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MECHANICAL TESTING OF COMPOSITES AT INTERMEDIATE STRAIN RATES

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Advanced Engineering Materials

ABSTRACT

This report details requirements for the development of test methods for characterising the strain rate dependent mechanical properties of fibre-reinforced polymer (FRP) composite materials. The focus is on the use of high-speed servo-hydraulic test machines for measuring properties at ‘intermediate’ strain rates, i.e. between 0.1 and 100 s-1. Insights have been drawn from interviews held with experts across the composites and materials testing landscape, alongside a systematic literature review. Measurement challenges preventing progress towards standardisation of methods have been highlighted and recommendations on activity and good practice guidance to overcome these challenges are provided.

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CONTENTS

1 INTRODUCTION

Fibre-reinforced composites are used extensively in light-weighting applications across many industry sectors. Several of these applications require structural integrity under dynamic loading. For example, automotive crash events or aircraft impact strikes that can impart loads onto components and structures at increasingly high strain rates. To prevent over-engineered design and ensure efficient numerical models are developed to simulate dynamic loading scenarios, mechanical behaviour of the materials used over a range of strain rates requires characterisation.

At present no test standard exists for measuring the mechanical properties of composite materials at elevated strain rates, and there is little published guidance on applicable techniques. In the first instance, the lack of standards and guidance may cause engineers and designers to overlook the benefits of composites reducing their uptake compared to metals. If composites are considered, in-house or adapted test methods are needed to characterise strain rate properties that can be integrated into analytical models for prediction of component performance. As methods have not undergone rigorous evaluation it is unknown how well they reflect the true strain rate behaviour of the material selected and could greatly misinterpret the way the component will perform either in full scale tests or when placed in-service. This uncertainty can lead to excessive iterative design costs. In addition, without the confidence test standards provide it is difficult to reliably compare materials and generate extensive material property data sets for designers and engineers to explore, further hindering the increased uptake of FRP composites and the realisation of their inherent benefits.

Standard test methods have been developed for characterising the strain rate behaviour of metals under tension, notably ISO 26203-1 [1] and ISO 26203-2 [2] which describe the use of elastic-bar type systems, e.g. split Hopkinson bar (SHB) method, and high-speed servo-hydraulic test machines, respectively. Alongside significant differences in their approach, the two methods occupy slightly different strain rate ranges with high-speed servo-hydraulic machines covering strain rates between 0.01–1000 s^{-1}, and elastic-bar type systems standardised to measure at strain rates above 100 s^{-1}. Both approaches have been adapted to characterise strain rate behaviour of composite materials in addition to instrumented drop weight towers and expanding ring tests. However, in most examples the focus has been on evaluating the behaviour of different composite material systems and not on a thorough evaluation assessing the applicability of test systems.

This report details requirements for test methods for characterising strain rate dependent mechanical properties of composite materials. The focus of the report is on the use of high-speed servo-hydraulic test machines for measuring properties at ‘intermediate’ strain rates, i.e. between 0.1 and 100 s^{-1}. Insights have been drawn from interviews held with experts across the composites and materials testing landscape alongside a systematic literature review. Measurement challenges preventing progress towards standardisation of methods have been highlighted and recommendations on activity and good practice guidance to overcome these challenges are provided. These recommendations may be used to direct future collaborative research activity in the field.

2 INDUSTRY REQUIREMENTS

The UK Composites Strategy has forecasted that a greater uptake of fibre-reinforced polymer (FRP) composite materials could result in significant economic growth for the UK economy and industry. The use of composites has the proven potential to make real improvements in the safety, energy efficiency and sustainability of products and systems. They can be applied to a multitude of industry sectors, applications and scenarios, offering unparalleled weight savings due to their exceptional strength and stiffness-to-weight ratios, provide high energy absorption for improved strength and crashworthiness and can create value through opportunities for parts consolidation. They require lower maintenance compared to more traditional materials hence significantly reduce through life costs of finished products.

Despite significant advances in their development, barriers still exist that are slowing, and in some cases preventing, the uptake of these materials and the realisation of the benefits available. These barriers exist in the areas of technology, skills, sustainability and regulation and must be addressed. In March 2019, a deep-dive workshop was organised by the National Physical Laboratory (NPL) on behalf of the Composites Leadership Forum (CLF) to debate the barriers to and opportunities for the uptake of composite materials to enable growth in advanced manufacturing sectors [3].

A key recommendation from this work was to accelerate the standardisation and publication of technical documentation underpinning highest point of reference material property measurements. These are required for physical and increasingly for virtual product assurance through the development of digital twins. In particular, there was an acknowledged gap in the standards infrastructure for the measurement of strain rate performance for composite materials. As part of a 10-year roadmap for addressing key missing codes, specifications and standards, the following activity was recommended to be undertaken for characterisation of strain rate behaviour:

- **Short-term (2019-2021)**
  Define the boundaries of current physical measurement methods to accurately derive properties for intermediate and high strain rate applications,

- **Medium-term (2021-2024)**
  Derive appropriate test methodologies and deliver interlaboratory comparison (ILC) exercises to validate test protocols,

- **Long-term (2024-2028)**
  Publish robust, acceptable methods and standards for measuring intermediate and high rate properties.

