TENSILE RATE-DEPENDENCY OF CARBON/EPOXY AND GLASS/POLYAMIDE-6 COMPOSITES

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Abstract
Full stress-strain curves for composites over a range of strain rates are needed to feed reliable data to the material models of today's indispensable predictive finite element models. A hydraulic pulse test bench has been employed to investigate the change of composite tensile behaviour with strain rate. Reliable curves are obtained by investigating the limits of the test set-up and only taking data from the valid range of strain rates. For the two tested composite material systems, both woven and unidirectional, it was found that the laminate rate-dependency follows the dry fibre trends for laminates with 25% 0º-fibres or more.

1. Introduction

Car manufacturers turn towards continuous-fibre reinforced polymer composites for structural parts to reduce the structural mass. To create both light and impact-resistant designs, the dynamic behaviour of the used composites should be known, since composite material properties depend on strain rate [1]. The goal of this work is, therefore, to investigate the tensile rate-dependency of two composite material systems: carbon/epoxy and glass/polyamide-6. Both are relevant for the automotive industry, and either of them is tested in multiple unidirectional and woven configurations.

Structural parts see strain rates ranging from quasi-static to about 200 s^{-1} during automotive impacts [2]. The current work focuses on obtaining full stress-strain curves over that range of strain rates. These curves are chosen as test output, because they are compact while still allowing researchers to extract a wide variety of material parameters specific to their material models. These models are, in turn, a necessity in the design cycle of automotive parts. Finite-element modelling is namely a necessity to limit the amount of tests required on structural parts and thereby keep the funds or time needed to develop these parts at a cost-effective level.

First, the test method is outlined and its limitations are discussed. Second, the materials and specimen shapes used in the test programme are detailed. Third, an overview of the test programme is given. Finally, a selection of results is shown from which conclusions are drawn.

2. Test method

A Schenck Hydropuls z25/20 hydraulic pulse bench is used for this research, because it is currently the only test method that can cover the entire strain rate interval without the need of a major equipment change. Force is measured using a piezoelectric transducer, strain is measured using both strain gauges and digital image correlation (DIC) on images captured using a high-speed camera. Figure 1 shows an overview of the data-acquisition during a dynamic tensile test. Special attention was paid to achieve a correct synchronization of the data streams which otherwise could lead to a false representation of material behaviour. All delays on the signal are therefore added in red to the figure. It was established that meticulously taking into account the delay of each component in the chains of acquisition is the only method that guarantees a correct synchronization and, therefore, reliable results [3].

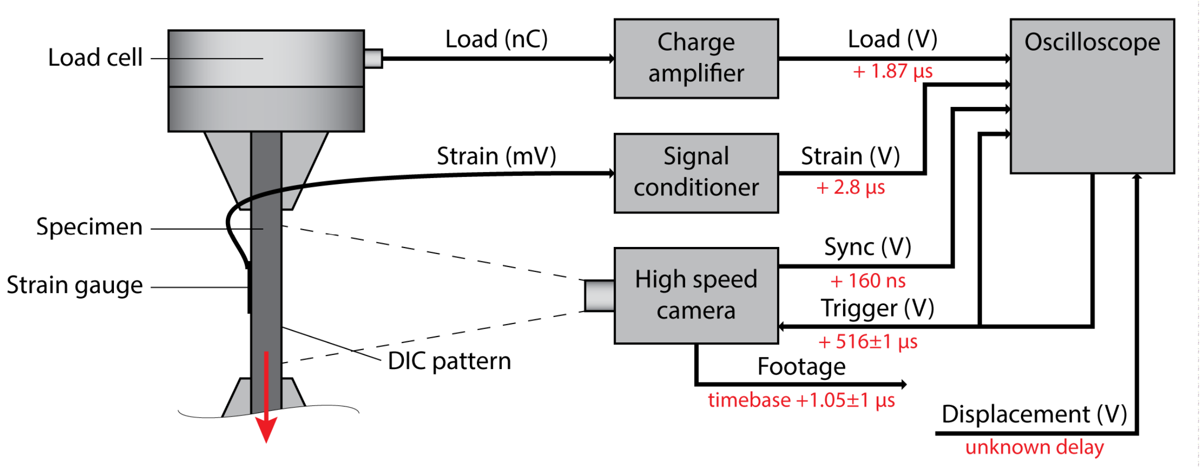

Figure 1. Delays in the data acquisition for dynamic tensile tests

The speed up to which one can obtain valid tensile test data using the method described above is limited to a maximum. Above certain levels of strain rate, dynamic side-effects can have a non-negligible influence on the results. With the help of explicit finite-element analysis, five aspects of the current set-up were identified which impose upper limits to the obtainable strain rate [3].

