes of the rubber sleeve, (v) inherent uncertainty in the strain measurement by laser extensometer.

The first effect can be minimised by an accurate design of the piston/cylinder coupling and an appropriate choice of O-rings. For the apparatus presented here the measured axial force in absence of water was smaller than 10 N at the fastest test speed of 50 mm/min; considering that the axial force at failure for the weakest PMMA specimen was of order 1500 N, we deduce that this effect is negligible.

To evaluate frictional effects between rubber and steel surfaces, we repeat the analysis of the system including the frictional forces acting on the upper and lower part of the rubber sleeve. Equation (3) is modified into

$$\sigma_s = \frac{1}{A_s} \left[\frac{R_0 h_R F}{A_0} - A_R \sigma_R(\varepsilon) - \mu p_{axial} (R_i^2 - R_0^2) \right] \quad (5)$$

where μ is the coefficient of dynamic friction and p_{axial} is the pressure at the interface between rubber sleeve and steel surfaces. The first and second term in the square parentheses can be measured accurately, while the third is harder to quantify. The coefficient of friction between rubber and lubricated steel is of order 0.25 [14]; the axial

pressure depends on the details of the constitutive response of the rubber material, which are difficult to evaluate. Assuming that p_{axial} is equal to its initial value due to the initial compression of the rubber sleeve (~ 0.3 MPa), the last term in parentheses is at most of order 10 N, for the case of the larger rubber sleeve; the first term in parentheses at the end of the test (i.e. at final failure of the specimen) is, for the weakest specimen tested (PMMA, $F_{max} = 1500$ N), of order 764 N. We conclude that frictional effects account for an uncertainty in measured stress of 1.3% at most. This uncertainty can be minimised by maximising the radius of the sleeve and minimising its radial thickness.

The hoop strain in the specimen varies with radial position; measuring this strain at the outer surface of the specimen introduces an uncertainty in the strain reading. Thick-walled tube theory shows that the ratio between hoop strain at the outer surface of the specimen $\varepsilon_{\theta out}$ and average hoop strain $\varepsilon_{\theta avg}$ is

$$\frac{\varepsilon_{\theta out}}{\varepsilon_{\theta avg}} = \left(1 + \frac{t_s}{2R_i} \right)^{-1} \quad (6)$$

where t_s is the radial thickness of the specimen, while the ratio between hoop strain at the outer and inner radius is

$$\frac{\varepsilon_{\theta out}}{\varepsilon_{\theta inn}} = \left(1 + \frac{t_s}{R_i} \right)^{-2}. \quad (7)$$

In all experiments presented here was $R_i = 20$ mm; the thickest specimens were those made from borosilicate glass, with $t_s = 1.6$ mm, giving $\varepsilon_{\theta out} / \varepsilon_{\theta avg} = 0.96$ and $\varepsilon_{\theta out} / \varepsilon_{\theta inn} = 0.86$. We deduce that these specimens were somewhat too thick to give an accurate measure of a stress versus strain history, however they were used in the tests

as thinner specimens could not be easily sourced. An improved version of the apparatus should have a greater value of R_i , to reduce issues with non-uniformity of stress and strain.

An additional source of uncertainty is represented by the fact that the expansion of the rubber sleeve was observed, in some cases, to be non-uniform; this occurred when testing fibre and tape specimens, of low bending stiffness. This could not be prevented with the current design of the apparatus; it was however monitored, by employing 2 or 3 hoop strain gauges and discarding tests in which the strain gauge readings differed by more than 5%.

5. CONCLUSIONS

We described the development and validation of a general method for tensile testing of engineering materials, including solids, fibre yarns or tapes, in the quasi-static regime. The test method was applied to a set of different materials with wide range of mechanical properties and it was shown to give results consistent with those from conventional test methods.

The apparatus offers several advantages over classical test methods and allows (i) testing of specimens of tubular forms, including those made from brittle materials; (ii) testing of long strands of fibre yarn or tape; (iii) easier conditioning of the specimens, due to its compact size, and (iv) testing of identical samples over wide ranges of strain rate. A detailed discussion on the application of the proposed method to high strain rate testing will be addressed in a separate study. The proposed method introduces

uncertainty of order 5% in stress/strain measurements, compared to those from conventional methods.

The measurements performed highlighted the good mechanical properties of the Dyneema® tape, characterised by a high specific strength and stiffness, and their sensitivity to strain in the quasi-static regime. Results for the high-modulus carbon fibre yarn confirmed a mild sensitivity of this material in the quasi-static regimes. Measurements also illustrated the pronounced strain rate sensitivity of borosilicate glass in the range investigated.

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FIGURES

Figure 1. Material specimens tested. (a) Steel; (b) PMMA; (c) Dyneema® tape; (d) Carbon fibre yarn; (e) Glass ring.

Figure 2. (a) A cross-sectional view of the apparatus; (b) cross sections of the rubber sleeves used in the hoop tests.

Figure 3. Geometry and free-body diagram of the active part of the apparatus.

Figure 4. (a) Load versus piston displacement recorded during preliminary tests on the rubber sleeve and on the assembly of rubber sleeve and a PMMA specimen; (b) Average hoop stress versus hoop surface strain for the rubber sleeve in the tests of part (a); the stress/strain history on a PMMA sample is shown for comparison.

Figure 4. (c) Hoop stress versus strain curves for the steel ring at strain rate 10^{-3} s^{-1} ; (d) Hoop stress versus strain curves for the Dyneema® tape at strain rate 10^{-3} s^{-1} ; strain measurements from strain gauges and laser extensometer are compared.

Figure 5. (a) Tensile stress versus strain curves for PMMA at strain rate 10^{-3} s^{-1} , obtained by the proposed hoop tension method and from conventional tests; (b) tests at a strain rate of 10^{-2} s^{-1} .

Figure 6. (a) Tensile stress versus strain curves for the carbon fibre yarn, at strain rate 10^{-4} s^{-1} , obtained by the proposed hoop tension method and from conventional tests; the inset shows a SEM image of the carbon fibres (b) tests at a strain rate of 10^{-3} s^{-1} .

Figure 7. Tensile stress versus strain curves for the Dyneema® tape, obtained at different strain rates via the proposed hoop tension method or from conventional test methods.

Figure 8. Tensile stress versus strain curves for the borosilicate glass, obtained at different strain rates via the proposed hoop tension method.