The work detailed in this report is designed to address the short-term requirements outlined above and scope future activity to derive appropriate test methodologies. As part of this activity, a light-touch survey of industrial requirements was undertaken, with the following salient findings:

- Generally, engineering design and modelling were the key drivers for intermediate/high rate characterisation; there was little requirement from a material development or qualification perspective,
- Stress and strain derived properties were of interest over the entirety of the stress-strain response i.e. not just modulus or strength,
- The effect on data quality from resonances in the load-cell and/or load-string was considered a primary issue when using high-speed servo-hydraulic test frames,
- Force equilibrium was identified as an issue for both elastic bar type specimens and high-speed servo-hydraulic machines,
- Strain measurement and unverified/unvalidated specimen geometries were considered a challenge across all loading frames and strain rates.

3 MECHANICAL TESTING OF COMPOSITES AT DIFFERENT STRAIN RATES

Understanding material behaviour under dynamic loading conditions is crucial for both performance and safety of many engineering structural applications. Many studies have demonstrated that the mechanical behaviour of composite materials exhibit significant strain rate dependency in part due to the viscoelastic nature of the polymer matrix [4]. Being able to comprehend the relation between the material properties and failure behaviour with varying strain rate will allow optimised structural design specific to the application and loading conditions.

3.1 TEST SYSTEMS AT DIFFERENT STRAIN RATES

Attention to the dynamic behaviour of materials (higher strain rates) can be traced back to the beginning of the 20th century, starting with the work of John and Bertram Hopkinson whose work was the foundation for the invention of the split-Hopkinson pressure bar by Kolsky in 1948 [5]. Since then, several studies have reported the strain rate behaviour of materials. A review of testing techniques applicable to the high strain rate behaviour of materials was presented by Lindhoim in 1971 [6] and later, in 1994 [7] , Meyers classified strain rates into five different regions based on their magnitudes and the dynamic events which need to be considered as presented in Figure 1. [6,8,9].

At low strain rates (10^{-5} s^{-1} up to 10^{-1} s^{-1}), constant load, conventional screw driven, and standard servo-hydraulic test machines are most commonly used to characterize material behaviour. Under slow loading rates specimens are in a state of stress equilibrium and undergo homogenous deformation [10], with the stress-strain behaviour of a material obtained from quasi-static testing considered to be an inherent property of the material.

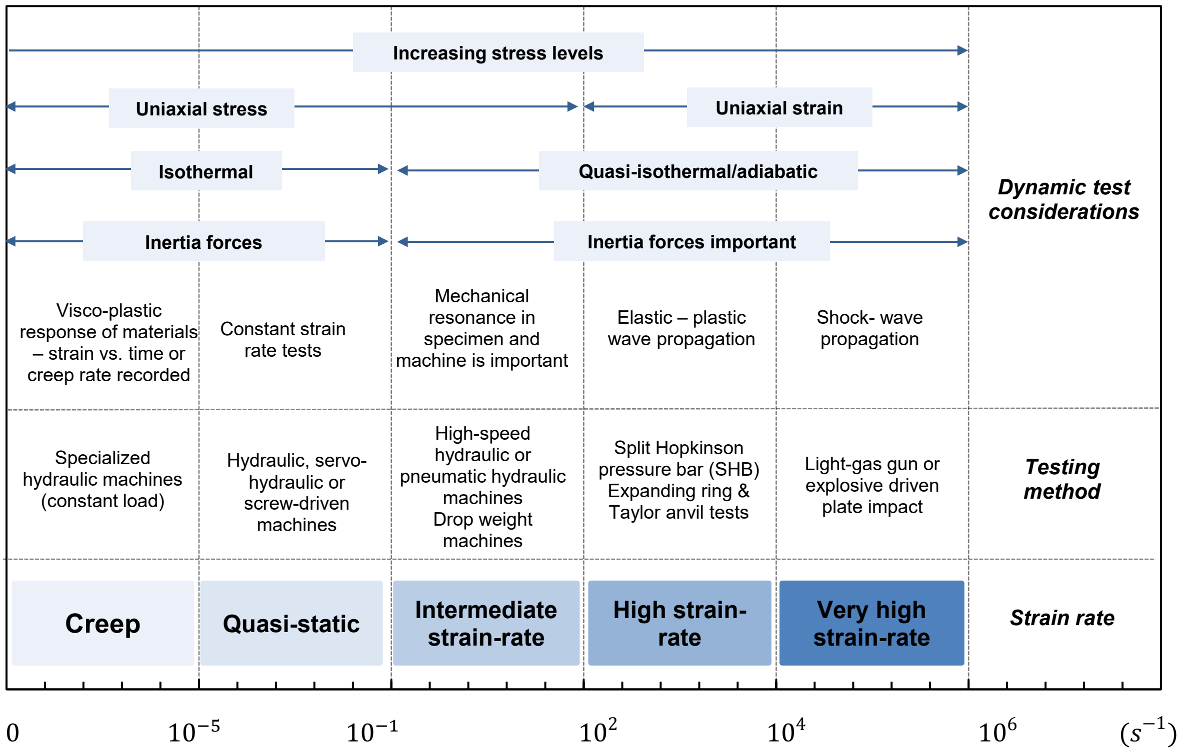

Figure 1. Strain rate regimes with associated testing systems and dynamic considerations.