1. Test bench capability. The theoretically maximum obtainable strain rate depends on the maximum velocity of the test bench divided by the gauge length. The actually obtained strain rate lies below the theoretical value [4], likely because bench deformation reduces the velocity which is felt by the specimen on its actuated side.
2. Frequency response of measuring equipment. Testing faster than an amplifier can follow results in smoothing of the data. This limit depends on the maximum global frequency of the test signal, which can be approximated by assuming that the test result resembles a quarter sine up to the failure point [5].
3. Maximum sample rate of the data storage. The advised lower limit is four times the signal frequency [6]. This frequency can either be taken as the bandwidth of the amplifying device, or can be approximated using the method described under the previous point (e.g. for digital image correlation).
4. Load cell ringing. For the current set-up, the natural frequency of the load measuring assembly poses the most stringent limit on strain rate. It was found that the test duration should exceed ten times the period of load cell ringing for the results to be practically free of oscillations.
5. Approximate equilibrium. Even if the capabilities of the equipment are sufficient, there is a physical limit which bounds the strain rate to a certain value. The fact that load and strain are measured on different locations namely requires the set-up to be approximately in equilibrium. The numerical results showed that the test duration should not drop below the time needed for a stress wave to travel three times back and forth in a specimen [3].

A test campaign was executed for which the results violating any of the limits on strain rate mentioned above were identified and removed, something which is rarely done in literature.

3. Materials

Two different composite material systems were subjected to dynamic tension in this research. The first is Pyrofil™ TR/360 carbon/epoxy, where the epoxy is modified to cure in less than 5 minutes above 140 °C. Both a UD variant (TR 360E250S) and a plain weave variant (TR3110 360GMP) were used for the current research. The second material investigated is Cetex TC910 E-glass/polyamide-6 composite, also in two variants: a UD and a twill woven architecture. Both systems are relevant for the automotive industry. Only balanced and symmetric laminates were tested, conditioned to a dry state.

Three different specimen shapes were used in the test campaign, see figure 2, and cut from the base plates using water jet cutting. The first shape was used for pure matrix specimens, according to type IV from the ASTM standard [7] for pure epoxy and according to the ISO standard [8] for pure polyamide-6. Laminates with up to 50% fibres in the 0º-direction (or 25% for laminates with unidirectional layers) were tested using shape 2 from figure 2. This is a dumbbell shape scaled from De Baere et al. [9] to have a width at the clamps of W_c = 20 [mm], a gauge length of L_g = 50 [mm] and a straight-sided length at the clamps of L_c = 22 [mm]. Laminates with only fibres in the 0°-direction, or only in the ±45°-direction, or $[0/90]_{ns}$ laminates, were given a rectangular specimen shape (shape 3 in figure 2). These specimens had a total length of L = 94 [mm]. The width W_c was taken so that the maximum load needed to break the specimens would not exceed the capabilities of the test bench. It was taken 20 [mm] for all ±45°-specimens, and 10 [mm] for the other laminates.

