Deformation and fracture of unidirectional GFRP composites at high strain rate tension

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Abstract

This work deals with experimental investigation of the high strain rate behaviour of unidirectional (UD) glass fibre-reinforced (GFRP) composite materials. The related experiments were performed with a high rate test machine to determine the mechanical properties of UD E-glass/epoxy composites. The specimens were tested separately under quasi-static and high-speed conditions with loading rates of up to 20 m/s. All specimens were tested to failure in order to characterise the effect of high strain rate on failure strength of the material. The results show that high strain rates have a significant effect on the properties of UD GFRP composites. The increment of an ultimate strength with high strain rate is proportional to the strain rate in a given range with remaining elastic modulus.
Keywords: composites, dynamic tensile load, mechanical properties, fracture.

1 Introduction

Composite materials are widely used in civil and military engineering, aerospace, marine and automotive industries. In last thirty years research on the high strain rate response of laminated fibre reinforced composites significantly expanded as these materials are increasingly used in variable lightweight structural applications. In some cases, the loading on these structures is dynamic. Up to now, most structural designs are based on the material properties obtained through quasi-static tests at low strain rates. However, there is some evidence [1, 2, 3] that in many cases the mechanical properties of composite materials are significantly dependent on the strain rate. For example, the ultimate strength or modulus of elasticity for composites could increase compared with the value under quasi-static loading conditions, [4, 5]. The behaviour of the fibre-reinforced composite materials at high strain rates has been experimentally studied in many aspects [6, 7], mostly under impact compression load by the Split Hopkinson Pressure Bar (SHPB) method [8], which is widely used to obtain high strain rate test data of composites under compression, tension and torsional loading as it gives the possibility to test materials over a wide range of strain rates. In paper [7] over 120 articles dealing with high strain behaviour of composites were reviewed. It showed that SHPB method is most popular, but use of split bars for composites needs very complex study of wave propagation in composite materials because elastic wave propagation like dispersion and edge reflect effects are dominant and must be taken into account in results interpretation at any strain rate range, [9, 10]. In excellent review paper [11] experimental methods used to determine the dynamic properties of composites and test data from 31 papers are summarized. The results are very controversial. For example, authors of work [14] have founded a decrease of the ultimate stress for unidirectional glass/epoxy specimens, which is clearly in contradiction with the results form paper [1]. The longitudinal elastic modulus of the same material is found, on the one hand, to increase by up to 50% by some authors and, on the other, to be equal for static and dynamic case, [11]. Only a few works are provided for detailed experimental analysis of dynamical tensile loading of composites by not using SHPB method, such as [5, 13, 14]. The problem of wave propagation can be minimised and sometimes almost eliminated by using servo-hydraulic machines, which produce excellent and highly repeatable results without superimposition of stress waves, [5, 15, 16]. The use of such a machine could cover the stain rate range from quasi-static to 100 s^{-1} and only the velocity of actuator or hydraulic piston limits bigger value. Towards this objective unidirectional E-glass/epoxy composite specimens are specially manufactured and tested on an Instron high strain rate machine to investigate the effect of strain rate on the tensile strength of the UD composites.

2 Materials and techniques used

Tensile tests have been performed on a unidirectional and cross-ply E-glass reinforcement and epoxy matrix composite specimens whose fibres were oriented longitudinally (0°) to the direction of tensile load.

2.1 Specimen fabrication

For both quasi-static and dynamic test specimens with identical physical and mechanical properties E-glass/epoxy 5-ply ($[0_5]$ - unidirectional) laminate panel was manufactured using vacuum bag forming from E-glass pre-preg with epoxy matrix curing at the high temperature in oven. The nominal fibre volume fraction V_f, was about 60%. The prepreg material was unidirectional E-glass SP Systems SE84LV/EGL/300/400/37 type. The panel sizes after trimming was rectangular 600 × 500 mm. The unidirectional samples of size 250 mm length, 15 mm width, 1.2 mm thickness were then cut from the plate using a high-speed circular diamond saw with water-cooled blade. Specimen dimensions are shown in Fig.1 and conditions for quasi-static tests were chosen according to the ISO Standard, [17].