For strain rates exceeding 1 s^{-1} dynamic effects are introduced during material loading. Two types of equipment have been used to generate data at intermediate strain rates (up to 100 s^{-1}), the high-speed servo-hydraulic testing machine and the drop weight impact machine. In drop weight tests, a weight is guided along rods through two bearing assemblies. It is raised and released from a specified height onto a beam or plate type specimen [11]. For drop weight tests, accurate results can be generated with relatively simple and inexpensive equipment. In addition, different specimen geometries can be accommodated at varying strain rates. Still, this technique is very sensitive to stress wave reflection to the specimen which can cause noise in the results, making them difficult to interpret [11,12]. More recently, the use of servo-hydraulic machines has been given more attention, as in the past they were limited to strain rates up to 10 s^{-1}. High-speed servo-hydraulic testing presents a more standard mechanical testing approach in which constant strain rate can be achieved. However, inertia effects of the load cell and grips and wave propagation can set limitations in achieving the condition of stress equilibrium in the specimen. Such effects are described in more detail in Section 4.2.1.

Testing at higher strain rates is accomplished using expanding rings, pressure bars, flyer plates, and Taylor impact. Of the abovementioned testing techniques, split Hopkinson pressure bar (SHB) is the most widely studied and used technique to investigate material behaviour under the strain rate range of 10^2 up to 10^4 s^{-1} and is standardised for metallic materials in ISO 26203-1 [1]. In this method an elastic wave traveling inside a solid medium is transferred to the specimen to deform the material under high strain rates. A schematic representation is shown in Figure 2. This technique provides the capability to test materials at high strain rates while maintaining a uniform uniaxial stress state within the sample [4]. SHB can be used to test in tension, compression, torsion or flexure as well as on triaxial tests [6,13] For yet higher strain rates beyond the range of Hopkinson techniques, other techniques are required (see Figure 1). For very high strain rates, plate-impact tests are most commonly used.

Despite different test methods and machines being capable of testing materials at the same strain rate, there are significant differences between them. Hence it is important to understand which methods are most appropriate according to the requirements of the material properties to be tested. The principal focus of the current review is on the use of high-speed servo-hydraulic testing machines in the intermediate strain rate regime, where inertia and wave propagation effects begin to influence the test. While specimens used in this type of equipment appear to be similar to the specimens used under quasi-static loading, the dynamic nature of these test systems means the test methods and standards established for quasi-static tests are not valid [10]. This is attributed to the difficulty of the basic requirements to be achieved, in order to obtain valid stress-strain data under dynamic loading.

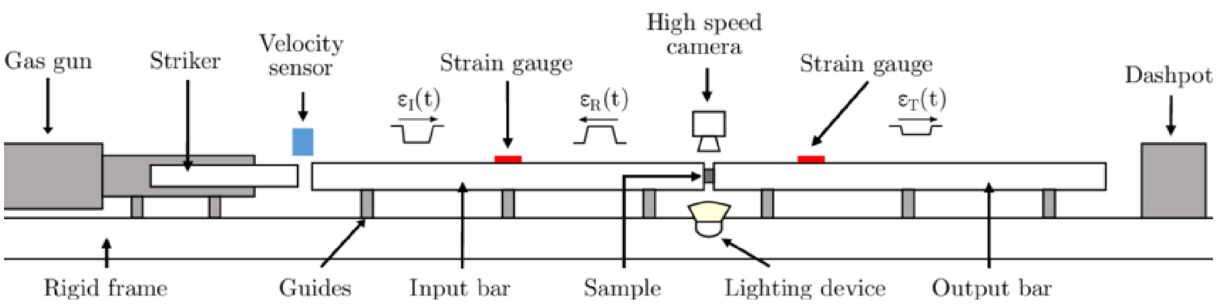

Figure 2. Schematic of the split Hopkinson pressure bar.

3.2 STRAIN RATE BEHAVIOUR OF COMPOSITES

3.2.1 Stress equilibrium state

To obtain valid stress-strain data in a material test, the specimen should be in a state of stress equilibrium and undergo homogeneous deformation in the gauge section. In quasi-static tests, the loading rates are slow enough, and the stress wave has enough time to travel back and forth inside the gauge length of the specimen. Thus, a quasi-equilibrium state is achieved. After many years of research and development of standards, optimised specimen geometries for different quasi-static tests have been developed to ensure deformation homogeneity. In dynamic loading however, these requirements are more difficult to achieve [10]. The duration of loading under dynamic conditions is much shorter and the time needed for stress waves to travel over the length of the specimen is almost the same. If the stresses build up in the specimen by relatively fewer stress waves, the condition of dynamic stress equilibrium may be invalid. To ensure the validity of a dynamic test, the specimen should be in a state of dynamic stress equilibrium. The strain rate needs to be almost constant for homogenous deformation to be achieved. According to the SHB theory, at least three round trips are needed for the stress wave to travel over the length of the specimen before reaching the dynamic stress equilibrium. This criterion has also been verified to apply to the dynamic tensile tests conducted using a high-speed servo-hydraulic machine. However, under high strain rates, cracks do not have enough time to propagate along the weakest path within the specimens. In these circumstances, multiple diagonal cracks tend to be formed in the specimen, thus leading to an increase of absorbed energy and material strength [14].