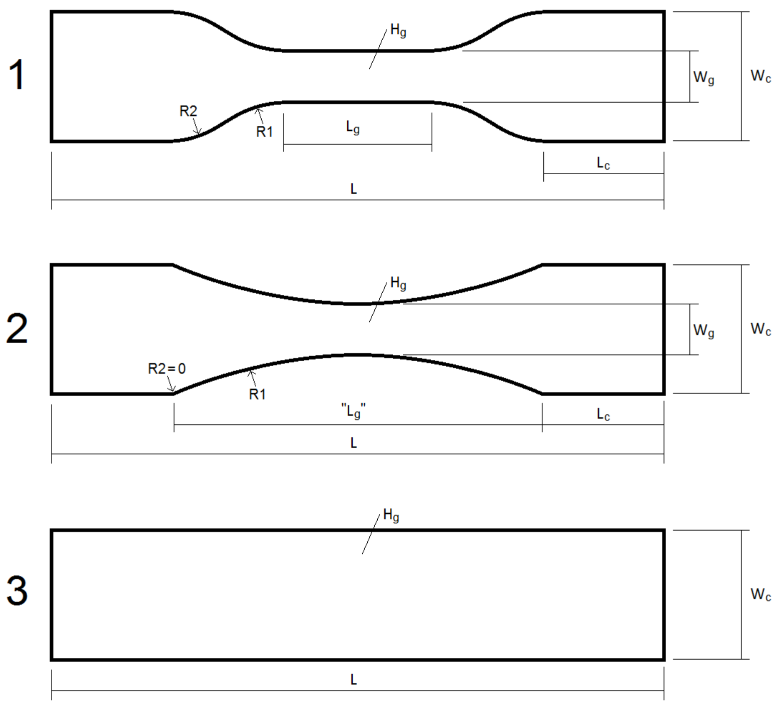

Figure 2. Specimen shapes used in the test campaign (figure dimensions not to scale).

4. Test programme

Table 1 contains an overview of the full test programme. The table shows that the obtained strain rates cover the range from quasi-static to 200 s^{-1} as mentioned in the introduction. In many high-rate cases, however, the data will not be reliable because one or more of the limits on strain rate mentioned in section 2 have been surpassed, indicated by the colours in the table. The results are most strongly influenced by the laminates with the least failure strain, as the test duration for these laminates is shortest: compare e.g. the 90º UD results to those for the woven ±45 laminates. The data in the table shows that, for the current set-up, load cell ringing influences the results from the lowest strain rate of all effects. It is also the most difficult to solve, as the other effects section 2 can be solved either with better equipment or by using a shorter specimens. The only solution for the ringing seems to measure load on-specimen, avoiding the need for a load cell altogether. Proposed solutions are a 'dynamometer section' [6] or using optically measured local accelerations [10]. Both have their challenges: materials with a rate-dependent Young's modulus for the former, and non-quasi-isotropic lay-ups and the relatively low strain rates of this research for the latter.

Table 1. Strain rates in [s^{-1}] for the full tensile test programme determined from the strain-time histories. Each entry is an average of at least five test results.

		Test speed [$m\ s^{-1}$]					
	Material	0.0001	0.005	0.05	0.5	5	15
Carbon/epoxy	Pure epoxy	0.0014	0.067	0.55	6.0	49	113
	$[90]_8$	0.0017	0.086	0.61	5.6	59	112
	$[\pm45]_{2s}$	0.0011	0.055	0.51	2.8	80	176
	$[45/0/-45/90]_s$	0.0008	-	-	-	57	-
	$[\#(0/90)]_{4s}$	0.0006	0.027	0.22	1.9	48	155
	$[\#(90/0)]_{4s}$	0.0007	0.027	0.22	1.5	46	136
	$[\#(\pm45)]_{4s}$	0.0012	0.057	0.52	3.4	67	191
	$[\#(\pm45)/\#(0/90)]_{2s}$	0.0008	0.029	0.26	2.8	47	135
Glass/polyamide-6	Pure polyamide-6	0.0008	0.041	0.37	4.4	43	114
	$[0]_4$	0.0011	0.053	0.47	6.0	60	102
	$[90]_8$	0.0017	0.077	0.62	5.9	72	138
	$[90/0]_{2s}$	0.0010	-	-	5.0	46	-
	$[\pm45]_{2s}$	0.0013	0.058	0.56	3.1	89	194
	$[\#(0/90)]_{2s}$	0.0009	0.040	0.32	4.1	55	116
	$[\#(90/0)]_{2s}$	0.0009	0.042	0.34	3.9	53	146
	$[\#(\pm45)]_{2s}$	0.0015	0.068	0.63	4.3	74	205
	$[\#(\pm45)/\#(0/90)]_s$	0.0010	0.049	0.39	5.4	57	155