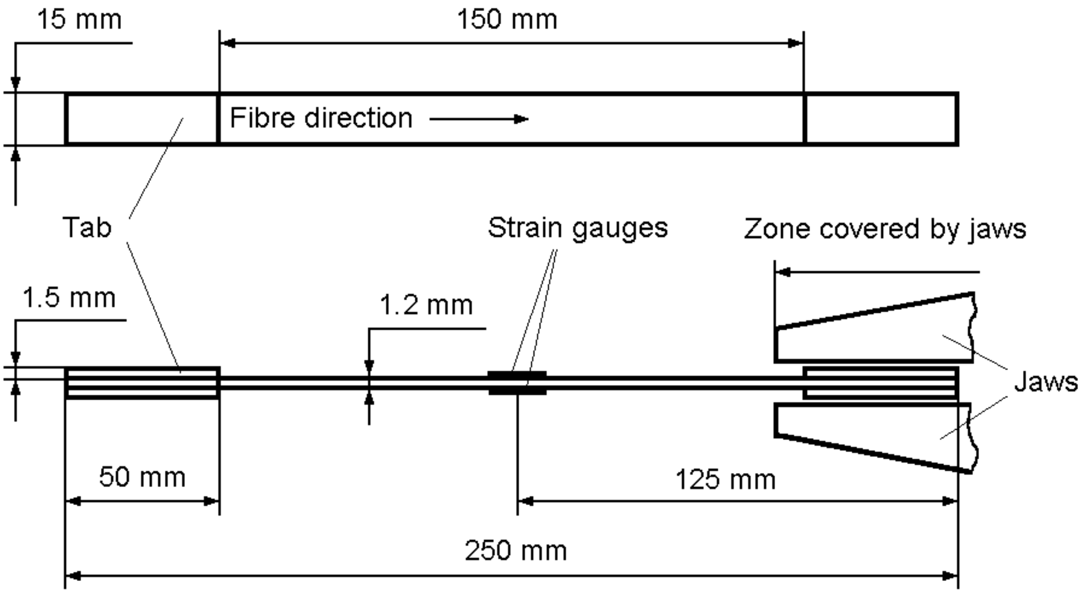

Figure 1: Geometry of the specimen (dimensions in mm).

2.2 Quasi-static testing

Quasi-static tests were carried out using a servo-hydraulic Instron 8802 testing machine at constant actuator velocity of 1 mm/min and correspondent strain rate was about 10^{-4} s^{-1}. An Instron Dynacell 100 kN load cell measured tensile load. The longitudinal strain of the specimen was measured by two TML® FLA-10-11 plane strain gauges with 10 mm gage length placed on both surfaces of the specimen and connected into opposite arms of Wheatstone bridge to eliminate possible bending strain influence during the test. The Araldite® 2011 multi-purpose epoxy with long working life and excellent impact resistance was used for bonding both stain gauges and aluminium tabs to the specimens for quasi-static and dynamic tests. To determine mechanical properties and ultimate caring capacity six specimens were tested to failure at quasi-static strain rate.

The tests showed linear elastic behaviour and brittle-like type fracture for the unidirectional composite material accompanying instant multiple failures with. Typical strain-stress curve and specimen view after the test are shown in Figures 2 and 3.