3.2.2 Tensile behaviour

Tensile behaviour of composite materials under the effect of increased strain rates has been extensively studied, but discrepancy in results has been evident. Some researchers have reported no influence of increasing strain rate on tensile properties [15,16] attributed to the fact that, in tension, behaviour of composites is dominated by the fibres, which are independent of the strain rate change. Other researchers who investigated the tensile behaviour in the fibre direction, observed no effect on the Young's modulus but a remarkable increase of tensile strength and ultimate strain [17-20]. An average increase of 50% compared to quasi static values has been reported on tensile strength, under strain rates between 30 s^{-1} and 400 s^{-1} .In addition to these studies, [14] reported that the tensile strength and Young's modulus of glass fibre-reinforced polymer (GFRP) composites increased by 152% and 103%, respectively at higher strain rates. Tensile properties in the transverse direction were studied by [15,21]. They both explained that mechanical properties in transverse direction were affected by strain rate as they are matrix dominated [11], and reported an increase in tensile strength of 18% and an increase in Young's modulus of 12% at strain rates of 100 s^{-1}.

3.2.3 Compressive behaviour

Very limited information can be found in literature regarding the behaviour of composites under compressive loading at higher strain rates. Most researchers have studied the effect of strain rates in compression mainly with the use of the split Hopkinson bar or drop weight impact. With respect to the compressive properties in the longitudinal direction, Korber et al. [22] performed dynamic tests on carbon fibre-reinforced polymer (CFRP) materials at strain rates up to 118 s^{-1}. An increase in the longitudinal compressive strength of ~40% was reported but longitudinal compressive modulus showed no sensitivity to the strain rates considered in the study. Similar conclusions were obtained by Martin et al. [23] and Schmack et al. [24] who also conducted compressive tests in the fibre direction. A 64% increase in the compressive strength of a polypropylene GFRP for strain rates up to 440 s^{-1} was reported by the former and increases in fracture strain and strength of up to 26% and 22%, respectively, at a strain rate of 4 s^{-1} by the latter. No significant strain rate dependency of the compressive modulus was reported by any source. The increase in strength has been attributed to the viscoelasticity of the matrix which plays a major role in compression due to the lateral support it provides to the fibres preventing buckling [25]. Similarly, compressive behaviour in the transverse direction is dominated by the matrix as well. Consequently, strain rate has a great influence on these properties. Schmack et al. [24] used a high-speed servo-hydraulic machine to test at strain rates up to 70 s^{-1}. Their work found the compressive modulus to be unaffected by the strain rate, but the matrix dominated properties to increase further, with the yield stress increasing by 56%. Slightly different results were reported by Hsiao et al. [25] and Pournoori et al. [26], who also studied the transverse direction but reported an increase in stiffness of 15% and 90%, respectively. The fracture of fibre-reinforced composites under compressive loading can be explained at the micro-level by buckling of fibres, a phenomenon called kink banding. However, other factors, such as specimen geometry [27] might have great influence on the properties and should be considered as important parameters for further investigation.

3.2.4 In-plane shear behaviour

Shear properties of composites are also dominated by the matrix and a strong strain rate effect can be observed. Hsiao et al. [25] studied the in-plane shear of unidirectional (UD) carbon epoxy specimens under off-axis compression tests. They noted a significant increase of shear strength by 80% compared to quasi static results. Similar results were reported by Gilat et al. [25] and Taniguchi et al. [21] who performed ± 45° tensile tests on CFRP specimens and reported 66% and 77% increases in strength, respectively. The latter observed that the strain rate dependence of the shear strength is much stronger than that of the transverse strength. Another study examined the in-plane shear behaviour of ± 45° laminates in both tension and compression. It was found that the shear stiffness and yield strength increased, while the failure strain decreased, with the increase in strain rate. The shear failure mechanism was the initiation and growth of micro cracks within the polymer matrix, which also changed dramatically with the increase of strain rate [28].

4 HIGH-SPEED SERVO-HYDRAULIC TEST MACHINES

As detailed within Section 3, high-speed servo-hydraulic test machines present a suitable method for testing materials at intermediate strain rates between 0.1 and 100 s^{-1}. The use of such machines for testing at these strain rates is currently standardised for metallic materials in ISO 26203-2 [2]. This standard along with other guides [29] detail test requirements, equipment, specimen geometries, instrumentation and calculation of key values associated with the measurement for the case of metals. This section of the report refers to these standards and guides, alongside use of high-speed servo-hydraulic test machines across the literature to highlight components, instrument integration and specimen geometries of importance to testing composites.

4.1 TEST MACHINE OPERATION

Due to limits on hydraulic output of conventional servo-hydraulic test machines, actuator speeds are typically limited to a maximum of 0.2 m s^{-1}; and even lower than this when attempting to reach the maximum load capacity of the test frame. These limits prevent the ability to apply load to materials at strain rates above 0.1 s^{-1}. High-speed servo-hydraulic test machines overcome this by using a system of hydraulic accumulators and large flow servo-valves to produce controlled high volume, high pressure hydraulic oil flow (up to 3000 l/min at ~280 bar) capable of generating actuator displacements up to 25 m s^{-1}. A schematic representation of a typical test machine design showing key components is provided in Figure 3. Testing can be undertaken in tension, compression, flexure and shear. The approach

