IMPROVEMENT ON DYNAMIC MATERIAL CHARACTERISATION OF CARBON/EPOXY COMPOSITES AT INTERMEDIATE STRAIN RATES

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ABSTRACT

This paper reports an experimental investigation on strain rate dependence of carbon/epoxy composites at intermediate strain rates. Dynamic tensile tests at strain rates between 0.1 and 200 per second are performed using a high-speed servo-hydraulic test machine equipped with an improved load introduction device. The data reduction analysis is performed to handle the inertial effect (i.e., system ringing on force measurement) during the testing. Load introduction technique is improved to mitigate the system ringing and lightweight grip systems are designed in order to increase the natural frequency of the test system. In addition, the inertial induced problems are resolved for strain measurement using Digital Image Correlation (DIC) technique. A general and robust experimental technique to characterise strain rate behaviour of carbon/epoxy composite materials are thoroughly investigated. As a result, an improved test protocol to perform dynamic mechanical testing at intermediate strain rates using a high-speed servo-hydraulic machine is proposed.

1 INTRODUCTION

The development of lightweight and cost-effective composite vehicle structures should ensure a high level of safety in crash scenarios. In particular, the safety aspect related to the ability of the structures to protect the occupants from serious injuries in crash events promotes underlying interests in understanding the energy-absorbing characteristics of these materials. Designing high energy-absorption composite structures is more challenging than designing metallic structures due to the anisotropic behaviour of the materials involved.

The development of new transportation structures relies on a wide test programme generally based on a building block approach. Whereas the lower level of the pyramid provides material data from coupons, the higher levels deal with components up to the full vehicle to gain insight in the complex failure modes expected in full-scale structures. Although the use of Finite Element (FE) software is widely used during design and analysis processes, experimental testing remains indispensable to provide the essential input data for these simulations. Especially the reliable and accurate material characterisations of fibre-reinforced plastics (FRPs) composite materials under varying loading conditions at coupon level are essential.

The dynamic mechanical properties at intermediate strain rates (1-200 s^{-1}) of various materials of interest have to be measured to numerically predict the crash behaviour of newly developed structures. Nevertheless, an interpretation of test results still presents many challenges due to inertial effect and non-homogeneous stress wave propagation. For these reasons, great attention is required to obtain accurate and reliable experimental results. Testing of continuous-fibre composites is inherently difficult due to the brittle behaviour, hence a proper execution of the load introduction and a sufficiently high output frequency of data acquisition are required due to the short test duration. Furthermore, during dynamic material testing, an introduction of the loading associated with a load introduction device generates a sudden impulse that can excite a test system at its natural frequency [1]. The common load introduction device called 'a slack adapter' allows the actuator to travel freely before engaging with the specimen grip and therefore achieving the desired strain rate. The load is transferred when a sliding bar goes into contact with a slack sleeve. The impulse causes inacceptable oscillation in load signals and appears as 'ringing' in measurements. This system ringing obscures the identification of true dynamic material properties and is one of the major experimental challenges for dynamic testing at intermediate strain rates. As a result, several approaches are implemented to lessen the inertial effect for intermediate strain rates testing (i.e., modifying test machine [2], developing new test devices/machines [3-5], and optimising specimen geometries [6], double shouldered specimen [7]).

Those improved techniques on reducing 'system ringing' from load signals are mostly focused on metallic specimens. In addition, Society of Automotive Engineers (SAE) J2479 [8] and International Organization for Standardization (ISO) 18872:2007(en) [9] suggested guidelines to minimize the force signal oscillation, but those protocols are still limited for dynamic testing of plastics. As a result, there is still a gap in the literature to cover experimental techniques on the dynamic testing at intermediate strain rates with continuous FRPs composites, which are usually used in lightweight structural applications. It should be noted here that specific interests dedicate to dynamic testing at intermediate strain rates using a high-speed servo-hydraulic machine. The details of other experimental test methods associated with other test machines can be found in [10, 11].