Colours indicate surpassing strain rate limits (see section 2):
Green: load cell ringing influences result
Blue: additionally, no more equilibrium
Red: additionally, camera acquisition rate insufficient

5. Results

As a presentation of all the results is not possible in this paper, only selected stress-strain curves are shown here. As mentioned in section 2, only those curves are shown for which none of the limits on strain rate have been surpassed. The figures in this section contain the original curves, as well as an average curve per test speed, obtained by fitting a fourth-order polynomial (11^{th} order for pure polyamide-6) to all available stress-strain data couples at that speed.

Figures 3 and 4 show the stress-strain curves obtained for pure epoxy and pure polyamide-6, respectively, at various strain rates. Clearly, the polyamide-6 shows a much more rate dependent behaviour. The strain to failure decreases and the maximum stress increases, until at some speed the specimens start to fail before any major plasticity occurs. The Young's modulus remains unaffected by

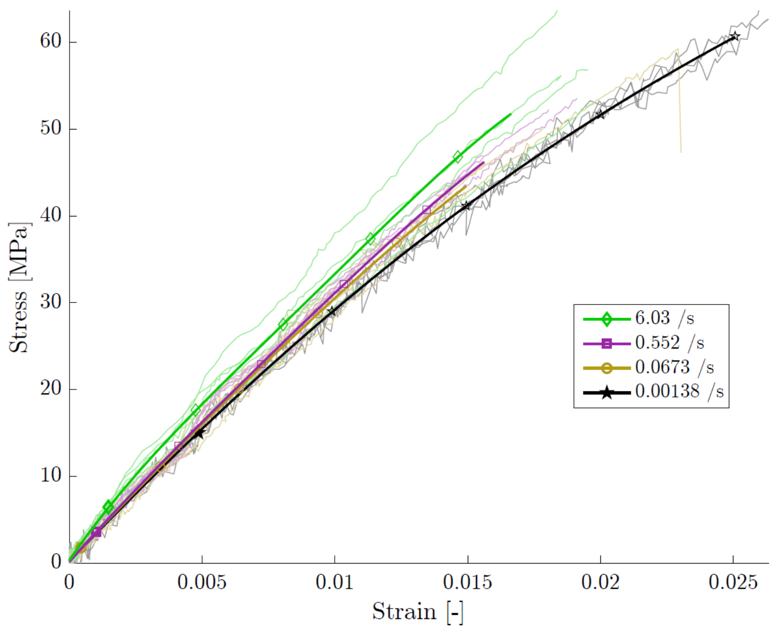

Figure 3. Stress-strain curves for pure epoxy.

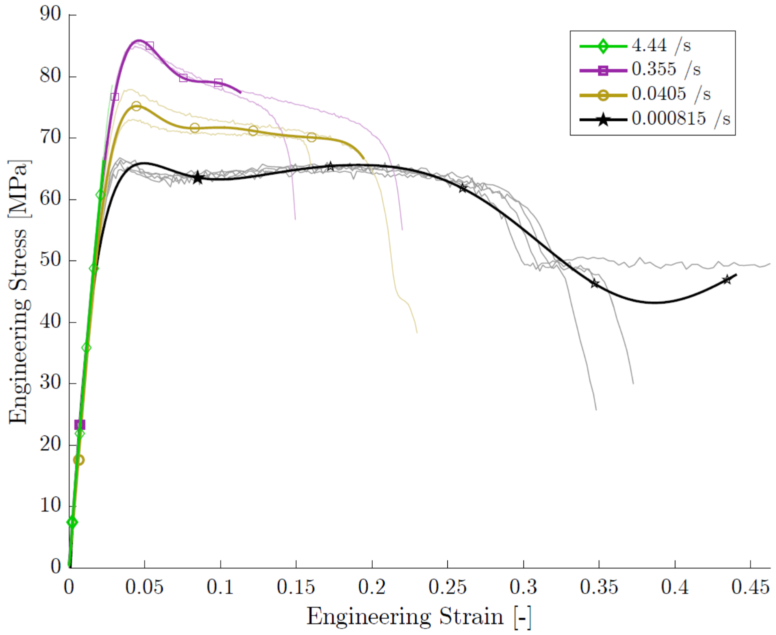

Figure 4. Stress-strain curves for pure polyamide-6.

rate. The epoxy shows no trend in stress or strain to failure which exceeds the variation, apart from the much higher values at the lowest rate, which is currently unexplained. A 20 % increase of the Young's modulus with strain rate is seen for epoxy over the valid range.