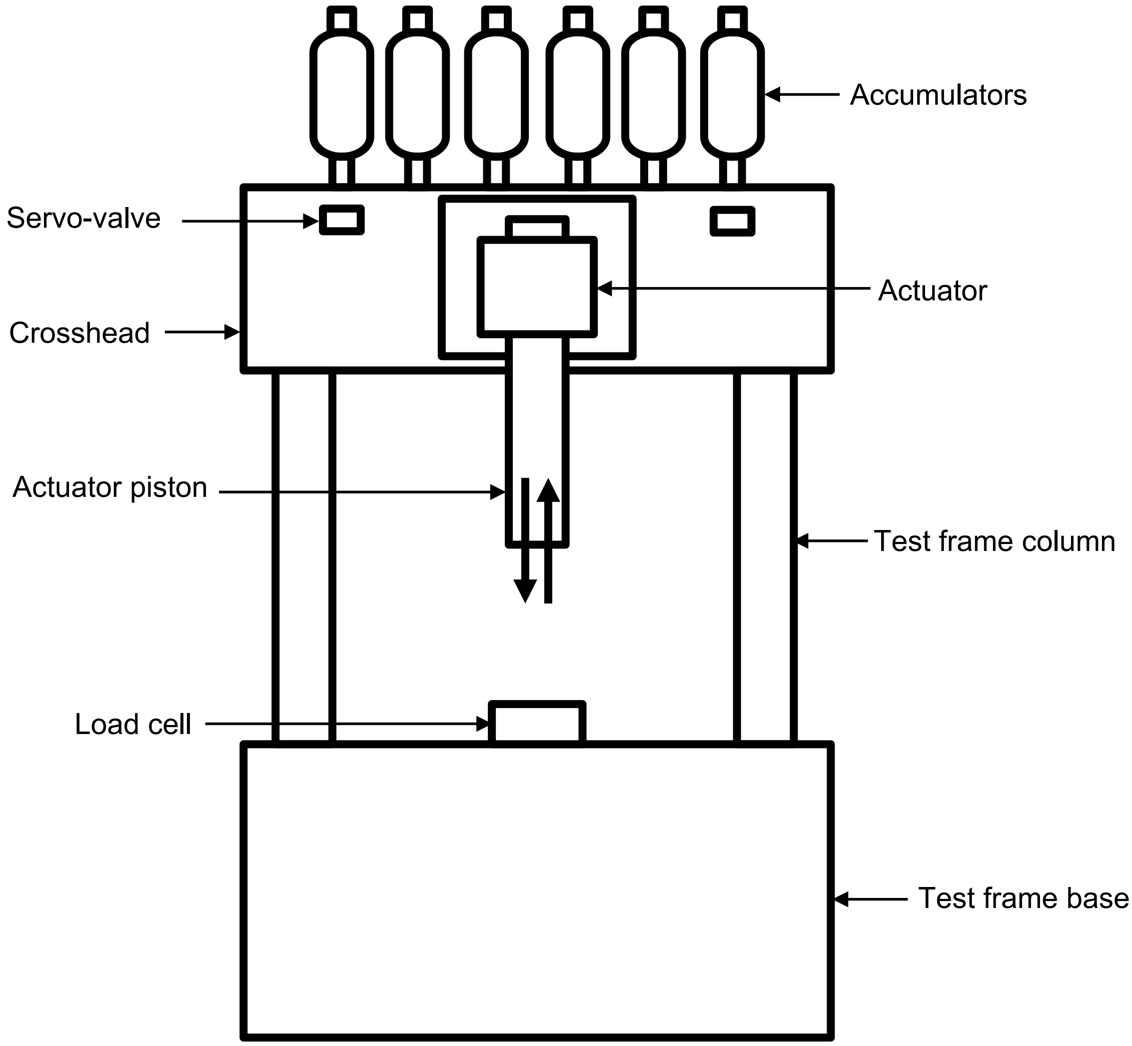

Figure 3. Schematic representation of a high-speed servo-hydraulic test machine.

across test modes is to fix the specimen to base of the machine leaving one end of the specimen free to be coupled with the moveable actuator. Specially designed grips, fittings and test rigs are used to transfer load to the specimen once the target test speed is reached by the actuator, i.e. not during actuator acceleration. Gripping approaches have been predominantly developed and verified for tension and include slack adapter or fast jaw grips. Further details on tension gripping methods can be found in [1, 29].

4.2 INSTRUMENTATION AND MEASUREMENT

4.2.1 Load

The standard configuration of high-speed servo-hydraulic test systems incorporates a dynamic piezoelectric load cell. These load cell types are required due their fast response time and relatively high frequency compared to conventional strain gauge load cells which have limited bandwidth and a low natural frequency [30]. To address the assumption of force equilibrium becoming invalid at elevated strain rates, any load measuring device is positioned as close as possible to the specimen gauge length, or region of strain measurement. This minimises the difference in stress state at the points of measurement enabling more accurate stress-strain synchronisation [2,29,31].

Despite their suitability over conventional load cells, problems are encountered when measuring load through piezoelectric load cells on high-speed test frames due to effects of system ‘ringing’ [32]. The transient nature of load engagement when testing at high strain rates generates high amplitude stress waves resulting in natural oscillations in the specimen and test frame. These oscillations become superposed over the force signal measured by the piezoelectric load cell [2,31,32] giving values that are not a true representation of material behaviour. The effect is more pronounced with increasing strain rate [33], greater distance between load cell and specimen gauge length, and if the load cell is not fixed to the static end of the test frame [29].