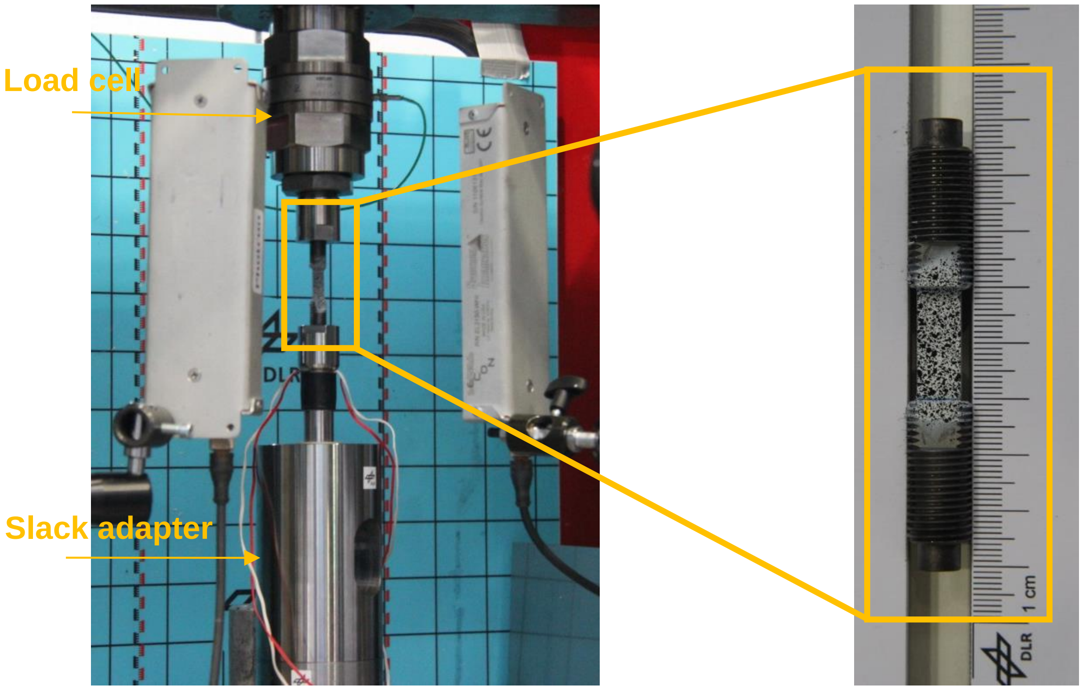
The main aim of this paper is the verification of a newly improved testing device, which was previously used on dynamic tensile testing of high strength steel by the authors [12]. This paper will examine the validity of the developed testing device for FRPs, especially for carbon/epoxy composites. Also, a clamping mechanism using adhesives is investigated. The dynamic material characterisation of carbon/epoxy composites is attempted for dynamic tensile tests at intermediate strain rates of up to 200 s^{-1}. Finally, the proposed method is validated by comparing the obtained results from this investigation and previously reported results.

2 METHODOLOGY

2.1 Materials

Dynamic tensile tests were carried out on $[0°]_{16}$ and $[0°/90°]_{4s}$ laminates in order to measure the tensile and shear material properties, respectively. Specimens were made of Hexply® IM7-8552 unidirectional carbon/epoxy composite pre-preg. This was cut into squares of 300 mm^2 and stacked accordingly to the desired layup, until achieving a nominal thickness of 2 mm. The panels were cured in an autoclave, according to the manufacturer's recommendations [13]. Fig. 1 (a) and (b) show a test system of dynamic testing and a prepared test specimen, respectively. All the specimens had a nominal width of 8mm, and the free gauge length was taken equal to 10 mm and 20 mm for the tensile and shear specimen, respectively. For the shear specimens, the dimension are chosen in an analogous way as recommended in the ASTM 3518/D3518-18 in order to properly capture the in-plane shear properties (Fig 1(b)). For these specimens the tensile loading is applied along the ±45° direction, and the ratio between the free gauge length and the width is fixed to be 2.5.