Figure 5 shows the stress-strain curves for 0º unidirectional glass/polyamide. The absence of plasticity in the curves, even for the lowest rate, shows that the behaviour is fibre-dominated. The maximum stress, maximum strain and Young's modulus all increase over the valid range of rates investigated. This matches the behaviour of glass fibres in literature [11], which are thus also expected to dominate the rate-dependence of the composite. 0º-unidirectional carbon/epoxy could not be made to fail correctly in the test set-up, due to a too small clamping area. Again fibre-dominated behaviour is expected, though, which should result in an absence of rate-dependency for this laminate [12].

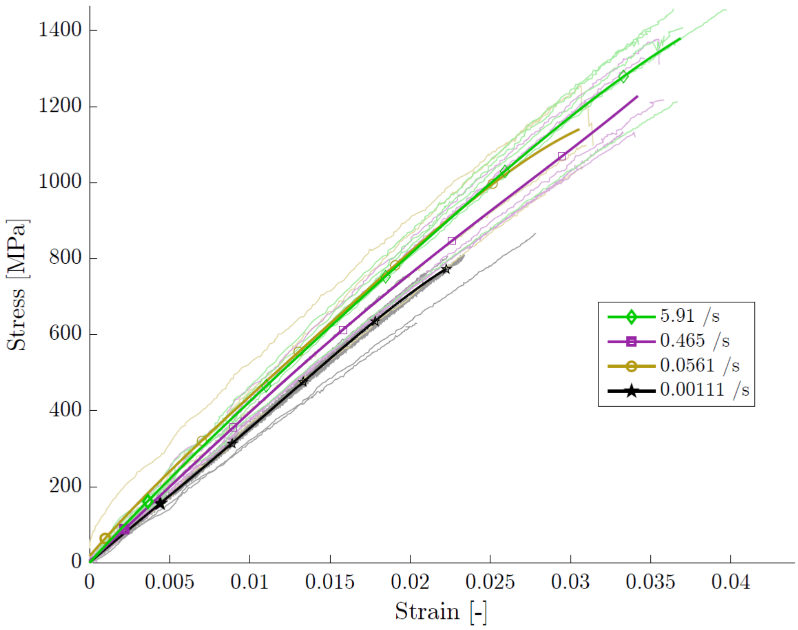

Figure 5. Stress-strain curves for 0º-UD glass/polyamide-6.

Figure 6 contains the stress-strain curves at various rates for plain woven carbon/epoxy in the 0º-direction. The curves show an absence of rate-dependency. The same can be said for the stress-strain behaviour of all investigated carbon/epoxy laminates which contain 25% or more fibres in the 0º-direction, woven or not. Hence, it is concluded that one 0º-layer in every four layers of a carbon/epoxy laminate is enough to invoke fibre-dominant behaviour and thus independency of strain-rate.

A similar conclusion can be drawn for glass/polyamide-6. Figure 7 shows the stress-strain curves for twill woven quasi-isotropic laminate at several strain rates. Although the modulus is reduced compared to the 0º-unidirectional case in figure 5, the behaviour is also fibre-dominated, and again the trend of rate-dependency is followed: stress, strain and modulus all increase with strain rate.