Methods for overcoming superposed oscillations have been considered. A local load measurement through strain gauges directly bonded to an area of the test specimen only subjected to elastic deformation is detailed within ISO 26203-2 [2]. This approach is suitable for metals which can easily be waisted into ‘dumb-bell’ specimens leaving a region of larger cross-sectional area away from the gauge length that will not undergo plastic deformation. This approach is however not suitable for all composite material types, e.g. UD composites, which should not be waisted into dumb-bell specimens [34]. Filtering load through low-pass filters, averaging, power-law functions [35,36], or the single degree of freedom model [37] have been used to smooth out oscillations. Accuracy is however dependent on user interpretation of which filtering method is most suitable. In addition, these filtering algorithms have predominantly been developed and tailored for metallic systems and their use may hide key stress-strain characteristics of composite materials, which predominantly display more brittle like behaviour. A force signal correction methodology specific for composites has been proposed by Acosta et al. [38]. The approach uses an aluminium specimen insensitive to strain rate and of known stress-strain behaviour to characterise the test machine natural frequency. This is used to correct the force signal when measuring composite specimens. Whilst showing great promise, further work is required to ensure the method is suitable across different set-ups and composite material types tested in compression, shear and flexure as well as tension. A comprehensive study assessing sources of error and uncertainty using this method through an inter-laboratory comparison would also be beneficial. An approach considered [32] but under evaluated could look at developing analytical models to predict test machine natural frequencies in conjunction with experimental results obtained using methods such as those described in [38].

It should be noted that standardisation activity is progressing under ISO/TC 61 (plastics) /SC 2 (mechanical behaviour)/WG 1 (static behaviour) to develop methods of validating and scoring the quality of load data obtained from piezoelectric load cells in high rate tests [39]. Whilst such a standard would help provide a framework for enabling comparison of material properties, it fails to eradicate the issue, limiting the ability of testing with high-speed servo-hydraulic machines to enable efficient material and component design.

4.2.2 Strain

As strain rate increase above 1 s^{-1}, conventional mechanical clip-on extensometers cannot be used. Strain measurement therefore requires either strain gauges bonded directly onto the specimen, or non-contact optical methods such as digital image correlation (DIC) used in conjunction with high-speed cameras (HSC) to capture images at the required frame rate. Consideration must be given on the sampling rate achievable, either the frequency response of equipment or the maximum frame rate of camera systems. This is of significance for composite materials, which display elastic brittle like behaviour, to ensure enough data points are captured to fully reflect the material’s stress-strain characteristics. Dependent on the composite material being tested and the instrumentation capabilities, the requirements for sufficient data points could put limits on the strain rate in which useful data is obtained with high-speed servo-hydraulic systems [30]. Such sufficiency and instrumentation requirements need to be standardised for a range of composite material types. In addition, little guidance has been published on the use of HSC images with DIC when testing under high strain rate.

Synchronisation of strain with calculated stress values can become an issue with increasing strain rate. With test durations typically < 50 μs, synchronisation errors of just 1 μs can have significant influence on mechanical properties determined. Accordingly, standardised approaches need to be developed to ensure repeatability and reproducibility of testing. Methods have been proposed by Spronk et al. [31] but require validation.

It should also be noted that strain measurement is not only essential for accurate stress-strain determination for calculation of mechanical properties, but also enables determination of the real strain rate experienced by the material. Such measurements are key for measuring the uniformity of strain rate over the test duration and providing assurance to validate models.

4.3 SPECIMEN GEOMETRIES

Any mechanical test requires careful consideration of the specimen geometry used, but particularly for composite materials which can be manufactured into a variety of formats and types. Specimen designs need to have geometries which can be prepared easily, appropriately fixed into test machines and ensure uniform load transfer into the specimen to adequately measure the material behaviour. Several different geometry types have been used across the literature for intermediate strain rate testing of composites in high-speed servo-hydraulic test machines.

Examples of compression, shear and flexural testing at intermediate strain rates using high-speed servo-hydraulic test machines are less abundant than tension. Specimen geometries investigated have therefore been limited. Compression specimens [24, 27] proposed have been similar to those prescribed in ISO 14126 [40], only with shortened end-tab lengths. Specimens for measuring in-plane shear properties have included shortened versions of ± 45° tension specimens [41, 42], modified from ISO 14129 [43] and ASTM D3518 [44]. Weng et al. [42] have also developed a novel specimen design and test rig for conducting interlaminar shear tests. Due to no requirement for specimen gripping, examples of testing at intermediate strain rates under flexure [45] have used standardised geometries, e.g. rectangular beams as provided in ISO 14125 [46] and ASTM D7264 [47]. With such sparse examples within the literature across compression, shear and flexure, clearly further investigation is required to assess the suitability of proposed geometries used with high-speed servo-hydraulic systems.

A greater range of geometries have been explored for tension. These tend to vary dependent on the composite format and type as well as the gripping configurations used. Geometries fall under one of the below categories, examples of which are in Figure 4:

- **Dumb-bell specimens** [15,20,30]
  Rectangular specimen 'waisted' to produce a parallel-sided gauge section of reduced cross-sectional area within which failure is expected (Figure 4a). Various radius for waisted regions, lengths of gauge sections and cross-sectional area reduction ratios have been used.