The specimens were adhesively bonded with slotted grips to reduce the weight of the grips compared to conventional clamping mechanism. These slotted grips have threaded endcaps that allow connecting the specimens to the slack adapter. Since the weight of the grips will directly affect the magnitude of the inertial effect, appropriate lightweight grips have been designed to increase the natural frequency of the test system and consequently minimise the oscillation in the load signal. The clamping technique using adhesives is borrowed from [14, 15] where it was used to connect the specimen to a Split-Hopkinson Pressure Bar (SHTB). A two components epoxy (Scotch Weld DP490 from 3M™) is used to establish the proper bonding between specimens and grips. After that, the bonded specimens are post-cured in the furnace at 65 °C for 2 hours to improve the performance of the bonding according to the manufacturer's recommendation.



(a) (b)

Figure 1: Dynamic testing set-up: (a) Test system with a test device and a test specimen, and (b) In-plane shear specimen.

2.2 Test method

Dynamic tensile tests were carried out at strain rates of 0.1, 10, 100 and 200 s^{-1}. The high-speed servo-hydraulic testing machine, Instron® VHS 100/20 was used with a piezo-electric load cell (Kistler-9317B, Kistler Instrumente GmbH, Germany). The force signals were amplified with Kistler type 5011B charge amplifier. Strain and strain rates were assessed through Digital Image Correlation (DIC) technique. The DIC images were captured with a high-speed camera (FASTCAM SA-Z, Photron®, Japan) and were then processed with GOM® Correlate. The surface field in the free gauge section was created with a facet size of 15 pixels and a point distance of 5 pixels. The size of the field of interest (FOI) is varied with respect to frame rates to ensure the necessary number of output data.

The strain at each frame was calculated by averaging the full-field measurements provided by the DIC over a region of a gauge section. Also, the strain rate is estimated using virtual extensometers with the length of 3 and 6 mm (for both tensile and shear tests, respectively) in the middle of the specimens. In addition, high-speed images were synchronised with force signals thorough NI-DAQ (USB-6251 BNC, National Instruments™, USA).

The damping materials, soft acrylic tape (3M™ 5952 VHB), were placed at the contact surface between the cone and the sleeve of the slack adapter as shown in Fig. 2 so that the hard metal-to-metal contact can be softened. The size of damping materials were 12 mm × 15 mm (L × W) with 1 mm thickness. A total of six strips of tapes were attached to the contact surface leading to a damped contact surface of 1080 mm^2. Tests were repeated at least three times, and dynamic tests without damping materials were also performed as a reference. Furthermore, applying digital filters such as low-pass filtering to smooth the distorted force measurement is one of common practices. However, the use of digital filters should be carefully applied as it may eliminate useful information during the cleaning process [16, 17]. For this reason, no digital signal processing was applied. Thus, the dynamic stress-strain responses shown in the following have not been post-processed and represent the real raw data.

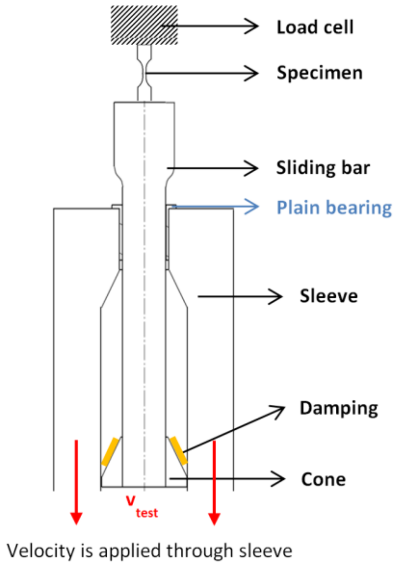


Figure 2: An illustration of a test device, slack adapter.

3 RESULTS AND DISCUSSION

3.1 System ringing

The Society of Automotive Engineers (SAE) standard provides with practical recommendations, particularly for plastics, as for example, the addition of damping materials in the load train to reduce the inertial effect and minimise the unacceptable oscillation [1, 8]. In this section, dynamic stress-strain data without using damping materials is reported to investigate the influence of damping in the load train.