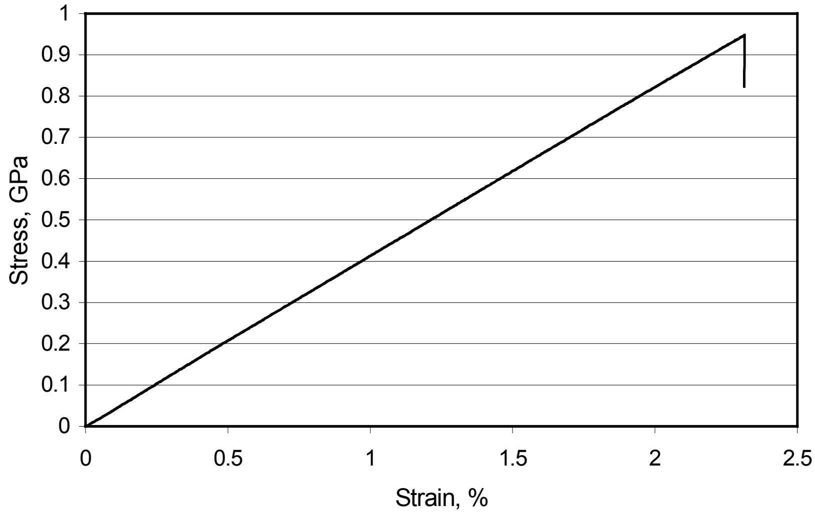

Figure 2: Typical quasi-static strain-stress diagram.

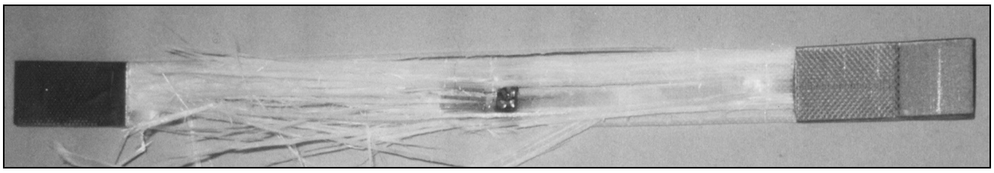

Figure 3: Specimen view after the failure.

The quasi-static test results are presented in the table 1, where E is elastic modulus, σ is maximum stress and ε is ultimate strain in longitudinal direction.

Table 1: Quasi-static test results.

Test	E (GPa)	σ (GPa)	ε (%)
Test 1	40.934	0.948	2.315
Test 2	41.095	0.934	2.278
Test 3	39.243	0.958	2.446
Test 4	40.838	0.887	2.176
Test 5	40.720	0.963	2.368
Test 6	39.331	0.888	2.389
Average	**40.36**	**0.93**	**2.33**

2.3 Dynamic testing

An Instron high rate testing machine VHS100/20 is used to perform dynamic tests on the composite material specimens. This machine is designed to operate at up to dynamic loads of 100 kN and actuator velocity of 20m/s. The actuator is controlled to a constant velocity during each test. The piston is accelerated to the required velocity before the grips are activated to apply load to the specimen. Fig. 4 shows the design of grips. In this design, wedges are used to keep the jaws of the grip apart despite a closure force generated by tightening four high-carbon steel bolts. Initially the actuator can descend with the specimen passing freely between the jaw faces. However two vertical knock-out rods pass through the wedges, and when the end of travel of these rods is reached, the wedges are pulled out, and the grip snaps shut onto the specimen.

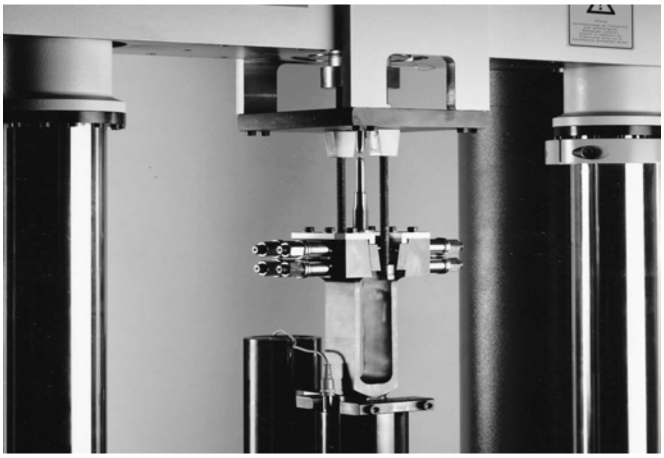

Figure 4: “FastJaws” grip design.

