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Test Method

Stress-strain synchronization for high strain rate tests on brittle composites

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ABSTRACT

Nowadays, many researchers develop rate-dependent composite material models for application in dynamic simulations. Ideally, full stress-strain curves at a wide range of strain rates are available for identification of the different parameters of these models. Dynamic tensile tests are needed to produce the experimental input data. However, especially for brittle materials, data acquisition during these tests becomes critical. The effect of synchronization on the test results was investigated by conducting a series of dynamic tensile tests on three different brittle continuous-fibre composite laminates. It is demonstrated that synchronization errors of the order of 1 microsecond already have a significant effect on the test outcome at high rates. With the aid of a finite-element model, the limiting factors on the maximum attainable strain rate are quantified.

1. Introduction

Car manufacturers attempt to reduce the mass of the next generation of vehicles by using composite materials for structural elements like door sills and B-pillars. In a vehicle crash, materials deform at rates between quasi-static and about 200 s^{-1} [1]. Composite behaviour is known to depend on strain rate [2] and the material properties should, therefore, be obtained under the right conditions. A test series is needed in which tests at several speeds are performed to obtain a global overview of material rate-dependency.

This current research aims at obtaining accurate stress-strain curves at every decade of strain rate between quasi-static and 200 s^{-1} to make a full rate-dependent parameter identification possible. The focus lies on relatively brittle composites with a strain to failure of 1% or lower, because these are found to be the most difficult to obtain high rate test data for.

1.1. Tensile rate dependence in the literature

The most common method of investigating material behaviour is the tensile test. It is less common to perform this test at strain rates close to the aforementioned upper limit. Dynamic tensile test data for composites in literature typically does not contain values in the strain rate range of about 10–500 s^{-1}. The reason for this is the following. One, stress progresses at a finite speed, invalidating the assumption of equilibrium at these deformation speeds. Measuring load and strain at different locations is then no longer possible. Two, the test duration approaches the period of the natural frequency of different parts of the test bench. Both effects mark the boundary above which a switch to bar-impact testing seems necessary, while at lower speeds the standard tensile test is most effective. Close to the boundary, both test methods are difficult to apply.

Literature with complete stress-strain curves of continuous-fibre composites close to the aforementioned upper limit, say between 100 and 300 s^{-1}, is scarce. Looking for works about composites with a typical failure strain at or below 1%, only four useful references were found. Three of these belong to a test series by Daniel. He managed to obtain curves for C/E at these strain rates by using an explosion to expand a composite ring, creating tension in the circumferential direction [3–5]. Strain was measured using strain gauges on the composite specimen. Stress was measured by expansion of an adjacent steel ring with strain gauges [5]. The other record that contains full tensile stress-strain curves in the range of interest is by Kuhn et al., who used a split-Hopkinson pressure bar (SHPB) adapted to apply tension [6]. They performed dynamic tension tests on unidirectional C/E in the transverse direction. The average strain rate of the tests amounts to 271 s^{-1}, and their full stress-strain curves go up to a strain of about 0.8%. No data below that rate was given, probably caused by the limits of the chosen test method.

No test standard is available to date that deals with high-rate tensile

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testing of continuous-fibre composites. The only related documents available either deal with metals [7,8] or with polymers [9,10]. It is worth mentioning that the ISO 18872 standard for polymers evades the use of high rate testing by using the results at low- and intermediate rates to estimate the behaviour at high rate by extrapolation [9]. The formulae used are optimized for pure polymers and would probably produce wrong results when applied to composites.

1.2. Dynamic tensile test methods

Typically, dynamic tension experiments are carried out using (i) a standard test bench close to its high velocity limit, (ii) a drop-weight tower with some mechanism to convert the impact load to tension, (iii) a hydraulic pulse machine, or (iv) a SHPB set-up with a special striker mechanism to produce a tensile strain wave [2].

The expanding ring test method mentioned earlier is a relatively uncommon way to test composites in tension, and Daniel shows it can be used to test both quasi-statically and at strain rates close to the currently required upper limit (e.g. Ref. [5]). The material is, however, provided in plate shape for the current research, so the method is not further considered here.

The hydraulic pulse test bench is the only machine that can serve for all current strain rates of interest without the need for a change in equipment or method. It applies an open-loop scheme for the higher velocities, and a slack rod allows for some unconstrained acceleration of the actuator before it pulls on the specimen at a fairly constant velocity. The use of a single test set-up for all strain rates removes the possible effect of a change of equipment on the results. The question remains whether the set-up is suitable to achieve the target rate of 200 s^{-1}.