Fig. 3 shows the dynamic stress-strain data gained from ± 45° tensile specimens for in-plane shear properties at strain rates of up to 200 s^{-1}. At strain rate levels of 0.1 and 10 s^{-1}, experimental results show a non-linear behaviour due to yielding and damage onset in the matrix. On the other hand, unacceptable oscillation in stress-strain curves can be seen at strain rates higher than 100 s^{-1}. Thus, the identification of the yielding point is not straightforward because of the system ringing.

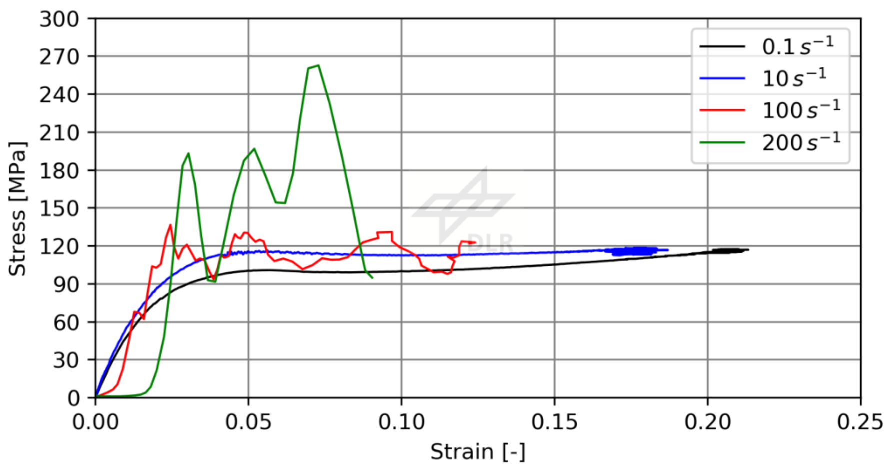


Figure 3: Dynamic stress-strain data of ± 45° tensile specimens for in-plane shear properties at different strain rates without damping materials.

Furthermore, a shifting of dynamic stress-strain curves is observed as strain rate increases. This observation is explained by the fact that high frequency components superposing to the load signals are generated by the metal-to-metal contact taking place in the slack adapter. These high frequency signals propagate at a lower speed and reach the load cell with a certain time delay. Since the strain is measured through a non-contact optical technique, a time lag between force and strain measurements arises. The delay of the force signals can be also observed in dynamic testing with SHPB technique. High frequency stress waves propagate slowly compared to that of low frequency waves. This phenomenon is referred to as the geometric dispersion effect. It is typically restrained by using a soft material called a pulse shaper, which is placed on the impact surface of the striker bar to eliminate oscillation in the force signal [18, 19]. These observations indicate that it is essential to achieve proper damping in the load train during dynamic testing at strain rates higher than 100 s^{-1}.

3.2 In-plane shear properties

Dynamic in-plane shear stress-strain curves of IM7/8552 carbon/epoxy composites at nominal strain rates from 0.1 s^{-1} to 200 s^{-1} are shown in Fig. 4. The in-plane shear properties are processed in accordance with ASTM 3518/D3518-18. Detailed properties are summarised in Table 1. It can be observed that the shear modulus shows virtually strain-rate insensitivity while the shear strength substantially increases with the strain rate. Those results reveal the fact that dynamic testing with damping materials can eliminate the unacceptable oscillation in force signals. Hence, it is clear that the use of damping materials can help to overcome inertial problems in load signals.