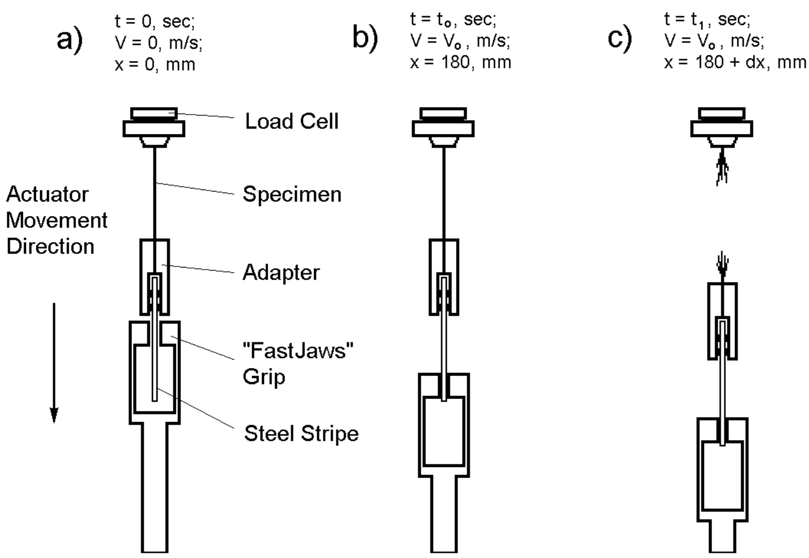

Figure 5: Schematic view of specimen loading and fracture by “FastJaws” grips.

For performing a tensile test, the sequence of operations is as illustrated in Fig.5. The supply pressure accumulators must be fully charged – these provide the energy, which will be dissipated in the test. Then a calibration file is used to read off the valve drive signal needed to reach the target velocity for the test, and the valve are opened by applying this constant drive signal to the electric current amplifier. The actuator will accelerate to its terminal velocity, taking up slack in the load string (a). The machine will have been set up to ensure there is enough slack to allow the actuator to reach its steady state velocity before engaging the specimen (b). Once engaged, the specimen is deformed until it fails (c), whilst the load, position and strain are monitored and recorded by computer control and data acquisition system.

The main experimental feature of this investigation was to use exactly the same coupon configuration specimen and strain gauges both for quasi-static and dynamic tests to be sure that geometrical sizes and ends fixing conditions do not affect to tensile load and strain measurement results. To achieve this and also to prevent the crushing of composite specimen due to sidekick from jaw faces of "FastJaws" grips at the initial moment of clamping and subsequent failure from edge effect special adapter was designed. This adapter provided a rigid connection between the composite specimen and disposal mild steel stripe with 5 mm thick and 30 mm width, which was loaded first and transferred tension from actuator to the composite specimen. Typical signals from the compact-size piezoelectric Kistler® load cell, strain versus the time and stress-strain curve for the specimen tested at 5 m/s velocity (test 1 from Table 2, actually) are shown in Fig. 6.

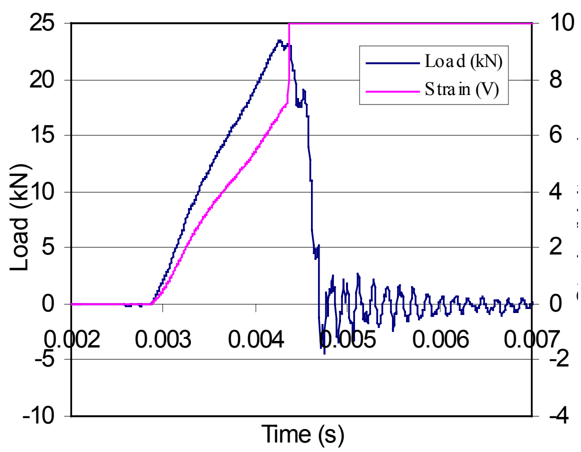

Figure 6: Signals from load cell and strain gauge.