- **Straight sided symmetrical end-tabbed specimens** [17,18,19,48]
  Rectangular specimen with straight parallel sides along its length and end-tabs bonded onto the specimen ends to produce an area of greater cross-sectional area than the central gauge section (Figure 4b). Various specimen widths, gauge section lengths and end-tab dimensions have been used.

- **Straight sided asymmetrical extended end-tabbed specimens** [16,49,49]
  Rectangular specimen with straight parallel sides along its length and end-tabs bonded onto the specimen ends to produce an area of greater cross-sectional area than the central gauge section (Figure 4c). The end-tab on one side of the specimen is extended to enable gripping of an accelerating 'fast-jaw' type grip.

Dumb-bell type specimens can help provide shorter gauge lengths to generate higher strain rates for a given machine displacement rate. They also promote failure within the reduced cross-sectional area away from the high stress concentration regions where end-tabs are gripped. The shorter gauge lengths whilst enabling higher strain rates do bring into question issues with stress concentrations and require consideration of volumetric effects when assessing strength data. These geometries are also inappropriate for UD composites due to potential longitudinal splitting from shear stresses inside the waisted regions leading to unacceptable failure modes. Straight sided symmetrical end-tabbed specimens are a more typical composite specimen geometry applicable to a wide range of composite types. The longer gauge length reduces issues with Saint-Venant's principle and alleviates influence from volumetric effects. This does however place limits of the strain rate achievable for a given displacement rate. Straight sided asymmetrical extended end-tabbed specimens have been developed based on the ISO 26203-2 specimen for metals used with fast-jaw grips [2]. These are applicable for all composite types and tend to have shorter gauge lengths capable of producing higher strain rates. The extended end-tabs enable delayed gripping to allow the actuator to reach target speeds helping maintain constant displacement and therefore strain rate in the material. They are however still be susceptible to high stress concentrations depending where the specimen is gripped.

The above points bring into question whether the geometries used best represent true composite material behaviour. Whilst appreciating there is no perfect specimen geometry, a comprehensive evaluation is required to establish the most appropriate geometry for the

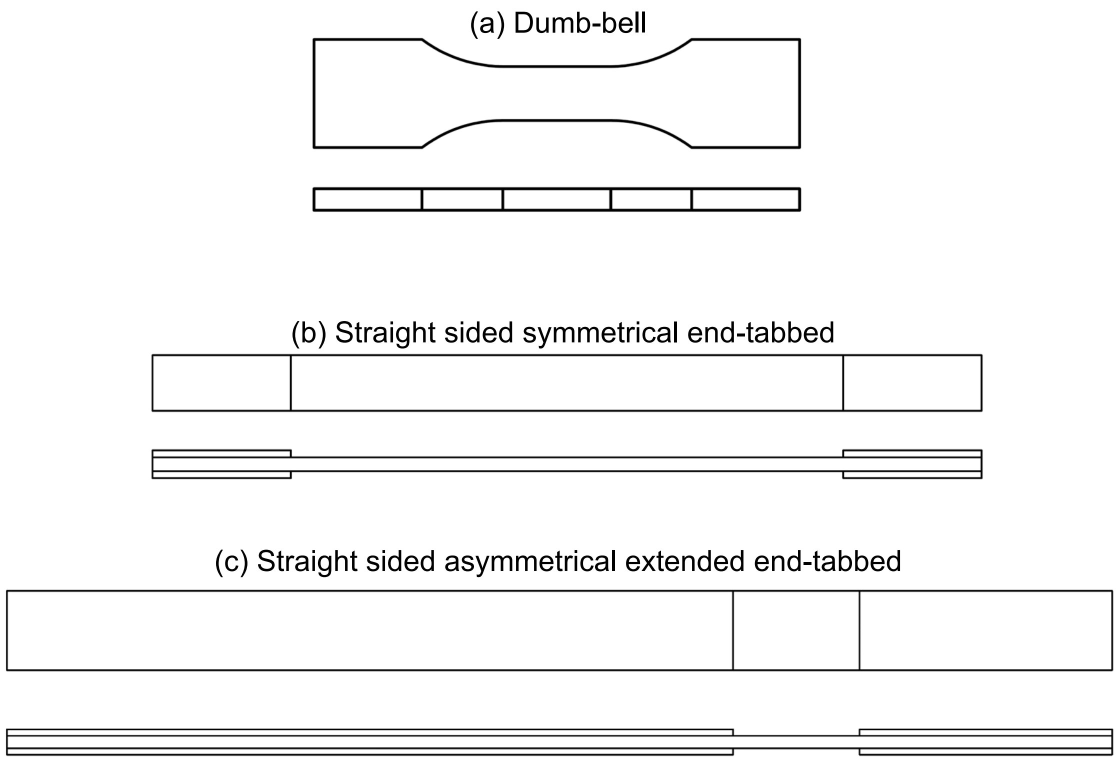

Figure 4. Tensile specimen geometry types used for intermediate rate testing.

different classes of composite. Without a standardised geometry, no basis exists for ensuring repeatability and reproducibility of results. Together with the established standardised geometries, guidance is required on the appropriate gripping methods and tests rigs across tension, compression, flexure and shear for verified geometries.