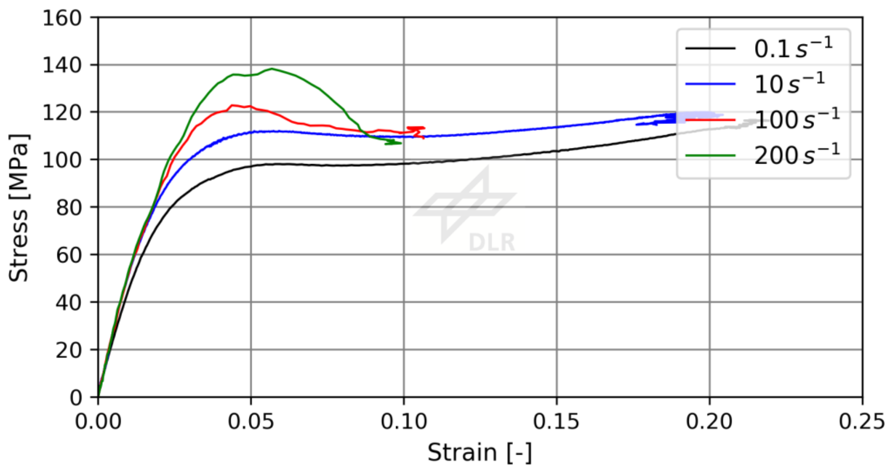


Figure 4: Dynamic stress-strain data of ± 45° tensile specimens for in-plane shear properties at different strain rates with damping materials.

Strain rate (s^{-1})	Shear modulus (G_{12}, MPa)	Shear strength at 5 % strain ($\tau_{12}^{s5\%}$, MPa)	Shear strength at 0.2 % offset ($\tau_{12}^{s0.2\%}$, MPa)
0.1	4820.79 ± 246.66	97.85 ± 0.91	59.66 ± 2.16
10	5474.54 ± 153.83	111.52 ± 0.98	66.31 ± 0.67
100	5351.61 ± 216.14	125.54 ± 2.92	75.15 ± 1.26
200	5776.18 ± 125.42	135.20 ± 3.63	71.06 ± 3.91

Table 1: Summary of dynamic in-plane shear properties of IM7/8552 carbon/epoxy composites with damping materials.

3.3 Transverse tension properties

Fig. 5 depicts dynamic transverse tension stress-strain curves at nominal strain rates from 0.1 to 200 s^{-1}. The transverse tension properties are calculated in accordance with ASTM 3039/D3039-17. Table 2 summarises the results obtained. Transverse tension results exhibit a weak strain rate dependence on Young's modulus while tensile strength increases with increasing strain rates. The influence of damping materials is critical at dynamic testing at higher strain rates as tests without damping materials shows spurious oscillations. These results indicate that the interpretation of Young's modulus is difficult when the damping material is not used.

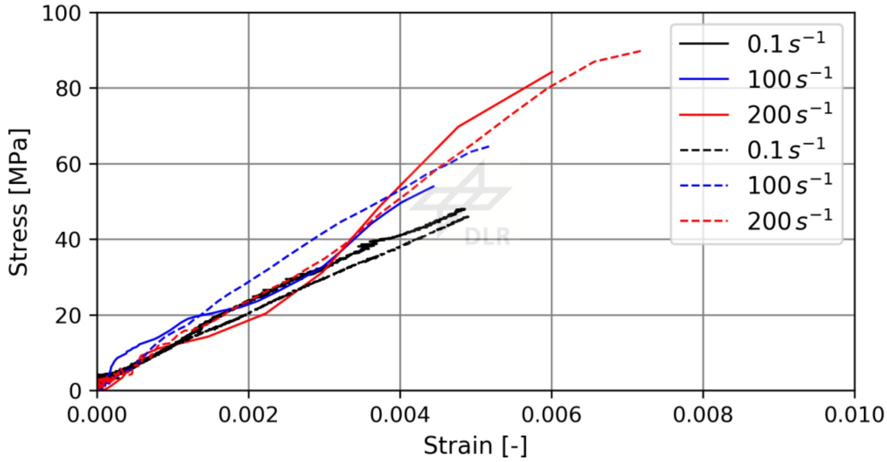


Figure 5: Dynamic stress-strain data of 90° tensile specimens for transverse tension properties at different strain rates without (solid lines '-'), and with damping materials (dot lines '--').

Strain rate (s^{-1})	Young's modulus (E_2^t, MPa)	Tensile strength (σ_2, MPa)
0.1	9557.903 ± 721.853	42.372 ± 6.724
100	12026.893 ± 1399.434	65.576 ± 1.148
200	11416.916 ± 1004.151	80.208 ± 9.012

Table 2: Summary of dynamic transverse tension properties of IM7/8552 carbon/epoxy composites with damping materials.