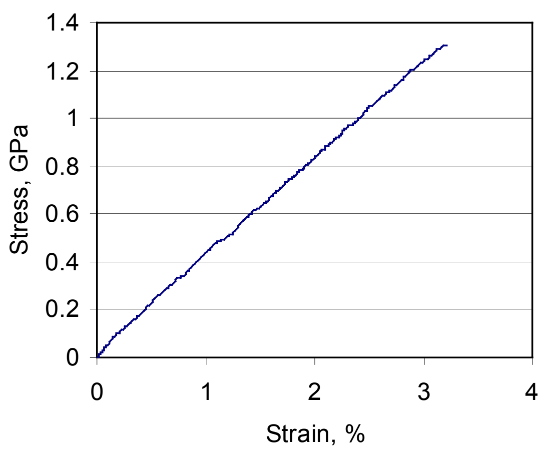

Figure 7: Strain-stress diagram

All signals showed in Fig. 6 were not subjected to any digital filtering or computing interpolation. The slight non-linearity in the beginning of the loading process caused by instant acceleration of additional mass (specimen with adapter and steel stripe) totally self-compensated when time was taken out as parameter from stress-strain curve. For all dynamical tests presented here the peak value of the load matched with maximum value of tensile strain signal; this indicates fact that real specimen fracture moment was observed before strain gauges failed. After taking out the time like parameter we obtained strain-stress diagram presented on Fig. 7.

Table 2: Dynamic test results.

Stress to failure (GPa)						
velocity	test 1	test 2	test 3	test 4	test 5	**Average**
1 mm/min						**0.93**
1 m/s	1.27	1.359	1.343	1.297	1.204	**1.294**
5 m/s	1.305	1.324	1.375	1.321	1.28	**1.321**
10 m/s	1.424	1.411	1.251	1.405	1.40	**1.378**
15 m/s	1.427	1.345	1.541	1.470	1.408	**1.438**
20 m/s	1.495	1.581	1.476	1.446	1.354	**1.47**

Strain to failure (%)						
velocity	test 1	test 2	test 3	test 4	test 5	**Average**
1 mm/min						**2.33**
1 m/s	3.07	3.21	3.42	3.31	2.92	**3.19**
5 m/s	3.2	3.36	3.28	3.53	3.25	**3.32**
10 m/s	3.44	3.38	3.07	3.55	3.43	**3.37**
15 m/s	3.54	3.45	3.59	3.41	3.74	**3.55**
20 m/s	3.69	4.24	3.68	3.52	3.57	**3.74**

Young modulus (GPa)						
velocity	test 1	test 2	test 3	test 4	test 5	**Average**
1 mm/min						**40.36**
1 m/s	41.434	42.36	40.984	39.208	42.562	**41.307**
5 m/s	40.709	41.363	41.882	42.074	40.202	**41.246**
10 m/s	42.779	41.115	40.611	42.234	41.149	**41.577**
15 m/s	40.465	39.279	40.751	41.309	39.802	**40.321**
20 m/s	41.438	39.395	41.119	41.01	38.697	**40.332**

Strain rate (s^{-1})						
velocity	test 1	test 2	test 3	test 4	test 5	**Average**
1 mm/min						**10^{-4}**
1 m/s	3.55	3.87	4.05	3.97	3.55	**3.8**
5 m/s	22.64	22.25	22.50	23.11	22.74	**22.65**
10 m/s	37.28	29.21	37.47	26.32	32.95	**32.64**
15 m/s	42.63	46.51	36.01	45.70	28.42	**39.85**
20 m/s	38.74	47.79	45.41	37.69	34.83	**40.89**

Totally 25 specimens were tested at five different velocities: 1, 5, 10, 15 and 20 m/s to validate the reproducibility of results and they are shown in the table 2. The specimens viewed after the failure are shown in Fig. 8.

It is quite visible that with load velocity increasing the character of the fracture of composite specimens is changing: the failure became more total; the length of single fragments decreases and for high velocity above 15 m/s the specimen virtually disappeared because of total disintegration on small fragments and glass fibres particles.