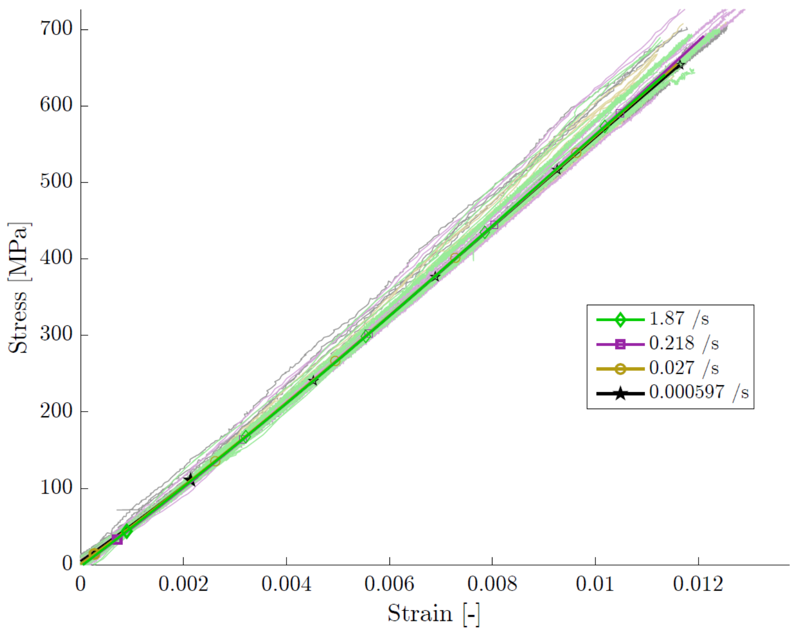

Figure 6. Stress-strain curves for carbon/epoxy [#(0/90)]$_{4s}$.

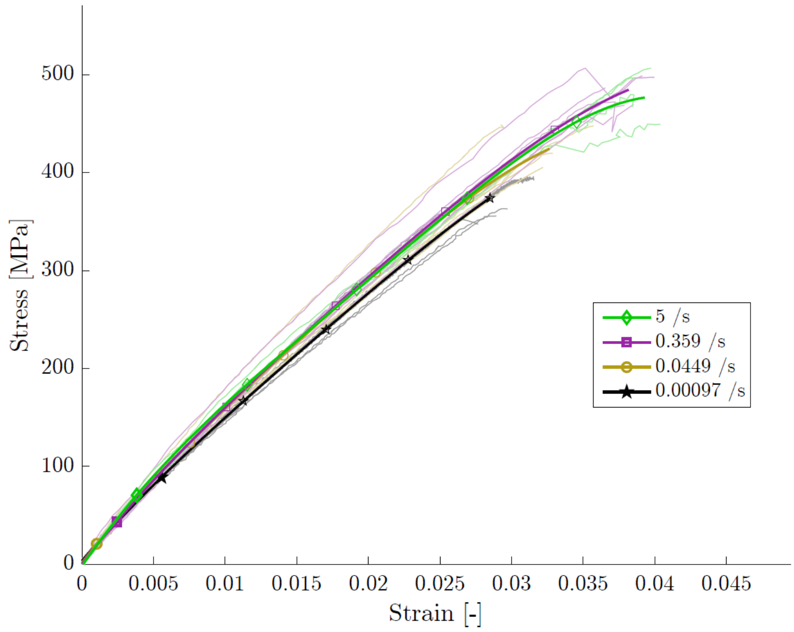

Figure 7. Stress-strain curves for glass/polyamide-6 [#(±45)/#(0/90)]$_s$ (quasi-isotropic)

It is therefore concluded that when a laminate shows fibre-dominant stress-strain behaviour, which is found for any laminate with 25% 0º-fibres or more, also the rate-dependency of that laminate follows the trends of the fibres.

6. Conclusions

A hydraulic pulse test bench was used to obtain full stress-strain curves over a range of strain rates for a variety of composite laminates. Care was taken to obtain a correct synchronization of stress with strain. Conclusions were based solely on results that are free of dynamic influences which are caused by testing at a too high strain-rate. It was found that rate-dependency of a laminate follows the behaviour of 0°-fibres for laminates which show fibre-dominant behaviour. Carbon/epoxy laminates containing more than 25% fibres in the 0°-direction, woven or unidirectional, can thus be assumed rate-independent in the range investigated. Glass/polyamide-6 laminates with the same percentage of 0°-fibres show an increase of maximum stress, strain to failure and Young's modulus with strain rate.

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