3.4 Comparative study

In this section, experimental results at the strain rate of 0.1 s^{-1} from current test campaign reported in section 3.2 and 3.3 are compared to previously published results from NCAMP NASA test report [20] and P.P Camanho *et al.* [21]. As both reported results were tested in accordance with ASTM 3518, this comparison will provide the validity of the newly developed test device and of the test protocols for fibre-reinforced composite materials. A summary of comparison of IM7/8552 material data is presented in Table 3.

Reference	Shear modulus (GPa)	Shear strength (MPa)	Young's modulus (GPa)	Tensile strength (MPa)
This study	4.82 ± 0.25	97.9 ± 0.9	9.56 ± 0.72	42.4 ± 6.7
NASA report [20]	4.69 ± 0.15	91.2 ± 1.5	8.96 ± 0.30	64.1 ± 6.1
Camanho *et al.* [21]	5.29 ± 0.13	92.3 ± 0.6	9.08 ± 0.09	62.3 ± 5.3

Table 3: A comparison of published experimental results with current study.

An overall good agreement is observed with the material data from different sources. It can be seen that the shear modulus of this study lies within a bound of standard deviation from NASA reports while the shear strength is approximately 6% higher than that of both reported values. The slightly higher shear strength compared to the published results can be explained by the fact that the dynamic testing in the presented test campaign was performed at the strain rate of 0.1 s^{-1}. Although the strain rate is still in the quasi-static regimes [10], the testing speed of 2 mm/min from ASTM standard equals to approximately a strain rate of 0.0001 s^{-1}, which is three order less than the tested strain rate in this study. In that case, the increase of shear strength can be explained with the higher applied strain rates. The change of shear strength can also be observed for the dynamic test of the ±45° tension specimens [14, 22]. Despite the fact that the size of the tested specimens is smaller than the specimen size recommended in the ASTM standards, those results indicate that the methodology used in this study is applicable to generate in-plane shear properties at intermediate strain rates regime.

In contrast, the transverse tensile strength from this study is approximately 33% lower than that of reported results. Those discrepancies can be explained by the fact that the failure occurs at the top of the grip as seen in Fig. 6. This indicates that the grip influences the results (i.e., edge effect). Although the trend on strain rate dependence on transverse tension properties can be captured, the use of small specimen should be carefully analysed. Using larger specimen size will minimize the edge effect from the grips.

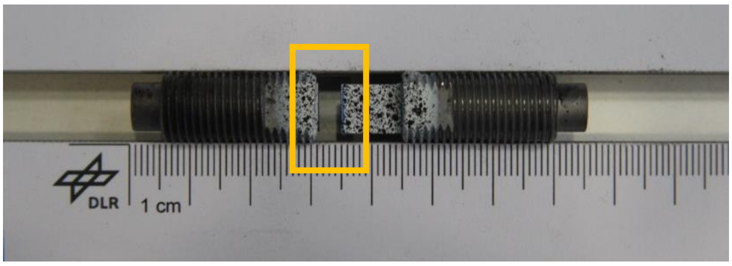


Figure 6: Failed transverse tension specimen after dynamic testing at a strain rate of 0.1 s^{-1}.

4 CONCLUSION

This paper reported the improvements in measuring dynamic material properties of carbon/epoxy composites at intermediate strain rates up to 200 s^{-1}. Dynamic tensile tests are performed with an improved slack adapter and an adhesive bond clamping method. The influence of the damping material in the testing device is also investigated and leads to mitigation of the inertial effect on load measurements. The addition of the damping material is crucial to obtain true dynamic properties. The difficulties encountered when measuring dynamic properties are addressed and solutions are presented.

For transverse tension testing, IM7/8552 carbon/epoxy composites show little changes in Young's modulus whereas tensile strength is increased with increasing strain rates. On the other hand, the test of the in-plane shear specimens (±45° tension) shows clear rate-dependent shear behaviour with increasing strain rates. The shear strength is increased while the changes in shear modulus remain marginal. Finally, the comparison of current results and values from literature provides the effectiveness of the proposed test protocols associated with the slack adapter, the use of damping material and the adhesive bond technique.

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