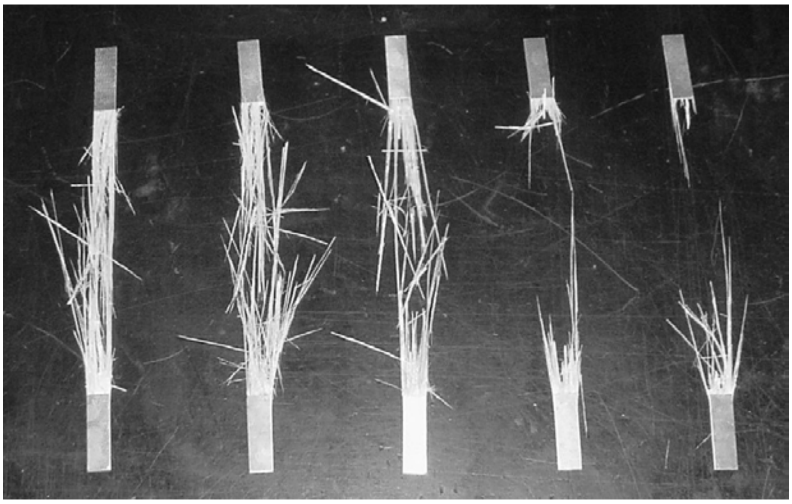

Figure 8: Specimens view after the dynamic failure.

3 Results and discussion

To analyse the obtained results and compare the static and dynamic properties of the unidirectional GFRP composite the following simple calculations were made. The stresses and strains for each of the velocities tested were averaged to obtain a set of 6 stress-strain curves corresponding to different loading velocity.

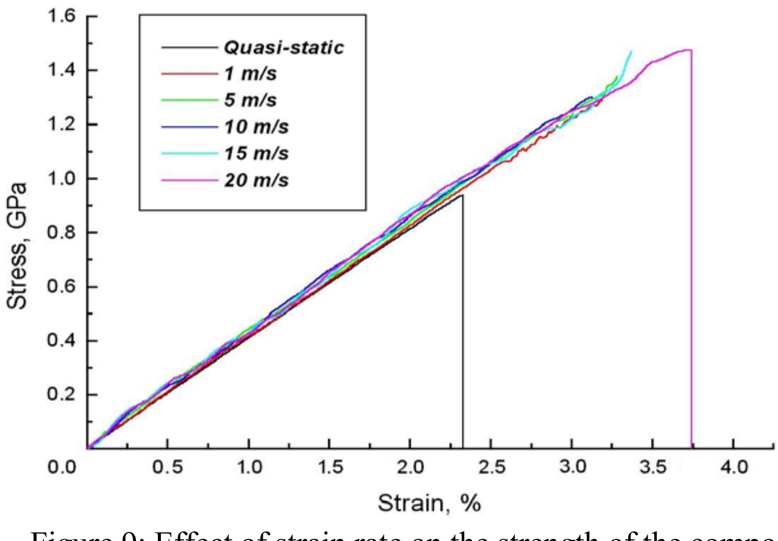

Figure 9: Effect of strain rate on the strength of the composite.

Because the sampling rate for all dynamic tests was identical and the same was used for all quasi-static tests the averaging was conducted by taking the mean value from five tests for every point on stress-strain diagrams for particular velocity. The result is presented in Fig. 9. As can be seen, with the increase of strain rate, the failure strength increases. The effect of the strain rate is remarkable on the ultimate strain and stress: the increment is more than 40 and 50 % correspondingly, while the effect of strain rate on the Young's modulus is less significant and the increment is about 1-2 % and is within limits of accuracy of the experiment.

So the elastic behaviour for the UD GFRP composite with longitudinal fibre orientation is not very sensitive to the strain rate: the Young's modulus stays more or less constant due to elevation of strain rate or elevates only slightly. However the very significant strength increment with almost constant elastic modulus and absence of any visco-elastic effects leads to the conclusion that dynamical properties of that composite are mostly dominated by the glass fibres properties.

4 Conclusions

The analysis of experimental results shows that high strain rates have a significant effect on the properties of unidirectional GFRP composite. The most important of this are:

- the behaviour of material under quasi-static and dynamic loading conditions is linear elastic up to the failure and its character does not change;
- a significant increment of ultimate strength within high strain rate is proportional to the strain rate in a given range with remaining elastic modulus;
- the dynamical properties of unidirectional glass-fibre reinforced composite are determined by the fibres properties and not the matrix.

5 Acknowledgments

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