1.3. Data acquisition

The challenge of dynamic tensile testing of brittle materials is the very short test duration. The failure strain of a 90-degree-unidirectional (UD) composite is small: typically 0.6% in the case of one of the materials used for this research. Consequently, the test duration is 30 µs at the maximum requested rate of 200 s^{-1}. Such a short time period has consequences for the data acquisition.

1. Any signal conditioning or amplifying device should be capable of handling sufficiently high frequencies. The SAE recommended practise for high strain rate tensile testing of polymers advises ten times the approximate maximum signal frequency, which is determined by assuming the shortest test resembles a quarter of a sine up to the yield point [10]. Taking the failure point as the yield point, the minimum test duration of 30 µs results in a maximum frequency of 8.33 kHz. The SAE then advises a minimum frequency response of 83.3 kHz. ISO 26203–2 for testing metallic materials at high strain rates states that the frequency response on strain should be at least 100 $\dot{\varepsilon}$, and that on force at least 1000 $\dot{\varepsilon}$ [8]. This amounts to 20 kHz for strain conditioning and 200 kHz for force.
2. Data storage should take place at sufficient samples per second. A minimum would be the Nyquist frequency, which would be at twice the maximum frequency response of the conditioning equipment. ISO 26203–2 advises four times the limit frequency of the force measurement system, which would lead to 800 k Samples s^{-1}.
3. The output of multiple different measuring systems needs to be synchronized. On a hydraulic pulse machine, force is typically measured by a quartz transducer and strain using strain gauges. A 30 µs test duration means that these should be synchronized to, at the very least, within a single microsecond. Typically publications about dynamic tensile testing contain no information about data stream synchronization, nor do the standards. Two minor exceptions are found. The first is the SAE J2749, in which it is stated that the *data streams may need to be reconciled* because of a *measurable time lag* [10] but gives no mention about how this should be done or what is the origin of this lag. The second is a recent publication in which optical strain measurement was applied for dynamic tensile tests on a woven glass/vinylester composite where *load and strain data were manually synchronized* [11].

Several questions thus arise about tests on brittle continuous-fibre composites in dynamic tension. First, how can individual data streams be synchronized in order to obtain meaningful material data? Second, what would be the maximum strain rate attainable with a hydraulic pulse set-up and what are the limiting factors?

2. Experimental programme

The goal is to obtain full stress-strain curves at several strain rates between quasi-static and 200 s^{-1}. Six strain rates were chosen: 0.002, 0.02, 0.2, 2, 20, and 200 s^{-1}.

2.1. Materials

Two composite material systems, both relevant for the automotive industry, were investigated. One was Pyrofil™ TR/360 carbon/epoxy, where the epoxy is modified to cure in under 5 min above 140 °C. Both a UD variant (TR 360E250S) and a plain weave variant (TR3110 360GMP) have a failure strain of around 1% or below and were used for the current research. The second material was Cetex TC910 E-glass/polyamide-6 composite. Only the UD variant formed part of this work because it fails at strains of around 1% in the transverse direction.

2.2. Tensile test set-up and instrumentation

A Instron VHS z25/20 test bench was used to carry out the experiments. The maximum load capacity of the machine was 25 kN, and it can pull at speeds of up to 20 m s^{-1}. The piston was connected to the

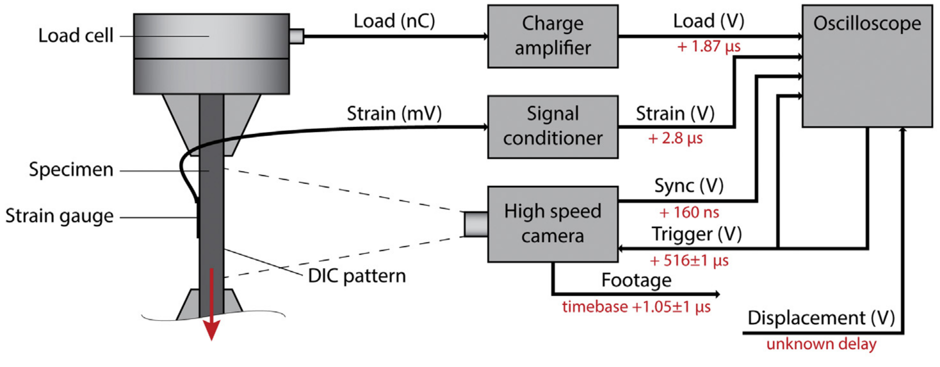

Fig. 1. The data acquisition in the dynamic tension set-up. The figures in red are the non-cumulative delays of the respective signals when recording at the highest rate: for the total delay of e.g. the camera timebase, the indicated values need to be combined in the correct manner. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)