5 MEASUREMENT CHALLENGES & RECOMMENDATIONS FOR FURTHER WORK

The previous sections of this report have detailed the requirements to progress measurement techniques for measuring mechanical properties of composite materials at intermediate strain rates. High-speed servo-hydraulic test machines have the capability to test within this intermediate strain rate, however several measurement challenges exist that need to be addressed to progress widespread use of the technique. These are summarised in Table 1.

Table 1. Summary of measurement challenges.

Aspect	Measurement Challenge	Description	Priority
Load	Verified approach to mitigate test machine oscillations on load measurements	Test machine and specimen oscillations are an inevitable consequence of dynamic high inertia testing. Approaches have been developed to minimise the effect on load measurement data, however none have been fully verified	High
Specimen geometries	Standardised test geometries for different composite material types and fibre formats for tension, compression, shear and flexure	Several geometries have been proposed within the literature, predominantly for tension. However, these are yet to be systematically analysed to ensure they generate representative material property data	High
Strain	Guidance on the use of the high-speed cameras and their operation with digital image correlation (DIC) for strain measurement	Many advantages can be obtained when utilising HSC and DIC, including full-field strain mapping and insight into deformation characteristics. A lack of guidance specific for high strain rate mechanical tests however means their use is subject to user experience and interpretation	Medium
Instrumentation	Established instrumentation requirements to ensure adequate data sampling and synchronisation of stress and strain	Guidance on instrumentation requirements to achieve the required response frequency for adequate characterisation when testing composites at intermediate strain rates. Inadequate instrumentation capabilities may lead to stress-strain synchronisation issues	Low
Test set-up	Evaluation and guidance of gripping systems and test rigs	Following the establishment of suitable geometries, guidance on gripping systems and test rigs across test modes to ensure correct use and	Low

		understand the limitations of each approach	
Measurement uncertainty	Assessment of data quality and uncertainty quantification	The complexity of high strain rate testing in comparison to conventional quasi-static tests places greater importance on ensuring data quality and an understanding of measurement uncertainty	Low

In order to address these measurement challenges, a roadmap (Figure 5) of research activity has been formulated to progress the development and publication of robust, acceptable methods and standards for measuring intermediate rate properties. The roadmap uses the same timeframe as set out in Section. 2.

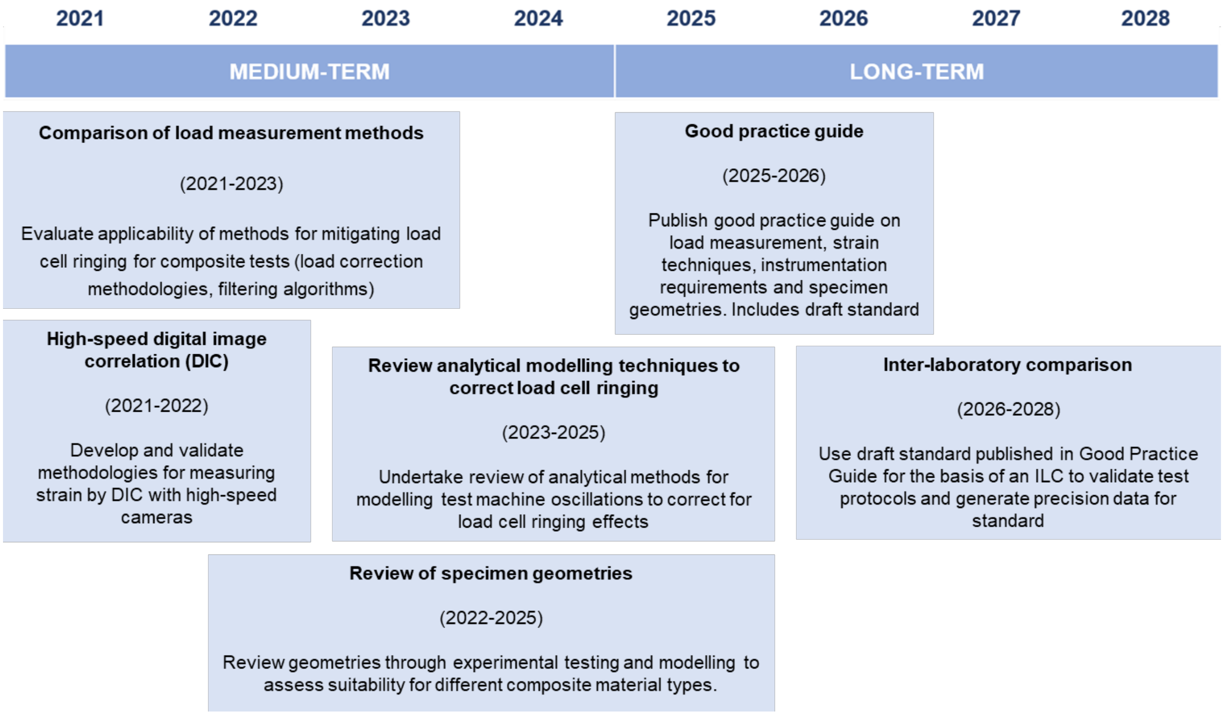

Figure 5. Roadmap of activity to address measurement challenges and progress standardisation.

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